Regional Approaches to Climate Change for Pacific Northwest Agriculture

Climate Science Northwest Farmers Can Use

Building Resilience to Climate Change in Cereal Production Systems: agroecosystem components and integrative approaches

Articles published in a Specialty Section: *Agroecology and Land Use Systems*, within the journals Frontiers in Ecology and Evolution, Frontiers in Environmental Science, and Frontiers in Plant Science

REACCH
Regional Approaches to Climate Change – PACIFIC NORTHWEST AGRICULTURE

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About REACCH

The work presented in the following articles was primarily supported by a large USDA CAP grant entitled "Regional Approaches to Climate Change (REACCH) in the Pacific Northwest" as well several collaborative grants funded by USDA and NSF-IGERT. The REACCH project is an interdisciplinary research effort that was developed across three states (Oregon, Washington, and Idaho), and between four institutions–the University of Idaho, Oregon State University, Washington State University, as well as the USDA Agricultural Research Service.

The REACCH project is designed to enhance the sustainability of cereal production systems in the inland PNW under ongoing and projected climate change, while contributing to climate change mitigation by reducing emissions of greenhouse gases. REACCH is a comprehensive response to the implications of climate change for the already challenging task of managing cereal production systems for long-term profitability. Scientists from many disciplines, including engineering, climate science, agronomy, sociology, and economics, are working together to ensure greater relevance of the information provided to regional cereal farmers and their associates. Our aim is to conduct the best agricultural science relevant to regional climate projections and the needs for adaptation and mitigation, and to extend this science to our diverse group of stakeholders.

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Building Resilience to Climate Change in Cereal Production Systems: Agroecosystem components and integrative approaches

Contents

Building Resilience to Climate Change in Cereal Production Systems: Agroecosystem components and integrative approach

About this Research Topic

The dryland, cereal grain production systems of the inland Pacific Northwest (IPNW), serve as an important source of soft white and hard red winter wheat to the global grain market. A marked precipitation gradient exists across the wheat production zone within the IPNW with mean annual precipitation varying from 150 mm in the west to over 750 mm in the east. This gradient leads to differences in biophysical constraints to crop growth. Social and economic drivers also change across the gradient, impacting cropping systems and the adoption of conservation practices. Without major sources of irrigation over much of the region, warmer and drier summers predicted by global climate models will likely force growers to adapt their cropping systems to maintain economic viability. The complex issue of increasing yields to meet the demands of future global population growth while building resiliency to climate change requires cross-disciplinary approaches to understanding the biophysical and socio-economic drivers within these systems. In this special issue we highlight not only the results of integrated study of multiple IPNW agroecosystem components (crops, weeds, insects, stakeholders, etc.), but an overall approach to working on large-scale, cross-disciplinary agroecological and climate change projects. While our focus in on IPNW systems, the approach and data reported here will be broadly applicable to cereal production systems around the world.

The wide range of precipitation and temperature across this region provides a unique opportunity to identify thresholds where growers are currently modifying their cropping systems in response to biophysical, social and economic factors. Managing crop type, rotation and variety to take advantage of future markets, applying the appropriate residue and tillage management to conserve water and minimize erosion, prescribing optimal fertilizer, and applying targeted and timely pesticide applications to avoid widespread crop failure are all effected to some degree by climate change.

The complexity of climate forcing in these ecosystems requires solutions developed from diverse interdisciplinary teams. The work presented in these articles was primarily supported by a large USDA CAP grant entitled "Regional Approaches to Climate Change (REACCH) in the Pacific Northwest" as well several collaborative USDA and NSF-IGERT grants. The coordination of research through these major grants allowed for a very thorough and detailed look at strategies to build resilience to climate change in this complex cereal grain production region.

In this Research Topic, we welcome articles authored by interdisciplinary teams of scientists, which in turn provide a thorough understanding of some of the major recommended adaptation strategies across the region. In addition, we would like to focus on the social dimensions that will influence change within different climatic zones of the IPNW as well as studies of the general scientific approach taken within the region to study climate change and agriculture. This Research Topic will also offer a global context by the inclusion of articles focused on an international arid cereals conference hosted by the REACCH project.

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REVIEW
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Integrating Historic Agronomic and Policy Lessons with New Technologies to Drive Farmer Decisions for Farm and Climate: The Case of Inland Pacific Northwestern U.S.

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Climate-friendly best management practices for mitigating and adapting to climate change (cfBMPs) include changes in crop rotation, soil management and resource use. Determined largely by precipitation gradients, specific agroecological systems in the inland Pacific Northwestern U.S. (iPNW) feature different practices across the region. Historically, these farming systems have been economically productive, but at the cost of high soil erosion rates and organic matter depletion, making them win-lose situations. Agronomic, sociological, political and economic drivers all influence cropping system innovations. Integrated, holistic conservation systems also need to be identified to address climate change by integrating cfBMPs that provide win-win benefits for farmer and environment. We conclude that systems featuring short-term improvements in farm economics, market diversification, resource efficiency and soil health will be most readily adopted by farmers, thereby simultaneously addressing longer term challenges including climate change. Specific "win-win scenarios" are designed for different iPNW production zones delineated by water availability. The cfBMPs include reduced tillage and residue management, organic carbon (C) recycling, precision nitrogen (N) management and crop rotation diversification and intensification. Current plant breeding technologies have provided new cultivars of canola and pea that can diversify system agronomics and markets. These agronomic improvements require associated shifts in prescriptive, precision N and weed management. The integrated cfBMP systems we describe have the potential for reducing system-wide greenhouse gas (GHG) emissions by increasing soil C storage, N use efficiency (NUE) and by production of biofuels. Novel systems, even if they are economically competitive, can come with increased financial risk to producers, necessitating government support (e.g., subsidized crop insurance) to promote adoption. Other conservation- and climate change-targeted farm policies can also improve adoption. Ultimately, farmers must meet their economic and legacy goals to assure longer-term adoption of mature cfBMP for iPNW production systems.

Keywords: adaptation, mitigation, diversification, intensification, socioeconomic, policy, socioeconomic, win-win

INTRODUCTION

Agriculture is an important player in climate change. The contributions of global agriculture to greenhouse gas (GHG) emissions and climate change are well recognized (Reicosky et al., 2000; Snyder et al., 2009), setting the stage for agriculture to play a positive role in GHG mitigation through implementation of numerous agronomic practices (Smith et al., 2007; USDA-ERS, 2016). Furthermore, innovations are needed to increase resilience of agricultural systems to climate change and to exploit the opportunities that climate changes present (IPCC (International Panel on Climate Change), 2007a,b). The United States Department of Agriculture (USDA) established goals for climate change mitigation and adaptation in its 2010–2014 and 2014–2018 strategic plans (USDA, 2010, 2014). Performance measures included tracking crop production, fertilizer use and conservation practices. The U.S. General Accounting Office (GAO) requires USDA to provide these performance measures to inform Congress and the general public about the USDA program progress. It has determined that USDA programs face major challenges in encouraging farmers to modify farming practices geared toward climate change adaptation and mitigation. A report to the Energy and Commerce Committee of the U.S. House of Representatives made the following recommendations: (i) translate, distill and deliver climate science research information in user-friendly formats and tools, (ii) provide financial incentives to encourage farmer adoption of what we will refer to as "climate-friendly Best Management Practices" (cfBMPs), and (iii) provide crop producers with farm level economic enterprise costs and returns of adapting cfBMPs, with the guiding principle of identifying systems that provide economically attractive pathways to advancing farm level climate change adaptation and mitigation (GAO, 2014). Addressing these recommendations has required detailed characterization and modeling of biophysical drivers associated with crop growth and production across different agroecological cropping zones. It has also required an understanding of the principle drivers of whole cropping patterns linked to changes in weather (Stöckle et al., 2017) and other drivers that influence farmer decision making.

The recommendation of the Energy and Commerce Committee will have different implications for specific crops and growing regions. This review focuses on wheat (*Triticum aestivum)*-based cropping systems of the Inland Pacific Northwest of the USA (iPNW), and has three objectives: (i) describe the historical evolution of iPNW wheat (*Triticum aestivum)* based cropping systems and efforts to achieve economic and environmental goals, (ii) review farm-level biophysical, socio-economic and agronomic decision drivers that include cfBMPs and potentially shape win-win scenarios across iPNW agroecological zones, and (iii) describe integrated cfBMPs' potential abilities to improve adaptability and flexibility of cropping systems that also contribute to system-wide GHG reductions. Its overall goal is to use historical lessons of multidisciplinary and integrated research, extension and stakeholder engagement to define pathways toward simultaneously achieving farm economic, legacy and climate change goals.

Win-win scenarios are defined herein as mature cropping systems with integrated cfBMPs that achieve shorter-term goals by improving farm profitability and building a stable farm legacy, while enabling longer-term GHG mitigation and flexible adaptability to annual weather and long term climate change. Synergistic impacts occur when multiple management strategies are integrated into whole cropping systems (Zentner et al., 2002), potentially creating these win-win cropping systems.

Developing and sustaining win-win scenarios relies on progressive farmers who are economically motivated to change and adapt new cfBMP integrated systems. These new systems must align with climate friendly iPNW farming goals (Kruger, 2004) by integrating agronomic management variables: conservation tillage and residue management, organic carbon (C) and nutrient recycling, refined N management, and crop diversification and intensification. All are well-recognized conservation management strategies and now they are also recognized for their potential to help dryland farmers achieve climate change adaptation and GHG mitigation (CGIAR, 2012).

HISTORICAL LESSONS ON MOVING TOWARD WIN-WIN CROPPING SYSTEMS

The history of iPNW wheat production is marked by a recurring theme of tradeoffs between farm profitability and the deterioration of soil health, air and water quality, organic matter and nutrient depletion (**Table 1**). The region has been dominated by soil-erosive but profitable cereal-fallow farming with little crop diversification (Schillinger and Papendick, 2008), despite recognition of soil deterioration during the first generation of regional wheat farming (Spillman, 1906; Sievers and Holtz, 1922). A similar history of wheat farming and soil degradation has also been documented in the Canadian western prairies (Janzen, 2001). Balancing farm profits while reducing environmental degradation is a main challenge in identifying effective win-win strategies for the iPNW and similar wheat growing regions.

Recurring History of Economic and Environmental Tradeoffs

The history of soil management in the iPNW mirrors that of the rest of the U.S. Individual land ownership and management on American farms forced pioneer farmers to choose between economic survival and soil stewardship, since soil rebuilding was slow, costly and sometimes not achievable with the available resources. Early government programs only addressed farmers' economic concerns without prioritizing land stewardship (Gray et al., 1938). Further compounding the problem, the iPNW evolved toward the segregation of animal and cropping systems soon after settlement, with wheat farming displacing sheep, cattle and hog ranching (McGregor, 1982). This regional trend of crop-animal segregation reflected a broader global disruption of organic nutrient cycling and C inputs (Magdoff et al., 1997), which was further accelerated by the advent of inexpensive fertilizers and global grain marketing that made exclusive crop farming more profitable regionally (McGregor, 1982) and globally (Kirkegaard et al., 2011). Lack of organic inputs combined with accelerated soil erosion contributed to the rapid decline of soil organic matter (SOM), native fertility and overall soil health and productivity (Spillman, 1906; Albrecht, 1938). Early conservation principles were primarily focused on using fertilizers and lime to replace depleted soil nutrients that were removed from the crop-soil system by grain harvest (Fulmer and Heileman, 1899). Soil restorative practices such as integration of grass pastures and animal manure, and rotating with grain legumes and mustards were recognized (Spillman, 1906), but not widely adopted. As a result, SOM continued to decline in the iPNW, with soil erosion occurring at annual rates of 10 to more than 67 MT/ha (Kaiser et al., 1954; Schillinger and Papendick, 2008). Conventional tillage and fallowing have been the primary contributors to SOM decline in the iPNW (Machado, 2011). Gray et al. (1938) attributed the lack of significant progress in adopting soil conserving practices to a failure to address short-term economic needs of farmers.

In 1975, iPNW research and extension programs, Solutions to Economic and Environmental Problems (USDA-funded STEEP, nd[1]; Oldenstadt et al., 1982) followed by the USDA-funded Columbia Plateau PM10 (CP3) project were established with specific goals to develop and implement economically viable solutions to reduce water and wind erosion. Viable reduced- and no-tillage systems were the major research outcomes of these projects, followed by vigorous extension efforts to translate the research into grower-adaptable individual best management practices, principally outlined in compendiums of soil management guides (STEEP nd[1], Papendick et al., 1985). The projects fostered collaborations among researchers, farmers, crop advisors and agribusinesses. Significant gains in conservation farming were documented, but adoption was not universal (Kok et al., 2009).

TABLE 1 | Historical timeline of movements, events and principles established in the inland Pacific Northwestern US (iPNW) wheat-based agriculture, and resulting tradeoffs between short-term economics and long-term impacts on soil, air and water quality.

Date	Key movements, events, and established principles
1880's	– pioneer wheat farming
1890's—1940's	– early recognition of nutrient, erosion and SOM depletion, requiring fertilizers, manures, other crops – wheat outcompetes livestock farming
1950's—1960's	– synthetic fertilizers, semi-dwarf wheat increase yields; nutrients replenished, but cover and green manure cropping diminished – decline in soil productivity masked by fertilizers
1970's—1980's	– grain peas, oilseeds introduced – record soil losses, declining water, air and soil quality – farm bill supports commodity crops and increased conservation – farmers, agribusiness and researchers spur development of no-till planting and fertilization equipment and BMPs
1990's	– decreased soil losses, improved NUE with rising fuel and fertilizer prices, conservation programs, environmental activism – grass roots farmer organizations – win-win scenarios vs. government regulations debated – projections of climate change and global crop demand – energy crisis, biofuel-commercialization of precision technology
2000's to present	– private, federal investments in climate change research – year and decade of soil: commitment to soil quality – soil carbon credits, societal carbon taxes proposed and debated. – win-win scenarios encouraged by US GAO for implementing cfBMPs

This history sets the stage for a new generation of cropping systems that minimize the tradeoffs by achieving both economic and environmental goals.

The Need for Integrated Systems

Research focused on specific practices such as tillage, however successful, failed to address the system-wide changes and farm scale economic implications required to incentivize farmer adoption. In addition, specific economic drivers can distort system-wide management for sustainability. Through the 1980s, commodity-based subsidies and growing global markets had fostered the winter wheat dominated cropping system in the region without regard to pest problems and erosion (Young et al., 1994a). Up to the mid-1980s producers moldboard-plowed their fields to bury residue and weed seeds prior to planting the following year's wheat crop. In addition,

[1]STEEP (Solutions to Environmental and Economic Problems) nd. Advancing sustainable agriculture in the Pacific Northwest. Conservation Tillage Systems Information Resource. Pullman, WA: Washington State University Extension Service. Available at: http://pnwsteep.wsu.edu/tillagehandbook/index.htm (Accessed on April 10, 2017).

rotations with spring pea (*Pisum sativum*) improved wheat yields, but required eight tillage operations between wheat harvest to post plant spring pea. In 1985, the USDA-ARS initiated a field-size, long-term Integrated Pest Management (IPM) research project for conservation crop production in the PNW (Young et al., 1994a). This was the first farm scale, multi-and interdisciplinary cropping systems research project that focused on weed management integrated with conservation tillage in the iPNW. This project demonstrated that integrated cropping systems research could lead to less risky alternative cropping systems that could motivate farmer adoption (Young D. L. et al., 1994).

Cropping system comparisons of variable costs demonstrated that reduced fuel and number of field operations with direct seeding are somewhat offset by the increased herbicide costs associated with the practice. The cost tradeoffs coupled with direct seed grain yields result in similar economic returns in the intermediate zone of eastern Washington (Esser and Jones, 2013) and the drier grain-fallow regions of eastern Oregon (Machado et al., 2015) when compared to yields obtained with conventional tillage. Comparisons of conservation-till 4-year crop rotation systems and conventional-till 2-year wheat-fallow rotation systems also demonstrated a marked reduction in water runoff and soil erosion in the conservation-till systems (Williams et al., 2013). Similar results obtained in drier traditional iPNW wheat-fallow systems led Janosky et al. (2002) to conclude that since no "short- or long-term economic sacrifice" was required to shift to a minimum tillage system when using existing on-farm equipment, a neutral-win solution to soil erosion could be achieved when reduced-till and conventional-till wheat yields were comparable. Yet, strict no-till systems required fixed-cost investments in expensive, specialized direct seeding equipment, so these systems had only been moderately adopted (Kok et al., 2009). While projects like the USDA IPM project, described above, developed integrated strategies identified as essential for protecting soil and water quality by the USDA (Batie et al., 1993) and encouraged early adopting farmers to try direct seeding, they fell short in economically motivating farmers into universal adoption of these no-till systems that required new equipment. The economic advantages of direct-seeded wheat cropping systems combined with alternative crop sequences, tailored N and weed management were later demonstrated as potential win-win scenarios for direct-seeded dryland wheat systems in western Canada (Smith et al., 2006).

Conservation Farming Enables Climate Change Adaptation and Mitigation

Now, new environmental challenges imposed by climate change require proactive changes in cropping systems, but history dictates that initial adoption may also require economic incentives. Well-recognized best management for protecting soil health, and air and water quality also have the ability to foster climate adaptive and GHG-mitigating systems, often by incorporating elements designed to conserve soil and nutrient resources. Furthermore, the same cropping strategies that focus on building soil, protecting air and water quality, and supplying crop nutrients have the ability to reduce costs associated nutrient inputs and losses. The US Government Accounting Office cited the USDA programming and performance goals on soil and water conservation and quality as examples of needed elements for USDA's current climate change strategic plan (GAO, 2014).

COMPLEX FACTORS DRIVING FARMERS' CROPPING SYSTEM DECISIONS

To translate climate change science into adoption of transformative systems, it is important to focus on decision drivers from a farmer's perspective (Reganold et al., 2011). The farmer's decision process involves information gathering from multiple sources (**Figure 1**). Historically, farmers have been challenged with seasonal fluctuations in weather, farm input prices, as well as local and global competition and markets (Coughenour and Chamala, 2000). They must assimilate massive amounts of information along all of these fronts in order to make appropriate agronomic management decisions with their foremost goals of sustaining a business, raising a family, supporting their community while enjoying farming life and building their farm legacies (Jonovic, 1997; **Figure 1**). There is a need for integrated efforts of researchers, extension advisors, environmental stakeholders, market end-users and policymakers to develop and drive cropping system solutions (Smit and Skinner, 2002) that are feasible for farmers to adopt at a local level (Caron et al., 2014). Farmers are familiar with the proven conservation strategies and affiliated government support policies. Many of these same practices are now recognized to provide climate change benefits, so current climate change research and extension can focus on improving and integrating these practices, rather than promoting substantial new changes that inherently come with greater risks and uncertainty. A focus on farmers' immediate concerns and priorities, with an emphasis on familiar conservation practices already supported by environmental stakeholders and policymakers, can help drive farm planning that includes agronomic management shifts that also provide tangential benefits to address climate change (Howden et al., 2007).

Biophysical Drivers of iPNW Alternative Cropping Systems

Farmers are very aware of seasonal weather variability and ways to deal with it. Furthermore, they generally acknowledge that weather patterns have recently shifted (Seamon et al., 2016). In support of these recently observed shifts, climate change models project temporal and spatial long-term shifts in temperature and precipitation means and extremes. In general, the iPNW is predicted to experience warmer, wetter winters; more frost-free days; drier, hotter summers; and more variability in temperature and precipitation (Stöckle et al., 2010; Abatzoglou et al., 2014). These projections suggest a need for flexible, diversified systems that enable nimble farm adaptability to

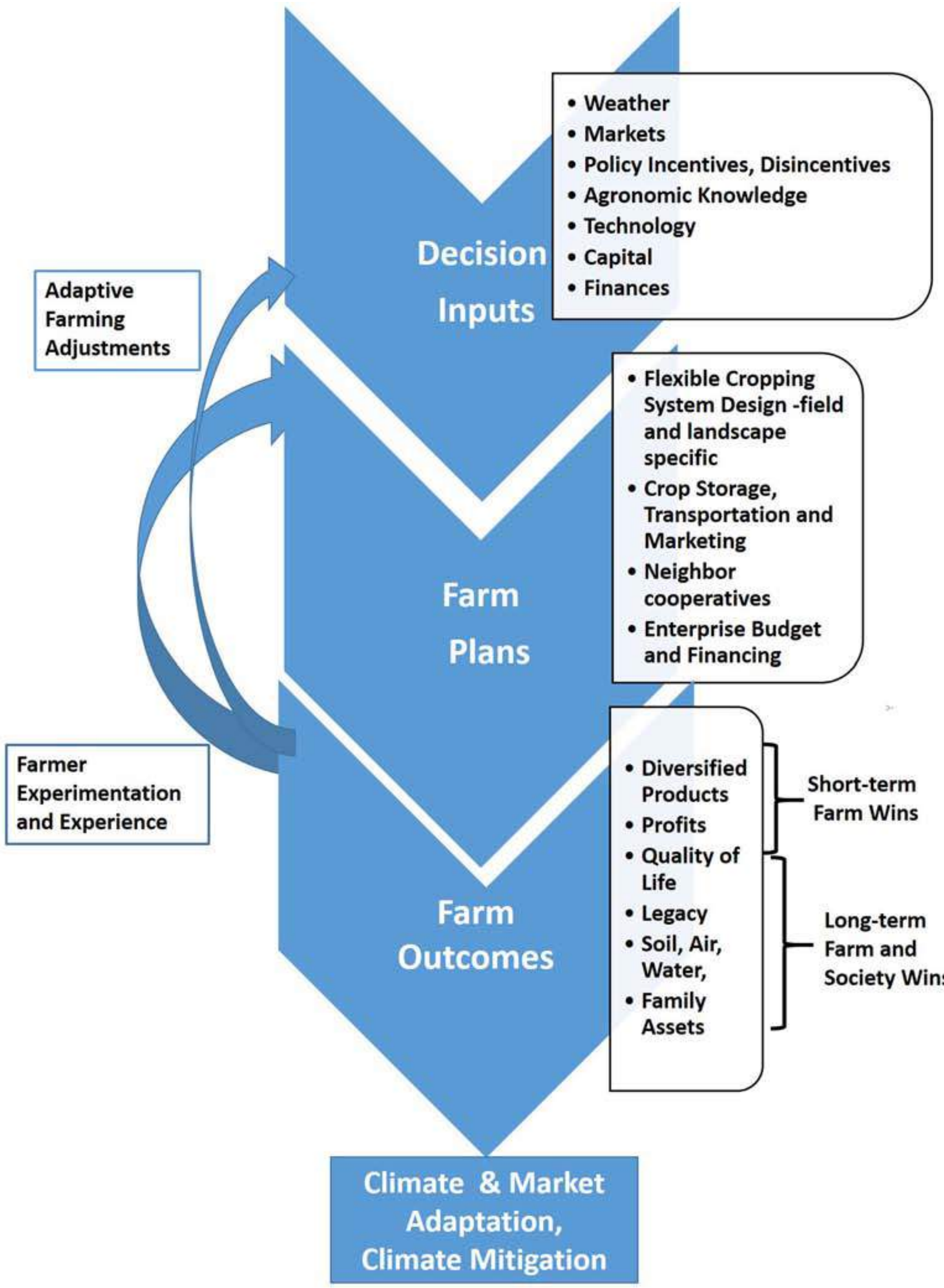


FIGURE 1 | Input drivers of farmer decisions and plans targeting short- and long-term farm outcomes, with government incentives and disincentives targeting long-term societal wins. Successes or failures in accomplishment of farmers' primary goals provide feedback for managing flexible, evolving farming systems. Win-win systems feature improved farm adaptability to markets and climate, while increasing greenhouse gas (GHG) mitigation as co-products.

climate change, as well as mitigating GHG. For example, future systems that encourage greater water infiltration and soil water storage combined with greater frequency of rotational winter crops that feature earlier flowering and grain development will help farmers adapt to the projected hotter, drier summers (Kaur et al., 2017).

Socioeconomic Drivers of iPNW Alternative Cropping Systems

A prevalent sociological factor that drives farmers' pursuits of improved soil health and conservation relates to their commitment to their farm legacies (**Figure 1**). This commitment is rooted in the multi-generational family farms prevalent in the iPNW, many extending back four generations to the earliest settlers of the early 1880s (McGregor, 1982). A survey of Washington "centennial farms" was conducted in the late 1980's in which there were 400 applicants and 210 approved 100 year family farms (Lang and Flynn, 1989). These farm families stay committed to maintaining healthy and sustainable farms that can be passed down to the next generation. Farm legacy and economically-driven cropping systems can still feature climate change adaption and mitigation as by-products, since climate change concerns rank low among farmers' priorities and recognized benefits of alternative systems (Seamon et al., 2016). Specifically, most iPNW farmers still see no need to make major changes to farming operations and crop rotations to adapt to climate change or contribute to climate mitigation (Seamon et al., 2016). Yet they are open to adopting cfBMPs such as integrating canola (*Brassica napus*; Pan et al., 2016b) and legumes (Vandemark et al., 2014) into their rotations for achieving shorter-term economic and agronomic benefits.

Incentives for adopting BMPs in general, can come from policy or market forces. These policies must be sufficiently substantial for farmers to invest time and resources to change practices (Ribaudo et al., 2011). High startup costs and lower initial yields associated with new systems often necessitate government support (Dillman et al., 1987). Yet, subsidy payments provided by conservation compliance programs may be insufficient to pay for high start-up costs of alternative management adoption such as direct seeding, which incurs expensive fixed and variable costs (Young D. L. et al., 1994). Additional cost savings and profitability of alternative crop rotations are now necessary for these systems to be fully implemented (**Figure 1**).

Win-win cropping systems should also be adjustable to socioeconomic market shifts. Farmers are already challenged to improve sustainability while increasing crop productivity per land base and supporting changing demands for diversified crop products such as food, feed, fuel and fiber products (Graham-Rowe, 2011; Tilman et al., 2011; **Figure 1**). Currently, the iPNW cereal production largely meets the bulk commodity, export cereal grain markets fostered by regional grain commissions; about 90% of the wheat produced is marketed to Asian countries (Washington Grain Commission, 2016). However, current market trends point toward the expanding demand for diversified, more-sustainably produced, crop-based food protein, healthy grains and oils (Greene et al., 2017).

Farmer networks also help drive adoption of alternative cropping systems. Emerging markets for alternative crop products challenge farmers to develop innovative networks (Klerkx et al., 2010; Reardon et al., 2016). To help farmers navigate these market opportunities, grassroots grower associations have developed certification recognizing sustainable practices, share knowledge amongst farmers and communicate eco-friendly farming practices to consumers. These iPNW organizations are attempting to redesign historical win-lose scenarios associated with conventional wheat farming (**Table 1**) and move toward win-win approaches. They are responding to environmental pressures and emerging food markets, simultaneously addressing societal concerns for food, soil, water and air quality. Some organizations are also using food labeling to capture market attitudes toward genetically modified crops, and organically and sustainably produced food. These attitudes will continue to shape market driven choices that in turn, shape the diversification of regional cropping systems.

These grower-based organizations push dual C pathways toward emerging grain markets while improving organic C cycling and soil C sequestration (**Figure 2**). For example, Shepherd's Grain is a farmer-based company that serves regional markets demanding high-quality grain by adhering to sustainable management practices with no-till seeding as a cornerstone. Its grain products are Food Alliance certified (Banks, 2016). The Pacific Northwest Direct Seed Association (PNDSA), a grass-roots, farmer-organization holds annual conferences focused on practical farming practices such as crop rotation, residue management and no-till systems that improve soil quality (**Table 2**; PNDSA, 2017). The PNDSA has also developed a certificate program, "Farmed Smart" that recognizes sustainable grain production practices and communicates to environmental groups that sustainability BMPs are practiced. Producing organically certified grain is difficult in the dryland iPNW given challenges associated with weed management and soil fertility (Borrelli et al., 2014; Tautges et al., 2016). Yet several farmers across the region (Lorent et al., 2016) have found means to overcome these barriers and are intent on enhancing soil health by storing more soil C (**Figure 2**) and reducing chemical inputs to meeting growing regional market demands for organic products.

Policy Drivers of iPNW Alternative Cropping Systems

State and federal policies provide financial and technical support to help initiate farmer adoption of new systems (**Figure 1**). For example, the USDA Conservation Compliance Program provides guidance, financial support and tools to farmers who participate in the program to control erosion on high risk land. Currently, farmers are required to implement and document a variety of conservation practices in order to qualify for most government programs such as conservation payments and crop insurance.

Some farm support programs have not been as successful at driving conservation adoption. A decade ago, C trading was initiated so that farmers might earn soil C sequestration credits to help balance the economic shortcomings of cfBMP adoption (Branosky, 2006). The relative costs and benefits of GHG emissions caps and N fertilizer taxing were debated (Avi-Yonah and Uhlmann, 2010).

These programs have had mixed success, as some farmers do not consider the financial support sufficient to compensate their costs and efforts of adoption (Conner et al., 2016). Nevertheless, the evolution of win-win cropping systems will potentially lessen farmer reliance on government support for achieving climate change adaptation and mitigation if these outcomes become by-products and integral part of more profitable farming business plans. The full implementation of mitigation practices requires a system-wide accounting of the market and non-market costs

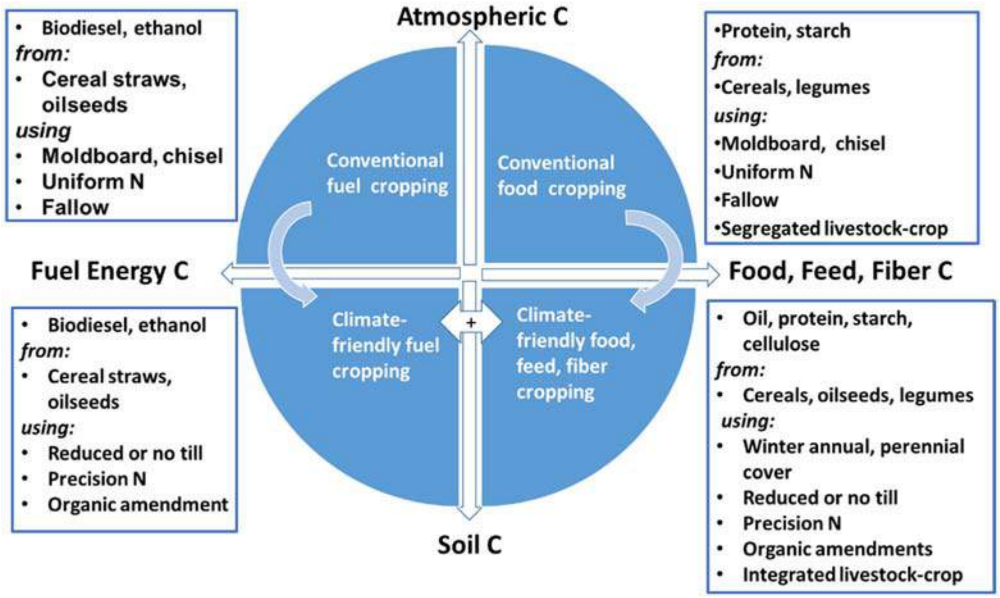


FIGURE 2 | Dominant fates of photosynthetic carbon toward food, fuel, atmosphere and soil of conventional inland Pacific Northwestern US (iPNW) cropping systems **(Top)** that have focused on food production while emitting greenhouse gas (GHG), moving toward aspirational iPNW cropping systems **(Bottom)** with integrated cfBMPs that produce food, fuel, feed and fiber while building soil C and reducing system-wide GHG.

and benefits of alternative agricultural practices, which should become the basis of policy and programs (Tilman et al., 2002).

The crop residue management practices promoted by the USDA-NRCS are also supported by farmer-governed state soil and water conservation districts that provide financial and technical knowledge support (**Figure 1**). Qualified farmers are currently provided incentives through NRCS's Conservation Stewardship Program (USDA-NRCS, nd[2]). Such activities include cover cropping, integration of big-rooted oilseed crops for improved water management, crop residue management, no-till practices, improved N management such as use of slow-release fertilizers, site-specific N management and riparian zone management. State programs also foster conservation programs that are climate change proactive. Local, state soil and water conservation districts apply for federal and state grant funding to assist farmers in conservation education, planning and implementation of activities designed to enhance soil, water and air quality, manage nutrients, control erosion and increase energy efficiency (Boie, 2016).

The need for win-win scenarios to drive integrated cfBMP adoption is well illustrated by current levels of adoption of precision agriculture practices. The NRCS conservation farming programs currently support farmer use of technologies touted to improve N fertilizer management. These incentives may initially entice progressive, early adopting farmers to try new technologies, such as slow-release N fertilizers and spatial soil test mapping for guiding prescriptive variable rate N applicators, but regional farmer surveys suggested that the incentive levels are often insufficient to sustain practices that might not otherwise demonstrate to be consistently economically profitable (Weddell et al., 2017). In contrast, farmers have rapidly adopted tractor mounted-systems that guide seeding and chemical applications. This technology demonstrates more visible costs savings when field operation overlaps are avoided, resulting in obvious economic and resource use benefits to farmers (Weddell et al., 2017).

Crop insurance is one of the most important farm policy tools that has a potential role to play in incentivizing adoption of cfBMPs by providing risk protection of existing or novel systems. Federal programs have been created to provide a safety net for producers. The Federal Cropping Insurance Program was created in 1938 and expansion in the 1990s. The 2014 Farm Bill shifted compensation away from direct payments to crop insurance-and whole farm revenue based safety nets as the primary mechanism for providing economic stability to the agricultural industry.

With volatile markets and climatic conditions that are projected to become even more extreme, crop insurance will continue to play a vital role in the economic viability and sustainability of agricultural production in the region. The federal crop insurance program has been administered by the USDA-Farm Service Agency (FSA) through a joint public-private partnership with the USDA-Risk Management Agency (RMA). In 2015, roughly 85 percent of major crop area in the US was covered by crop insurance representing a total liability of $102.4 billon (USDA-RMA, 2016). Crop insurance programs have offered yield and revenue based coverage options. From 2011 to 2015 the average annual indemnity payments from these multiple peril cropping insurance policies was $11.1 billion per

[2]USDA-NRCS. (nd). Conservation stewardship program. Available at: https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/csp/ (Accessed on March 20, 2017).

TABLE 2 | Cropping system climate-friendly best management practices (cfBMPs) for integration into win-win scenarios that address farmers' short to medium-term goals, and long-term climate change and sustainability goals.

Cropping System cfBMPs	Short-term Benefits to Farmers, Society (1–10 y)	Long-term Climate Change and Sustainability Benefits (40+ y)
reduced tillage: +chemical fallow +undercutter +no-till seeding + standing stubble	–soil erosion +surface SOM +soil water holding, infiltration +nutrient storage	+SOM; soil C storage –CO_2 emissions +soil quality
recycle organic N byproducts, eg manure, biosolids as soil amendments	+SOM +soil quality - synthetic fertilizer requirements	+regional nutrient cycles –system GHG emissions
prescription N fertilizer mgt: +refined recommendations +sensing and application technologies	-fertilizer costs -over-fertilization -contamination of surface, ground water	+fertilizer based NUE –system-wide GHG emissions
crop diversification and intensification: +legumes with advanced species and cultivars	+market diversification +flex rotation options –some pest cycles +biological N fixation + rotational NUE	–system GHG emissions + production of healthy plant based protein
crop diversification and intensification: +oilseeds with advanced species and cultivars	+market diversification +flex rotation options –some pest cycles +soil structure, water +animal/crop integration	+canola based biodiesel –life cycle GHG emissions + crop residues +food oil, animal feed +value added industries

year. The majority of these payouts were government subsidized with grower premium payments covering only 47% of the costs. Indemnity payments in Whitman County, Washington have been driven by market volatility and weather variability (e.g., heat, drought, flooding) with 82% of the claims focused on unexpected losses in wheat yield or revenue (**Figure 3**). In 2009 the largest payout was linked to a large decline in wheat prices, whereas excessive rain in 2010–2012, drought in 2014 and 2015, and extreme temperatures in 2016 resulted in large payments.

Government subsidies will continue to grow unless growers are encouraged to adopt more resilient and established win-win systems. Insurance premiums are currently set using a loss-cost method based on average historic losses for a particular county (Woodard et al., 2011). This method has been criticized as it encourages high-risk farming on poor ground with no incentives to minimize the risk of crop failure through building and restoring degraded soils (Wu, 1999; O'Conner, 2013). Insurance programs have been proposed where farmers' premiums are reduced based on measures of soil quality and health (O'Conner, 2013; Woodard, 2016). Such programs provide incentives for farmers to implement practices that build SOM and support a shift in C pathways toward more organic C sequestration and nutrient cycling (**Figure 2**). Crop diversification and nutrient

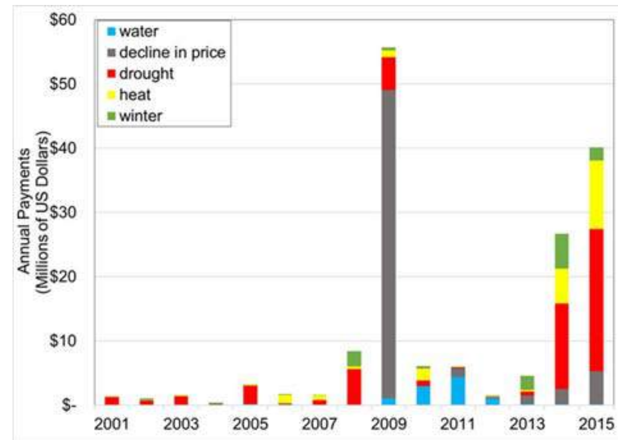


FIGURE 3 | Total indemnity payments broken down by reason in Whitman County, Washington state from 2001 to 2015 (USDA-RMA, 2016).

management strategies that reduce both market and crop loss risks have been further incentivized through reduction of insurance premiums. Management scenarios that may appear to be "break-even" on the short term, such as the adoption of no-tillage practices as described above, may become "win-win" if reduced insurance premiums make this practice more profitable.

Another way that state and federal policies can affect farming systems is through infrastructure support. As an example, the Washington State government supported infrastructure development to build markets for alternative crops (Lang, 2017). In 2006 Washington State created the Energy Freedom Program, which provided low-interest loans and grants to support the construction of oilseed crushers and other bioenergy-related facilities (O'Leary et al., 2013), thus creating a pull market for regionally produced oilseeds. Federal support for this program stemmed from the 2005 National Energy Policy Act (GPO Government Publishing Office, 2005) during a federal energy crisis, linked to turmoil and disruptions in international fuel supplies. State investments in biofuel crop production research and extension coordinated projects were then implemented (Sowers and Pan, 2012), in recognition that rapid and sustained adoption of canola in Australia and Canada occurred at the same time of increased financial investments in research and development (Maaz et al., in press). While these early investments were thought to be economically questionable on a biofuel basis (Young, 2009), today, Washington state has the processing infrastructure in place to supply increasing oilseed-based fuel, food and feed regional markets (Lang, 2017).

Diffusion of iPNW Cropping Systems Innovations

New iPNW agronomic systems have been initiated by innovators and early adopters, followed by early and late majorities and finally the latest adopters, referred to as laggards by the adoption theorists (Rogers, 1995). During historic integration of conservation farming and now cfBMPs for iPNW cereal-based systems, there has been a distinct and influential population of early adopters (Dillman et al., 1987; **Figure 4**). Early pioneers and adopters of new equipment were mechanically innovative and skilled (Carlson and Dillman, 1988). Farmer innovators and early adopters of no-till seeding drills and fertilizer technologies also developed family businesses around these enterprises (McGregor, 1982), providing added income and motivation. Crop development and seed production enterprises spawn from technological advances in seed development, evaluation, demonstration and sales by international or regional businesses that are sometimes farmer owned (Sowers, 2017). Early adopters of innovative cropping systems and practices have been documented in case studies produced by university extension programs (Mallory et al., 2001; Sowers et al., 2011, 2012; Lorent et al., 2016; Yorgey et al., 2017a). They exhibit natural curiosity, embrace the challenge of trying to do things differently in order to improve their farms and environment, with an overall commitment to "do things right." They typically have worked closely with researchers, private and government agency crop advisers to implement systems and define how their innovations have changed their systems. Most have taken advantage of farm programs and financing that support conservation practices. The mature, well-vetted win-win scenarios that feature stable, economic profitability of integrated stable cfBMP-based systems, will provide the free-market economic driver necessary to enable late adopters to changeover and to sustain these practices across all adopters with minimal government support and intervention. Late adopters enter when the systems are sufficiently developed and understood; some of the possible risks have been addressed, either through better management strategies or government support (**Figure 4**).

CLIMATE-FRIENDLY, BEST MANAGEMENT PRACTICES

Agronomic cfBMPs are reviewed herein: crop residue management, organic recycling, N management, crop diversification and crop intensification (**Table 2**). Alternative systems that integrate these agronomic strategies across the different iPNW subregions (**Figure 5**) have promise for achieving climate change mitigation and/or adaptation with integrated win-win strategies (**Figure 6**).

Reduced Tillage and Crop Residue Management

Climate-friendly crop residue management includes replacing plowing with reduced or no-tillage planting and growing alternative crops with greater quantity and quality of crop residue production. These options protect soil against erosional forces, increase SOM and C sequestration, while improving water soil water storage and yield potential, achieving a better balance of C flow toward SOM and food production (**Figure 2**).

Severe topsoil losses have occurred in fallowed fields seeded to winter wheat, burned stubble fields and wheat-seeded fields following crops such as spring peas (Kaiser et al., 1954). In

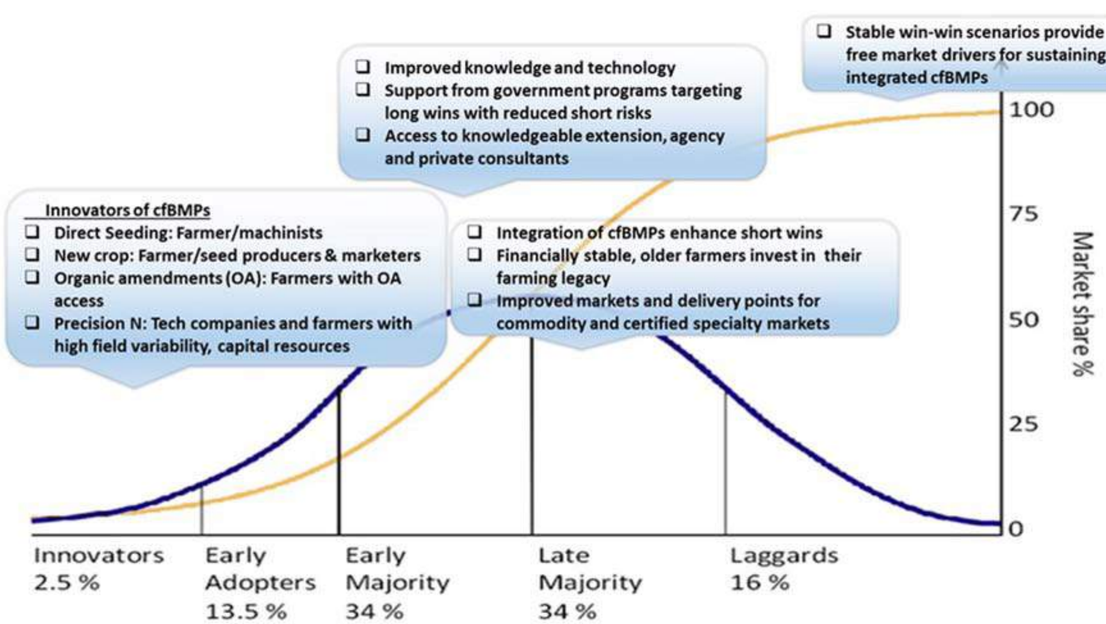
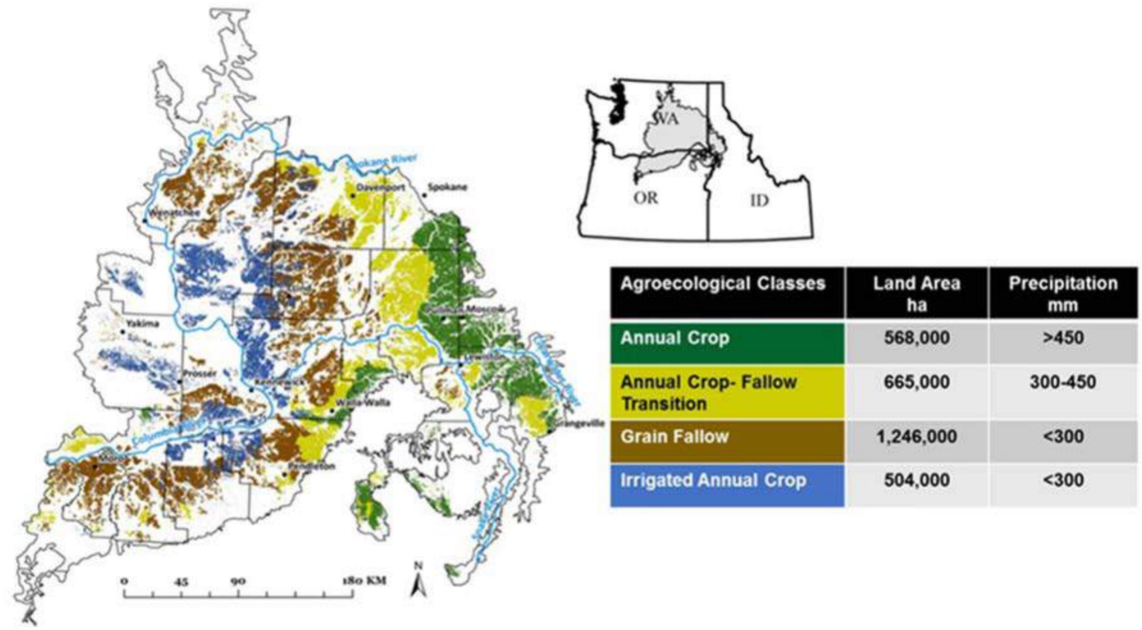


FIGURE 4 | Theoretical adoption curve modified from Rogers (1995) of relative numbers of adopters at different stages (blue line) and cumulative adopters (yellow line), applied to the adopter characteristics of the four major climate friendly best management practices (cfBMPs). Earliest inland Pacific Northwestern US (iPNW) innovators of no-till, organic amendment and new crop use, and precision agriculture technology have been farmers, businessmen, researchers and experimentalists. Early adopters took advantage of early innovators' knowledge and technology and government policy support. Late majority adopters responded to wider availability of knowledge and technology of stacked integrated cfBMPs. Latest adopters, coined "Laggards" by Rogers, convert systems when they are well established and economic and agronomic benefits are clearly demonstrated.



Agroecological Classes	Land Area ha	Precipitation mm
Annual Crop	568,000	>450
Annual Crop- Fallow Transition	665,000	300-450
Grain Fallow	1,246,000	<300
Irrigated Annual Crop	504,000	<300

FIGURE 5 | Major agroecological cropping zones, precipitation ranges and crop areas in the wheat-producing inland Pacific Northwestern (iPNW) U.S.

the iPNW, conservation tillage has reduced soil erosion and sediment loads (Kok et al., 2009; Brooks et al., 2010; Williams et al., 2014). Brown and Huggins (2012) reviewed 131 data sets from the iPNW and found that 75% of native ecosystems converted to agriculture lost at least 0.14–0.70 Mg C ha-1 year^{-1} and that the conversion from conventional tillage to no-till practices was predicted to increase SOC from 0.12 to 0.21 Mg C ha^{-1} year^{-1} for 75% of situations. By reducing erosion, protecting topsoil and maintaining SOM, conservation tillage practices also directly and indirectly affect soil health. In addition, nearly all measurable soil microorganisms, including bacteria, fungi and actinomycetes increase with no-tillage adoption (Stubbs et al., 2004). In addition, Johnson-Maynard et al. (2007) reported significantly higher earthworm densities in conservation tillage treatments as compared to conventional tillage in the annual cropping zone of the iPNW. Earthworms are important biological indicators of soil quality and can increase biodiversity and yields in managed systems (van Groenigen et al., 2014).

Maintaining surface crop residues before late summer planting of winter crops not only protects soil from eroding, but it also enhances snow capture and seedling establishment. No-till winter peas exhibited improved seedling vigor, reduced winter injury and increased grain yield compared to conventionally-tilled peas (Huggins and Pan, 1991). Biomass production is critical for maintaining seed-zone soil moisture in no-till fallow. Chen et al. (2006) demonstrated that tall stubble improved yields of winter lentil (*Lens culinaris*). Producers normally grow short, semi-dwarf varieties of winter wheat in this area, however, some farmers are starting to grow tricale (×*Triticale Wittmack*) which produces 50% more crop residue than semi-dwarf wheat in high residue farming systems (Port, 2016).

Brown and Huggins (2012) summarized long-term residue management experiments in iPNW and their conclusions showed a limited ability of reduced tillage and direct seeding of conventional crop rotations to maintain and increase SOM and soil C sequestration. Using these findings, Stöckle et al. (2012) projected that a 10% increase in no-till and reduced tillage in existing cropping systems could reduce GHG by >1,550,000 Mg CO_2e/y over the iPNW due to soil C accumulation over a decade, but some site-specific systems would come to equilibrium thereafter. These assessments assume tillage reductions within existing cropping systems. Further research is needed to determine what extent direct seeding in combination with other cfBMPs such as diversified crop rotations with more prolific roots and/or increased stable organic C inputs can more fully replenish and build SOC within the limitations imposed by climatic conditions. Recent developments in monitoring technologies have enabled the ability to assess system C balances between crops and soils while tracking CO_2 fluxes of managed fields to assess the effects of diversified crops, soils and fluctuating weather (Waldo et al., 2016; Chi et al., 2017).

Despite benefits of improving crop residue retention as soil C, there are immediate incentives for straw removal that include markets for mushroom and animal bedding, cellulose-based energy and paper-based packaging. Excess straw can cause difficulties in direct seed stand establishment, requiring field burning or straw harvesting. Site-specific straw removal is only recommended from areas of excessive straw production, and nutrient removal

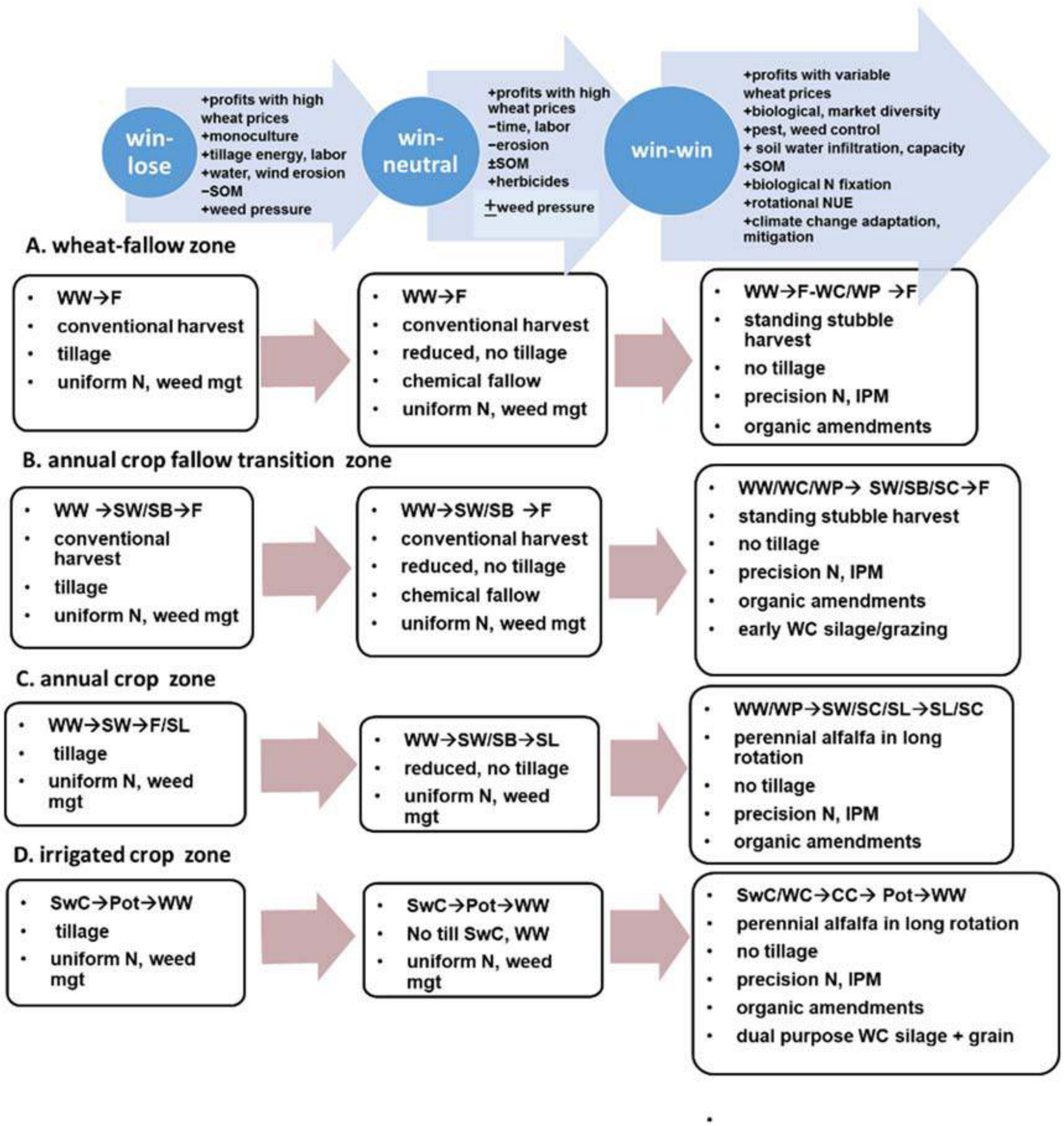


FIGURE 6 | Traditional win-lose (left), transitional win-neutral (middle), and aspirational win-win (right) inland Pacific Northwestern US (iPNW) wheat cropping systems scenarios tailored for the production zones of **(A)** low precipitation, wheat fallow, **(B)** intermediate precipitation, annual crop fallow transition, **(C)** high precipitation, annual cropping, and **(D)** irrigated annual cropping. Old agronomic management principles combined with new crop options and technologies (climate friendly best management practices (cfBMPs, **Table 2**) have moved, and will continue to move systems from left to right, from traditional win-lose systems to transitional win-neutral systems to current and aspirational win-win scenarios for achieving short-term economic profitability and long-term solutions to environmental quality, market and climate shifts of the twenty-first century. WW, winter wheat; WC, winter canola; WP, winter pea; WT, winter triticale; SW, spring wheat; SB, spring barley; SC, spring canola; F, summer fallow; SwC, sweet corn; CC, cover crops; POT, potato.

from the system needs to be replenished (Huggins et al., 2014).

Organic Resource Recycling

Recycling of available organic resources is considered a cfBMP for two reasons: (i) replacement of commercial fertilizers that have high GHG costs in production (Wood and Cowie, 2004; Brown et al., 2010) and (ii) their unique ability to sequester stable forms of soil C and supply nutrients (Bogner et al., 2007, **Table 2**). Early recognition of the important role of organic amendments (Spillman, 1906) has been supported by long term trials that consistently demonstrate that animal manure and human biosolids are more effective than crop residues for building SOM, sequestering soil C, improving soil structure, water infiltration and retention, increasing nutrient availability and enhancing microbial activity, while reducing soil bulk density (Yorgey et al., 2017b). These amendments offer a valuable strategy in the winter wheat-fallow region, where reducing or eliminating tillage has been insufficient for re-building soil C levels, due to low productivity and the resulting low levels of C inputs in residues (Machado, 2011; Gollany et al., 2013).

Organic amendments can promote large increases in total soil organic C (SOC) storage (Machado, 2011) with significant buildup of stable C forms (Pan et al., 2017b), reducing CO_2 release that would occur if these waste products were otherwise incinerated or left to rot. Yet most of the region is spatially separated from animal and human population centers, so the utilization of many common amendments is presently limited by transportation costs into most of the dryland areas of the iPNW. Nevertheless, opportunities do exist for distribution of biosolids and manures on dryland areas with nearby urban centers and large animal operations.

Biosolids applications can build soil C while producing equivalent or better grain yields than typical applications of inorganic N in tilled and untilled wheat systems (Koenig et al., 2011; Barbarick et al., 2012). These increased yields are often attributed to the phosphorus, sulfur and micronutrients provided by the biosolids (Ippolito et al., 2007). Other possible factors include improved soil physical properties. While biosolids applications generally raise grain protein when applied during the fallow year (Cogger et al., 2013), practical experience suggests that this is generally not great enough to negatively impact prices for soft wheats that can have high protein penalties. Likewise, the risk of N and P losses after biosolids applications is most often relatively low in regional dryland cereal systems, especially for one-time applications (Ippolito et al., 2007; Barbarick et al., 2012; Cogger et al., 2013). These anaerobically digested biosolids were later shown to also build stable and more labile soil organic C and N, while supplying sufficient crop N to a wheat-fallow system (Pan et al., 2017b).

Access and costs of organic amendments is the biggest challenge to dryland farmers of the iPNW. Since biosolids are a by-product that must be managed by wastewater treatment facilities financed by sewage taxes, they are available at no cost or reduced cost to farmers. In some cases, municipalities charge transportation and application fees, or a fee equal to the N value of the biosolids (Sullivan et al., 2015). The question remains of whether a similar system is feasible for manure management of concentrated animal operations. Over-irrigation pushes nitrate through shallow root zones to groundwater, causing water quality problems in the aquifer (Brown et al., 2011). Manure related water quality problems are driving public opinion and litigation, as well as public policy. Central Washington irrigated systems support a large dairy industry that has limited land to upon which to recycle manure.

There is an opportunity to replicate the biosolids success story by transporting manure to dryland wheat farms. Improved on-farm separation and concentration of nutrient-rich solids should increase economically viable hauling distances (Yorgey et al., 2014; Frear et al., in press). In the iPNW, animal production is located in concentrated production facilities, spatially separated from the dryland wheat farms. In south-central Idaho, where dairy farms exist in combination with dryland fields on high plateaus, manure is used as a nutrient source in the production of organically certified wheat sold at prices that are 2–3 times those of commodity wheat and organic alfalfa hay (Lorent et al., 2016). Manures that have solids separated, aged, dried and sometimes composted primarily benefit overall soil health by increasing SOM, rather than serving as a primary source of crop available N. For example, compost improved cereal yields by successfully restoring organic matter on eroded Palouse hilltops, with yield improvements achieved after N immobilization was overcome with additional N fertilizer input (Cox et al., 2001). Likely mechanisms for the yield gains include improvements in nutrient and water holding capacity, soil structure and water infiltration.

Other materials that may recycle nutrients and C include biochar (a charcoal-like material that is generated when organic materials such as forestry wastes are heated in oxygen-limited environments) and black liquor (an organic by-product that results from paper-making). Application of 10 tons/acre or more of alkaline biochar (pH 10) derived from forest wastes had mild soil liming effects and improved wheat yields near Pendleton, Oregon (Machado and Pritchett, 2014). While these results are encouraging, separate analysis suggests that biochar is not economical if only the effects on pH are considered (Granatstein et al., 2009; Galinato et al., 2011). Crop residues from cereal and grass seed systems can be used for paper-making and the first new paper pulp mill to be built in the U.S., and the largest straw pulping mill in the world is now under construction (Erb, 2017). Straw fibers are typically alkali-pulped, producing black liquor, a lignin-rich soil amendment that can be returned to the land to increase soil C, biological activity and wet stable aggregates (Xiao et al., 2007a,b).

Cover crops are grasses or legumes that are used primarily to provide seasonal protection against soil erosion and an organic soil improvement (Unger et al., 2006) Compared to amendments, which need to be transported and spread, cover crops generate organic materials in place. However, water is a major limitation in the iPNW and existing research with single- and multi-species cover crops in eastern Washington and in semiarid eastern Colorado (Nielsen et al., 2015) has not found agronomic and economic benefits (Thompson and Carter, 2014; Roberts et al., 2016).

Nitrogen Management

The improvement of N use efficiency (NUE) of cropping systems is a critical cfBMP of win-win scenarios, since N is an expensive farm input and it greatly affects GHG emissions (Snyder et al., 2009). Wheat farming began in the iPNW in the 1870s. Native soil N declined by 22% during the first generation of farmers and replenishing it was a recognized prerequisite for increasing soil productivity (Fulmer and Heileman, 1899). This situation was greatly helped by the mid-twentieth century development of synthetic N fertilizers and N soil testing. Recent estimates of regional N balances suggest crop N removal is being replenished with N biological and fertilizer inputs, although P and K are still being depleted (**Table 3**). The International Plant Nutrition Institute (IPNI) recognizes that the region as a whole has achieved N balance with regard to N inputs offsetting N removal by grain harvest, after conducting an extensive data analysis of nutrient balances across each county of the U.S. (IPNI, 2012). Yet, documentation of inefficiencies and N losses in the region suggest

TABLE 3 | Nutrient supply and removal in harvested grain* across the main wheat-producing counties of the inland Pacific Northwestern US (adapted from Borrelli et al., 2017).

	Primary nutrient		
	N	P	K
Nutrient source	**Metric tons $year^{-1}$**		
Commercial**	143,570	16,406	22,721
Recovered manure***	1,377	797	4,701
Biologically fixed by legumes***	25,322	0	0
Nutrient quantity			
Total nutrient supply	170,269	17,202	2,7422
Crop removed***	171,203	25,072	7,7265
Balance (supply-removed)	−934	−7,870	−49,843
Removal ratio (removal/supply)	1.01	1.46	2.82

**Methods described in IPNI (2012). Nutrient quantities converted to elemental metric tons per year. N, nitrogen; P, phosphorus; K, potassium. **1997, 2002, 2007, 2010–12 County level data interpolated and summarized by International Plant Nutrition Institute (IPNI) from fertilizer sales data collected by the Association of American Plant Food Control Officials (AAPFCO). ***Farm census data from USDA National Agricultural Statistical Service (USDA-NASS) Census of Agriculture, summarized by IPNI.*

that while there may be an overall balance of regional N inputs vs. grain N harvested, there are areas of over- and under-application of N fertilizers within fields, resulting in N leaching below the root zone, N runoff to local waterways (Keller et al., 2007) and N volatilization to the atmosphere (Venterea et al., 2012). Excess N is susceptible to nitrous oxide (N_2O) production (Snyder et al., 2009) and the release of this GHG can offset carbon sequestration benefits provided by conversion to reduced- or no-till (Stöckle et al., 2012).

Efforts to improve fertilizer N use efficiency in the iPNW (Huggins and Pan, 1993) paralleled the conservation farming movement of the late twentieth century. Several levels of technology adoption hold promise for improving regional NUE and thereby reduce system wide GHG emissions. The baseline opportunity is to increase adoption of soil N test-based N fertilizer recommendations that have existed since the 1950's (Pan et al., 2007). Accurate estimation of N fertilizer rate requirements is based on available water and soil N supplies (Pan et al., 2007, 2016a) with full root zone (0–180 cm) soil testing, but there are opportunities for increasing adoption of routine soil testing by regional farmers since a recent survey revealed that only two-thirds of regional farmers regularly take soil samples (Mahler et al., 2015). Recognition that a majority of crop N uptake comes from non-fertilizer sources (Sowers et al., 1995; Pan et al., 2016a) should provide farmers with ample motivation to take regular soil tests and collect other crop and soil information for optimizing their fertilizer use.

As alternative crops are adapted to the region, crop specific N requirements and recommendations need to be developed and evaluated for specific agroecological subregions. The basic 4R (four "rights") approach focuses on right fertilizer rate, placement, source and timing, which require adjustments for fertilizer management of alternative crops like canola (Norton, 2013). Canola differs in crop physiology from wheat, which dictates changes in N placement, timing and source (Pan et al., 2017a).

Fertilizer recommendations will need to be integrated with predictions of water supply in a changing climate (Pan et al., 2016a). Overall, adopting farmers need to understand that typical wheat N management principles do not necessarily apply to newly introduced crops.

The potential of site-specific N management for improving within-field NUE was recognized for more than 20 years (Fiez et al., 1994; Pan et al., 1997), but it was also recognized that the N recommendations based on regionally developed algorithms would be insufficient to make landscape level N recommendations since unit N requirements (kg total N supply per kg grain) and NUEs varied across the landscape (Fiez et al., 1994; Hergert et al., 1997). Several biophysical stressors such as limited water availability and compacted soil layers negatively impact NUE across the variable landscapes (Pan and Hopkins, 1991; Fiez et al., 1994; Ibrahim and Huggins, 2011), locations and annual precipitation (Maaz et al., 2016).

Recent technological advances have provided opportunities to more accurately assess landscape specific soil N availability and root stressors that will lead toward better landscape-specific N management within farm fields. These technologies include remote sensor systems, robotics, GIS spatial mapping for prescriptive soil management and new technologies for yield mapping and protein monitoring (Weddell et al., 2017).

As decision support systems become available to help farmers utilize large datasets, there will be potential improvements in the use efficiencies of fertilizers and pesticides, along with improved grain yield and quality that may provide economic advantages of technology adoption without government support. The economic driver of efficient N management is illustrated during times of high N fertilizer prices, when farmers tend to reduce their N fertilizer use and improve their cropping system NUE (Nehring, 2016). Another example is evident in iPNW high protein wheat production, where the ratio of fertilizer price to grain protein price premiums for hard red wheats influence the economically optimal N recommendation and use (Baker et al., 2004). Higher ratios result in lower N input recommendations and improve N use efficiency. A complex of biophysical drivers and crop responses have led to the identification of landscape performance classes for gauging site-specific NUE parameters that link to site-tailored wheat N recommendations (Weddell et al., 2017).

Regional NUE can be improved with the integration of old conservation principles with new fertilizer management technologies, substitution of commercial fertilizer with legume expansion and organic byproduct recycling and adoption of site specific 4R N management utilizing advanced precision technologies. Greenhouse gas production occurs at the fertilizer plant (Wood and Cowie, 2004) and with field applications of N fertilizer (Shcherbak et al., 2014). A 10% overall improvement in regional fertilizer NUE based on annual N fertilizer use (**Table 3**) would reduce GHG emissions associated with the reduced synthetic N fertilizer use of 13,000 Mg fertilizer N/year.

Crop Diversification

Alternative crop rotation design is another major cfBMP category that has great potential for achieving win-win scenarios (**Table 2**). Crop diversification changes immediately require adjustments in the other rotation-wide management practices to optimize the cropping system's economic and environmental impacts. Examples of cfBMP integration into alternative cropping systems are described for each iPNW agroecological zone below.

Diversification of cereal systems with broadleaf grains (oilseeds and legumes) or cover crops is useful to optimize pest management, nutrient cycling, N use and water use efficiencies, soil building and potential GHG mitigation (**Table 2**). Advantages of these "break crops" in rotation with wheat has been shown to result in significant increases in wheat yields worldwide (Kirkegaard et al., 2008). Crop diversification also diversifies marketing options, reducing price risk for farming enterprises. Regional crop diversification opportunities are large, given that the iPNW largely produces to meet the bulk commodity, export cereal grain markets. The iPNW region supports the production of both spring and winter cereals and there are opportunities for integrating both spring and winter oilseeds and pulse crops in each agroecological zone. New crop options need to be integrated into sustainable cropping systems with a new set of cfBMPs (**Table 2**).

Crop rotation impact on GHG emissions is complex. Some affected variables include amount and source of N inputs and N_2O losses, net soil C sequestration, net energy balance of external fossil fuel inputs and biofuel outputs. Diversification with legumes and oilseeds shifts the rotational N cycling, residual N carryover and on-farm production of N through legume-facilitated biological N fixation, all of which will reduce reliance on fertilizer N for subsequent cereal crops (Maaz and Pan, 2017). Important agronomic metrics impacted by alternative crop rotation include rotational N use efficiency, soil C storage, biofuel displacement of fossil fuel use and non-food products that can be credited toward C sequestration.

Weed management is a primary driver of farmer adoption of new crops. While it has no direct impact on climate change mitigation, it has indirect impacts as alternative crop rotations are established and sustained. For example, the persistence of winter annual grassy weeds severely diminishes wheat yield and quality in the iPNW. Diversifying winter wheat sequences with spring crops or fall-seeded broadleaf crops allows in-crop use of grass herbicides to reduce grassy weed populations and modifies the composition of weed populations (Burke et al., 2017). Well-established canola stands are competitive with weeds, providing a major driver in canola adoption (Long et al., 2016). Glyphosate-resistant spring canola provides opportunities for improved control of downy brome (*Bromus tectorum*), jointed goatgrass (*Aegilops cylindrical*), feral rye (*Secale cereale*), and Italian ryegrass (*Lolium multiflorum*) in annual crop systems (Young et al., 2016) and can reduce Italian ryegrass and broadleaf weed populations when used in place of spring non-glyphosate resistant legumes (Huggins and Painter, 2011). Winter wheat-fallow studies showed that diversifying with winter canola, along with split applications of quizalofop and glyphosate, controlled 90% of feral rye, eliminated seed production of feral rye and increased canola yield more than 40%. Use of glyphosate-resistant winter canola in tandem with glyphosate application can also help control feral rye (Young et al., 2016). Conventional canola cultivars lacking herbicide resistance are highly sensitive to sulfonylurea and imadazolinone herbicides, but new herbicide resistant cultivars are now available for overcoming herbicide carryover.

Additionally, herbicide-tolerant or resistant varieties would allow farmers to plant in fields with a history of imidazolinone and sulfonylurea herbicides and an increased selection of grass herbicides would be available in conventional canola (Young et al., 2016). Because glyphosate is the most important grass herbicide in summer fallow, the various canola scenarios would allow farmers to use other groups of herbicides to control grass weeds, thereby reducing the use of glyphosate in canola and mitigating the development of resistance of grass weeds to glyphosate. It is just as important to rotate herbicides as it is to rotate crops to reduce overall loading rates of any one herbicide. In addition, reduction in herbicide application rates are now enabled by the advent of imaging-based precision herbicide technologies capable of targeting post-emergence weeds in fallow (Riar et al., 2011).

Rotational diversification can also support win-win scenarios by suppressing soilborne fungal pathogens and nematodes that cause wheat and barley (*Hordeum vulgare*) diseases. In general, the population density of a pathogen increases with the increasing frequency of a host crop in a rotation. Using a rotation to suppress disease is most effective when alternate, non-host crops are available, precipitation is not limiting and conditions promote rapid residue decomposition. For example, planting a non-host broadleaf crop in place of a cereal crop can reduce some pest populations such as Hessian fly, orange wheat blossom midge, mites, Cephalosporium stripe and cereal cyst nematode, while not reducing Rhizoctonia, Pythium, and root-lesion nematode species (Eigenbrode et al., 2017; Kirby et al., 2017a,b).

Integrating legume pulse crops diversifies market opportunities for cereal farmers (Vandemark et al., 2014) but requires market infrastructure. As an example, advancement of chickpea (*Cicer arietinum*) storage, transportation and marketing in the region has greatly expanded iPNW chickpea production, driven by high prices (Maaz et al., in press). Similarly, the varietal development of edible winter dry peas promises to expand legume acreage into the drier agroecological zones, due to their greater yield potential and ability to survive harsh winters (Schillinger, 2017). Fall-sown dry peas and lentils are well-adapted for direct seeding into standing stubble and increasing demand for cover crop pea seed provides production incentive.

The need for oilseeds in iPNW wheat rotations was first published by Spillman (1906) for renovation of nutrient-mined, eroded soils. Recurring interest in oilseeds for a potential feedstock for biodiesel and jet fuel (Long et al., 2016) and a break crop in wheat rotations has been investigated for the last 50 years (Pan et al., 2016b). Efforts to push the regional adoption of canola based on agronomic benefits were unsuccessful until global markets for food oil improved, federal policies incentivized big rooted rotational crops and state government support for oilseed processing facilities began to pull grain through the supply chain (Lang, 2017).

Oilseed-based biodiesel has been assessed by U.S. EPA LCA to reduce system-wide GHG emissions by 50% when displacing conventional diesel (EPA, 2010) and perhaps higher GHG reductions occur in semiarid systems (Biswas et al., 2011; Kruger et al., 2015). Several factors help to moderate the negative impact on food production when inserting these oilseeds into rotation. Canola produces food oil as well as biofuels and a high protein animal meal by-product that contributes to the food chain (Long et al., 2016). Canola also has early maturing characteristics, its varieties offer unique options for weed control, thereby increasing subsequent wheat yield potential (Sowers et al., 2012; Pan et al., 2016b).

Recurring interests in regional energy production and crop diversification have focused efforts on canola food, feed and fuel production since the 1970s. Recently, over the past decade, there has been a four-fold increase in iPNW canola production due to a convergence of new regional processing facilities, improved global demand and competitive prices for canola, improved diversity of varieties and renewed extension and agronomic research efforts (Pan et al., 2016b). Winter and spring canola are being integrated into the iPNW cropping zones (**Figures 5**, **6**). In addition, interest in developing cellulosic biofuels (Huggins et al., 2014) and paper products (Xiao et al., 2007b; Erb, 2017) can stimulate movement toward higher residue producing crops that could serve conservation compliance and/or emerging markets.

Alfalfa (*Medicago sativa*) is a viable crop diversification and intensification option for integration with annual crops (Koenig et al., 2009). USDA cropland data layers showed that alfalfa comprised about 5% of the crop acreage in both the annual crop and annual crop-fallow transition zones from 2007 to 2014 (Kirby et al., 2017a). Its potential for addressing climate change is attributed to its capacity to build soil and fix N. Organic alfalfa can be produced economically, stands can be maintained 5-10 years before transitioning back into annual crops, depending on fluctuating markets. This crop provides a transitional land management option prior to organic grain production (Fuerst et al., 2009). Production of organic crops is increasing in the iPNW, primarily in the irrigated zone (Kirby and Granatstein, 2017). Future expansion of organic alfalfa is most likely to occur as a rotational crop in irrigated and high rainfall zones, but markets will depend on the growth of the organic dairy sector in the region.

Crop Intensification

Intensification of crop rotation is another strategy for potentially developing win-win scenarios. It is defined as the increase in rotational land coverage with growing crops. Intensification can be achieved with (i) annual fallow replacement with a crop, (ii) increasing over-winter cropping with cover crops, (iii) substituting winter crops for spring crops, or (iv) replacing annual crops with perennial crops. Crop intensification can increase food production, utilize rising atmospheric CO_2 for photosynthesis and sequester more soil C. The major challenge is the need to ensure that crop intensification is coupled with ecologically based management strategies such as conservation farming (Matson et al., 1997), as well as ensure short-term economic viability.

With sufficient available water, annual cropping maximizes biomass production and limits fallow periods between crops when soils are most vulnerable to erosion. Opportunities for intensification vary across the dryland iPNW with temperature and precipitation gradients, terrain and soil characteristics. Research in the annual crop-fallow transition and winter wheat-fallow regions has focused on strategies such as flexible fallow replacement with annual cropping in wetter than average years, or replacing spring crops with fall-sown crops. While these strategies will intensify production, increase C fixation and seasonal soil surface coverage, they can also have negative impacts on farm economics and risk if practiced in drier than average seasons (Young et al., 2015). Profitability of intensive cropping was found to be more variable than for wheat-fallow in the Great Plains, U.S. (DeVuyst and Halvorson, 2004).

Replacing spring crop sequences with fall-sown winter hardy crops intensifies rotations by providing overwinter soil cover with increased yield potential (Schillinger, 2017; Stöckle et al., 2017). Fall-sown crops mature earlier than spring-sown crops, thereby avoiding heat stressors and water deficits that may occur later in the growing season. This advantage of winter over spring cropping may become more critical for future systems to be better adapted to predicted warmer, drier summers (Kaur et al., 2017). For example, replacing spring legumes with a fall-sown pea or lentil provides greater crop biomass, residue and biological N fixation; fall-sown peas can have double the seed yield compared to spring-planted cultivars (McGee, 2016).

INTEGRATED WIN-WIN SYSTEMS BY CROPPING ZONE

The iPNW agroecological zones are largely defined by temperature and moisture gradients. Classification of USDA cropland data layers allows the identification and area estimates of four major iPNW cereal cropping zones: annual crop, annual crop fallow transition, grain fallow and irrigated (**Figure 5**). The area of these zones are projected to shift with regional climate change (Karimi et al., 2017).

Effective integration of BMPs is production-zone dependent (Zentner et al., 2002). In terms of gauging short term economic "wins," farmers and economists have historically conducted single crop net return comparisons of substituting alternative crops for traditional crops. In recognition of the potential rotational benefits of alternative crops and management systems, rotational enterprise budgeting tools are being developed to for specific production zones to help farmers understand a more complete economic impacts of system redesigns within production zones (Connolly et al., 2015, 2016).

Crop–Fallow Zone

The crop-fallow zone has insufficient annual precipitation (<300 mm) to economically support annual cereal cropping

(Young et al., 2015). This zone occupies the greatest regional area, which is projected to reduce in size with climate change scenarios (Karimi et al., 2017). Tilled summer fallow is practiced in this zone for storing soil water to produce winter wheat every other year despite its erosive impacts (Lindstrom et al., 1974). While minimum tillage or chemical fallow, direct seeded wheat-fallow have reduced wind erosion in win-neutral scenarios (**Figure 6**), it has done little to build SOM and restore soil health (Gollany et al., 2013; Ghimire et al., 2017). Reduced-tillage of summer fallow using an undercutter cuts weeds without inverting the soil, maintains surface residue cover for reduced wind erodibility and has similar economic costs to summer fallow (Young and Schillinger, 2012). However, with no increases in subsequent wheat yields, only a neutral-win scenario was achievable by protecting soil, but not improving profitability.

Integration of tillage management with different crop rotations have been and will continue to be evaluated. Continuous no-till spring cereal cropping produced more residue which reduced wind erosion on susceptible soils by 95% compared to the traditional winter wheat-fallow system (Thorne et al., 2003). Yet, it also exhibited poor N balances (Pan et al., 2001) and it was found to be economically less viable than conventional wheat-fallow (Young et al., 2015), thus judged to be an overall lose-neutral scenario. These findings have led to evaluations of diversified crop rotations with winter canola and winter peas (Young et al., 2014; Schillinger, 2017) produced in concert with minimum or no-tillage (**Figure 6**).

Recent introduction of winter canola into this region has met with mixed success, requiring more research to determine residue production and management requirements for more stable plant establishment and winter survival (Young et al., 2014). Tall standing stubble has been shown to increase water use efficiency and grain yield compared to shorter stubble in the Canadian prairie (Cutforth and McConkey, 1997; Cutforth et al., 2011), but seed zone moisture during summer fallow was not examined.

Production of high residue crops such as tall wheats and triticale, in tandem with a stripper header type combine, has resulted in tall standing stubble that can trap more snow and keep surface soils moist and cool during late summer establishment for improved crop establishment of no-till winter canola (Port, 2016). Insertion of alternative crops can have positive or negative effects on subsequent wheat production and rotational enterprise budgets (Connolly et al., 2015). Better weed control, enabled by insertion of herbicide resistant canola into wheat monoculture, has resulted in positive improvements in pervasive weed control, wheat yield and quality (Young et al., 2016).

This is the dryland zone closest to the irrigated central basins of Washington and Oregon (**Figure 5**) that produces large quantities of manure from concentrated dairy farms. In addition, this zone is closest to dense urban populations in western Washington and Oregon. The close proximity offers opportunities for processed manure and biosolids to be imported into this fallow zone, which will reduce fertilizer nutrient requirements. This would also build up the low SOM levels as has been demonstrated in a long-term manure trials at Pendleton, OR (Machado, 2011) and biosolids trials near Okanogan, WA (Cogger et al., 2013; Pan et al., 2017b).

Annual Crop-Fallow Transition Zone

The annual crop-fallow region (**Figure 5**) has traditionally supported winter wheat, spring wheat and spring barley in >50% of the zone, fallow in 27% and spring legumes in 10% of the zone with more fallow during drier years (Pan et al., 2016b). In wetter than normal years, continuous crop rotations have been grown. There is potential for crop diversification and intensification with winter and spring oilseeds and peas in this zone. This "flex cropping" in this zone allows farmers to intensify cropping in years with favorable field conditions and markets. Plant-available soil water is the most reliable indicator of potential yield. Farmers may take advantage of ample overwinter precipitation storage in the soil to plant a spring crop, replacing a traditional fallow sequence. Flexible decisions on direct seeding spring broadleaf crops in this zone, to conserve moisture and reduce erosion, should be based on over-winter soil water storage to 120 cm rooting depth and weather predictions for in-season precipitation (Pan et al., 2016a).

More specifically, Lutcher et al. (2009) stated critical levels of over-winter soil water storage required to trigger spring crop plant-back. This intensification strategy in a win-win scenario is further enabled by integrating direct seeding and canola diversification. Such a strategy has demonstrated improved weed control and economically viability while diversifying market opportunities enabled by a nearby canola processing facility in this production zone (Esser and Jones, 2013). Future win-win scenarios for this zone (may include direct seeded winter wheat, canola or peas, followed by direct-seeded spring crops or early planted biennial forage-grain winter canola, **Figure 6**). Fall-sown direct-seeded facultative spring wheat is another flexible option to normal spring wheat recrop planting. It is more competitive with annual weeds, it is better for erosion control with earlier established ground cover and it can yield better than spring planted cereals in a recrop scenario by enabling earlier plant development for avoiding summer heat stress (Bewick et al., 2008; Sullivan et al., 2013).

Annual Crop Zone

The high precipitation annual crop zone (**Figure 5**) supports annual cropping, with winter wheat, spring wheat and spring barley grown over 60% of the cropping zone land area and cool season legumes (lentils and dry peas) account for only ∼18% (Pan et al., 2016b). This zone is projected to increase with climate change scenarios (Karimi et al., 2017). Wheat-fallow in this region proved to be vulnerable to very high soil erosion rates, so continuous annual cropping of winter wheat, spring cereals and spring legumes was adopted, particularly with the advent of commercial fertilizers (Kaiser et al., 1954). Nevertheless, soil erosion rates were still very high when direct-seeding planters were first introduced into the existing crop rotations of the region (Papendick et al., 1985). A long-term study in this region, south of Moscow, Idaho, has shown that direct-seeded standard winter wheat-spring pea rotation has resulted in comparable yields while reducing erosion potential, compared to the same rotation that was conventionally tilled (Guy and Lauver, 2007).

The IPM project of the 1990s (introduced earlier) more fully integrated an economically viable crop rotation, weed management and residue management while maintaining surface residues for conservation compliance and increasing soil moisture (Young et al., 1994a,b,c). Nevertheless, it has since been determined that direct-seeded winter wheat-spring cereal-spring legume eventually builds up pervasive annual grassy weeds, including Italian ryegrass (Young et al., 2016). Spring canola substitution for spring wheat and more profitable chickpeas in place of peas are options currently being implemented. Typically, there is insufficient soil moisture and growing degree days following crop harvest to establish and grow winter canola in this zone, so the focus has been on adapting spring canola (Pan et al., 2016b). In replacing spring wheat with spring canola, a direct-seeded crop sequence of spring canola-spring pea-winter wheat provides two sequential broadleaf crops that enable better control of pervasive grassy weeds such as Italian rye, that otherwise are difficult to control with a winter wheat-spring cereal sequence. Future direct-seeded cropping systems should have flexibility to have two spring broadleaf crop options (oilseed and legume) in rotation with winter wheat to achieve biological and market diversification for improved rotational economic returns, while sequestering C and controlling grassy weeds and soil erosion. Crop intensification by integration of alfalfa and animal/crop systems also provide potential win-win scenarios in this zone, depending on relative competitiveness of fluctuating animal vs. crop grain markets (**Figure 6**).

Irrigated Crop Zone

Located in the temperate desert of central Washington and Oregon (**Figure 5**), the irrigated crop zone supports annual row crop rotations that include potatoes and sweet corn that are considered susceptible to nitrate leaching. Previous studies in the Columbia Basin have shown that cover cropping can reduce leaching and recycle N in shallow-rooted potato crop sequences (Weinert et al., 2002; Collins et al., 2007). More recent research showed that integrated reduced tillage-cover cropping could increase the NUE and N export efficiency (NEE), while increasing season surface coverage, reducing wind erosion potential of a potato-wheat and corn-potato cropping sequence (Madsen, 2017). The NUE of the potato-wheat cropping sequence increased significantly due to reduced tillage. In addition, the potato NEE increased significantly due to cover crop and reduced tillage. Additionally, cover crops reduced the amount of mineral N between 60 and 120 cm. The increase in NUE and NEE, without a decrease in yield demonstrates that integrated cover cropping and reduced tillage can be the basis of win-win irrigated cropping systems (Madsen, 2017). Soil N testing and predicted rapid N mineralization from cover crops in these agroecosystems will provide estimates of total soil N supply that can lead to reduced N fertilizer recommendations (Weinert et al., 2002). Cropping system modeling suggests that reducing tillage while controlling N fertilizer inputs in these irrigated systems has promise for reducing net GHG emissions (Stöckle et al., 2012).

Finally, the proximity of crop acreage in the irrigated and crop-fallow zones to concentrated livestock farming and western Washington and Oregon urban populations opens new opportunities for livestock grazing on crop residues (Yorgey et al., 2017c) and judicious use of manure and biosolids during cropping sequences. In return, these production systems provide food and fuel in completing the cycle with nutrient sources.

SUMMARY AND CONCLUSION

Farm management practices have been adopted if they directly benefited farmers in improving their profitability and farm legacy while diversifying their markets. Historically these practices have often been adopted at the expense of soil, air and water quality. Wheat farmers and farmer networks in the iPNW over the past 40 years have recognized the need to minimize negative impacts on their surrounding air and water quality, while sustaining and building soil health. Now, they are also being challenged to meet climate change mitigation and adaptation goals. If conservation and climate friendly practices do not lead to short term gains in farm profitability, then government incentives have been required to foster adoption, and even these incentives have fallen short of implementing universal changes. Integrated coordination of agronomic research and extension with emerging market opportunities and technological advances, farmer attitudes, and public policy is required to drive cropping system changes (Smit and Skinner, 2002; Robertson and Swinton, 2005) that will meet farmers' priorities as well as address climate change.

Adoption and integration of new crop rotations with alternative management strategies for crop residues, organic recycling and N fertilizers into flexible farming systems promise to produce synergistic impacts on the overall farm economics and agroecological goals. Successful implementation will require the extension and implementation of old conservation principles with new technology. Many of the historically recognized conservation practices are now also recognized to improve soil health and system-wide climate change adaptation and mitigation.

Moving forward, win-win scenarios are being tailored for subregional crop production zones principally defined by available water in the iPNW. Coordinated public and private efforts need to be directed at refining, enabling and integrating best management practices into win-win scenarios to support farmers in their roles as producers, land and environmental stewards and climate change warriors.

AUTHOR CONTRIBUTIONS

WP: Lead author responsible for writing team coordination, major text outline and writing, figure and table construction. WS: Dryland cropping systems contributions, including fallow management and winter pea production. FY: Dryland cropping and weed management, canola establishment sections. GY: Organic amendment first draft. EK: Crop rotation first draft. KB: Fertility section, overall editing. EB: policy related crop insurance summary. VM: Socioeconomic, policy section concepts, writing and editing. TM: Fertilizer management, NUE concepts, policy for crop adaptation. SM: Soil organic matter long term trends. JLJ-M: Earthworm, soil biota. IM: Irrigated crop zone cfBMPs.

LP: Coordinator of overall cropping systems project and data collection. KP: Socioeconomic section writer, editor. DH: Residue management, precision farming concepts, regional SOM summary. AE: Contributor of cropping systems comparisons in transition zone. HC: Contributor of irrigated systems findings and concepts. CS: Contributor of modeling outcomes and references. SE: Overall REACCH project leader and manuscript editor.

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REVIEW
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Northwest U.S. Agriculture in a Changing Climate: Collaboratively Defined Research and Extension Priorities

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In order for agricultural systems to successfully mitigate and adapt to climate change there is a need to coordinate and prioritize next steps for research and extension. This includes focusing on "win-win" management practices that simultaneously provide short-term benefits to farmers and improve the sustainability and resiliency of agricultural systems with respect to climate change. In the Northwest U.S., a collaborative process has been used to engage individuals spanning the research-practice continuum. This collaborative approach was utilized at a 2016 workshop titled "Agriculture in a Changing Climate," that included a broad range of participants including university faculty and students, crop and livestock producers, and individuals representing state, tribal and federal government agencies, industry, nonprofit organizations, and conservation districts. The Northwest U.S. encompasses a range of agro-ecological systems and diverse geographic and climatic contexts. Regional research and science communication efforts for climate change and agriculture have a strong history of engaging diverse stakeholders. These features of the Northwest U.S. provide a foundation for the collaborative research and extension prioritization presented here. We focus on identifying research and extension actions that can be taken over the next 5 years in four areas identified as important areas by conference organizers and participants: (1) cropping systems, (2) livestock systems, (3) decision support systems to support consideration of climate change in agricultural management decisions; and (4) partnerships among researchers and stakeholders. We couple insights from the workshop and a review of current literature to articulate current scientific understanding, and priorities recommended by workshop participants that target existing knowledge gaps, challenges, and opportunities. Priorities defined at the Agriculture in a Changing Climate workshop highlight the need for ongoing investment in interdisciplinary research integrating social, economic, and biophysical sciences, strategic collaborations, and knowledge sharing to develop actionable science that can support informed decision-making in the agriculture sector as the climate changes.

Keywords: actionable science, climate services, knowledge coproduction, climate change, mitigation, adaptation, agriculture, stakeholders

INTRODUCTION

Research at the nexus of climate change and agricultural production in the United States has focused on two distinct but related pathways of mitigation and adaptation. Mitigation efforts have attempted to quantify the impacts of agricultural production on climate change while also assessing practices that can be used to mitigate greenhouse gas (GHG) emissions associated with agricultural production. Adaptation research efforts have sought to explore the way adaptive practices can reduce the risks associated with climate change and build on opportunities. Research has been conducted for well over a decade on both mitigation and adaptation (e.g., Consortium for Agricultural Soils Mitigation of Greenhouse Gases, Washington State University Climate Friendly Farming Project, Southeast Climate Consortium). Recently, there has been increased emphasis on research focused on adapting agricultural systems to a changing climate, which coincides with a growing recognition in the land and resource management communities of the inevitability of an atmospheric doubling of carbon dioxide (CO_2) (IPCC, 2014a,b,c). Federal programmatic focal areas and funding for research in the past 5 years, exemplified by the United States Department of Agriculture (USDA) Regional Climate Hubs, reflect this intensified interest in agricultural adaptation (USDA NIFA, 2016; USDA, 2017). Additionally, there is increasing awareness that opportunities exist for "win-win" solutions that will improve farm economics while also making agricultural systems more resilient to a changing climate and lowering carbon footprints (Rosenzweig and Tubiello, 2007; Pretty, 2008; Power, 2010; Smith and Olesen, 2010; Duguma et al., 2014; Yorgey and Kruger, 2017).

The appeal of an approach that incorporates adaptation, mitigation, and profits is clear because it could provide a wealth of co-benefits to agriculture—and diverse stakeholders have articulated an interest in more research to evaluate the efficacy of potential management strategies across geographic regions and in multiple agroecosystems (Prokopy et al., 2015a; Allen et al., 2017). However, several intersecting factors make it difficult in practice to prioritize amongst management strategies across agro-ecosystems. First, many of these strategies have impacts that are spatially and temporally variable. This makes it difficult to make accurate projections of the costs and benefits for particular farmers. For example, building soil organic carbon (SOC) can enhance resilience by increasing soil water holding capacity, improving farmers' ability to withstand higher summer temperatures. It can also provide mitigation benefits by drawing carbon out of the atmosphere. However, the amount of SOC stored on an individual field or farm varies considerably. Factors including soil type and series, precipitation, and initial soil carbon levels can, in some cases, be even more important than management (e.g., reduction or elimination of tillage, cover crops, amendments) in determining the magnitude of soil carbon storage or loss (Paustian et al., 1997; Kemanian and Stöckle, 2010).

Second, the research and policy-making communities have limited understanding of how producers make management decisions, which makes it more difficult to identify and test realistic strategies that producers might choose to use. Agricultural producers must make resource management and investment decisions on the basis of highly complex and uncertain information from multiple sources. Thus, it is difficult to assess what information will be most relevant and useful to producers (Lemos et al., 2012; McNie, 2012; Weaver et al., 2013).

Third, there are limitations in climate scientists' ability to project the degree and rate of change of future climate, project impacts for specific cropping systems, and forecast the extent to which current crops and agroecosystems will be viable (Abatzoglou et al., 2014; Antle et al., 2016; Cammarano et al., 2016). For instance, to what extent can a producer increase soil carbon storage to retain more water within an existing crop or cropping system, before needing to change crops or fundamentally redesign the cropping system in response to climate change? Limitations in our ability to fully understand the nature of future climate change complicate efforts to evaluate agricultural adaptation and mitigation strategies, despite ongoing improvements in the usability of climate change projections for agricultural decision-makers (Antle et al., 2016; Parker and Abatzoglou, 2016; Rupp et al., 2016).

Given the potential for severe climate change impacts on agriculture and limits on time and financial resources, there is a need for a strategic approach to prioritizing near-term investments in research and extension to improve adaptive capacity, even in the face of these challenges and uncertainties. The Northwest United States is a good test-bed for evaluating opportunities for adaptation and mitigation, and is well-situated to test a collaborative approach to setting research and extension priorities.

From a biophysical perspective, the region is geographically and climatically heterogeneous, with a diversity of agro-ecological systems. Dryland and irrigated cropland produces over 250 commercially important crops, including nationally significant production of apples, pears, cherries, berries, and wheat (USDA NASS, 2015). The region encompasses a marked precipitation gradient with mean annual precipitation ranging from 150 mm to over 750 mm, leading to variation in grain crop varietals, cultivation strategies, and economic opportunities and challenges for farmers (Schillinger et al., 2010). Livestock are also important, with nationally significant production of milk, cheese, cattle and calves, and livestock forage (USDA ERS, 2015; USDA NASS, 2015). In 2012, the value of crop and livestock agricultural production in Washington, Oregon and Idaho was over $21.8 billion (USDA, 2012). The heterogeneity of the region's agricultural systems and ongoing work across the region has the potential to highlight key differences among systems, generating information that could provide a benchmark that is helpful to other agricultural production regions.

From a social perspective, the agricultural research and extension communities have long collaborated with farmer and industry networks and advisory groups, including in the realm of climate change. Comprehensive, interdisciplinary research and extension programming in the climate change and agriculture nexus has been occurring in the region for nearly 15 years, leading to substantial knowledge development, technology transfers and management adaptations (**Table 1**). In addition, the public sector has become increasingly vocal in supporting long-term investments in adaptation capacity and infrastructure, such as new irrigation water supply infrastructure, which is necessary to maintain a viable, if changing, agricultural resource base.

However, the level of complexity and uncertainty associated with climate change impacts and potential responses suggests the need for reinvigorating and advancing these long-standing partnerships in new ways. Important enhancements include the participation of a broad group of decision-makers at multiple organizational levels, such as crop advisors, irrigation districts, state and federal agencies, and private sector technology, and service providers (Bizikova et al., 2014; Prokopy et al., 2015b; Allen et al., 2017). There is also a need to more actively facilitate a feedback loop between researchers and stakeholders, as the applications of climate science to agricultural decision-making may not be as straight-forward as the application of new crop variety testing, innovations in machinery, or other similarly applied areas of science (Prokopy et al., 2015a).

In an effort to prioritize and catalyze future regional research and extension efforts, a workshop titled "Agriculture in a Changing Climate" was held on March 9–11, 2016 (AgCC, 2016), a first step toward reinvigorating those partnerships. The workshop's 82 participants spanned the research-practice continuum, including university faculty and students, crop and livestock producers, and individuals representing state, tribal, and federal government agencies, industry, nonprofit organizations, and conservation districts (**Figure 1**). They included many representatives of research teams and boundary entities involved in studies to inform adaptation and mitigation in agriculture in the region. Participants worked together to synthesize recent research findings and identify priorities related to climate mitigation and adaptation in the Northwest, with a particular focus on actions for the next 5 years (AgCC, 2016).

This article documents insights and priorities from the workshop, and expands the synthesis of recent research findings through a more systematic review of the literature on agriculture and climate change in the Northwest U.S. The findings of the literature review summarize the state of the science on climate impacts and mitigation, vulnerabilities, and opportunities to adapt, and help articulate the knowledge gaps and challenges. The research and extension priorities proposed for the next 5 years are based on the outcomes of the workshop and target identified gaps, challenges, and opportunities. Priorities are discussed in four topic areas identified by conference organizers and participants: (1) cropping systems, (2) livestock systems, (3) decision support systems to help producers and others incorporate climate change considerations into longer-term decisions (e.g., land transactions, perennial crop plantings, irrigation system investments); and (4) efforts to foster effective partnerships and communication between researchers and stakeholders (AgCC, 2016). Effective, sustainable mitigation and adaptation solutions will require addressing these interrelated topic areas in coordination with one another.

While the priorities discussed here are specific to the tri-state region of Oregon, Washington, and Idaho, many of these recommendations are also relevant in other regions of

TABLE 1 | Major climate change and agriculture-related efforts in the Pacific Northwest from 2003 to 2016.

Project title	Description
Climate Friendly Farming Project (http://csanr.wsu.edu/program-areas/climate-friendly-farming/climate-friendly-farming-final-report/, Kruger et al., 2010)	Research and assessment of the potential for improved management and technology deployment to reduce agricultural greenhouse gas emissions in the Pacific Northwest
Regional Approaches to Climate Change for Pacific Northwest Agriculture (REACCH) (reacchpna.org)	Enhance sustainability of PNW cereal systems and contribute to climate change mitigation
BioEarth (http://bioearth.wsu.edu/, Adam et al., 2015)	Regional earth systems modeling to improve understanding of the interactions among carbon, nitrogen, and water at the regional scale, in the context of global change
OFoot (https://ofoot.wsu.edu/ and http://csanr.wsu.edu/organic-farming-footprints/)	Estimating carbon footprints for organic cropping systems
Site Specific Climate Friendly Farming Project (Brown et al., 2015)	Precision N use in dryland cropping systems
US Dairy Adoption of Anaerobic Digestion Systems Integrating Multiple Emerging Clean Technologies (http://csanr.wsu.edu/anaerobic-digestion-systems/)	Enhancing anaerobic digestion in dairy systems through advancement of add-on technologies
Animal Agriculture in a Changing Climate (national project with a western region) (http://articles.extension.org/pages/60702/animal-agriculture-and-climate-change)	Fosters animal production practices that are environmentally sound, economically viable, and that create resiliency for animal producers and their partners
Watershed Integrated Systems Dynamics Modeling (WISDM) (http://wisdm.wsu.edu/)	Improve understanding of interactions between water resources, water quality, climate change, and human behavior in agricultural and urban environments

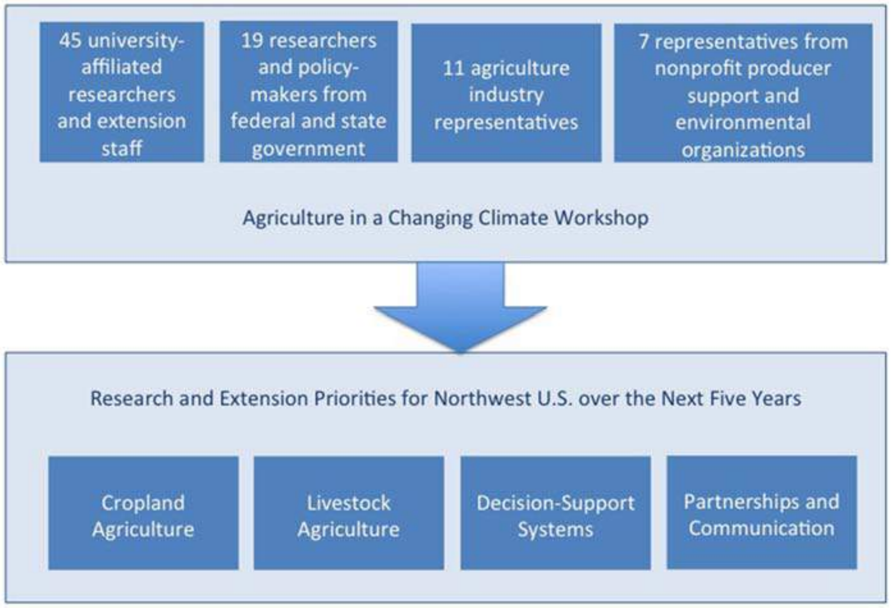

FIGURE 1 | During the "Agriculture in a Changing Climate Workshop," 82 participants from across the research-practice continuum worked collaboratively to identify priorities relating to climate change and Northwest U.S. agriculture in four focus areas: cropping systems, livestock systems, decision support systems, and partnerships and communication.

the U.S. with similar environmental conditions—for example, other irrigated cropping regions of the Western U.S. In addition, universal challenges are explored related to the development of climate-related decision support systems and effective partnerships along the full research-extension-practice continuum. Nationally, there has been a rise in the number and influence of institutions focused on coordinating efforts to support agricultural sustainability and resilience, such as the U.S. Department of Interior's Landscape Conservation Cooperatives and the U.S. Department of Agriculture's Climate Hubs. This article contributes to the ongoing discussion about how best to integrate mitigation and adaptation research and extension priorities, and demonstrates of the relevance of supporting researcher-stakeholder partnerships across the country.

CROPPING SYSTEMS IN A CHANGING CLIMATE

Climate Impacts and Vulnerabilities

Climate change in the Pacific Northwest is projected to lead to warmer temperatures, especially in summer; more frost-free days; wetter winters, and more variability in temperature and precipitation (Mote et al., 2013; Abatzoglou et al., 2014). Projected effects of climate change on agriculture in the temperate climate of the Northwest U.S., tend to be less severe than impacts projected for subtropical and tropical regions of the world (Parry et al., 2005; Schlenker and Roberts, 2009). The region's relatively cool climate also means that projected warming may be less detrimental than in other regions for some crops, and potentially beneficial for others. Because historical inter-annual variability is high, many cropping systems also have a significant amount of climate resilience built in, insulating them from some impacts of climate change. Taken in combination, these effects may lead to some benefits for the Northwest, when markets are national, or even global. However, projected climate change effects depend on the specific agricultural sector, geographic location, global climate models, and greenhouse gas concentration pathways considered (Eigenbrode et al., 2013).

Existing literature provides insights into crop yield and water availability vulnerabilities in multiple regional crop production systems. Increasing atmospheric CO_2 levels are expected to contribute to CO_2 fertilization and greater water use efficiency for dryland cereals, leading to stable or increased Northwest dryland wheat yields until mid-century (Tubiello et al., 2007; Hatfield et al., 2011; Karimi et al., 2017; Stöckle et al., 2017). By later in the century, projected further annual average warming of up to 3.3–4.4°C (6–8°F) in a high emission scenario may overwhelm the positive yield impacts of CO_2 fertilization by accelerating wheat senescence, reducing grain-filling, and grain shriveling (Ferris et al., 1998; Ortiz et al., 2008; Stöckle et al., 2010; Cammarano et al., 2016). Some recent research also indicates that warmer, drier summers may lead to increased fallowing throughout this century for rainfed areas that are currently cropped on an annual basis (Kaur et al., 2017). This could reduce overall yields, accelerate erosion, and decrease carbon sequestration compared to current conditions, increasing sustainability challenges.

For irrigated crops, a range of crop-specific impacts on potential yields are projected, assuming the absence of water, nutrient, or other stressors. Impacts depend on the relative importance of positive carbon dioxide effects and generally negative warming effects for each specific crop (Rajagopalan, 2016). Pastures and grasses are an important exception because these crops take advantage of a longer available growing season and are benefited by carbon dioxide fertilization, and thus see relatively larger increases in potential yields (Rajagopalan, 2016). Warming generally affects annuals negatively, as the positive carbon dioxide fertilization effects are outweighed by negative effects from a shortened growth season. In terms of irrigation demands, warming may allow for earlier planting (once spring soil wetness is considered) and accelerated crop development rates, leading to greater early irrigation demand for some crops (Rajagopalan, 2016).

Meanwhile, in Washington, some watersheds are expected to have reduced summer water supply (Hall et al., 2016). In combination with changes in demand, this creates an increase in the likelihood of water shortages (Hall et al., 2016) and curtailment of water use (Vano et al., 2010; Rajagopalan, 2016), but with reduced crop yields still within historical ranges (Rajagopalan, 2016). Because drought severity and frequency are expected to increase, drought will remain a key vulnerability for irrigated crops. More work is needed to identify the specific management challenges likely to arise for Northwest agricultural systems.

Climate change may also contribute to crop quality issues, particularly important for the many speciality crops produced in the Northwest. Warming trends could lead to insufficient chilling for some fruit and nut crops to develop, leading to reduced crop quality and yields (Luedeling et al., 2011). There are also indications that warming leads to decreased quality for potatoes (Alva et al., 2002; Timlin et al., 2006) and some current Northwest grape varieties (Jones, 2007; Diffenbaugh et al., 2011) and warming combined with drought stress may be implicated in the presence of diseases in vegetable seed crops. At the same time, warming trends may allow some species and varieties of tree fruit, nuts and grape varietals that are cold sensitive to be grown successfully in the region (Jones, 2007; Diffenbaugh et al., 2011; Luedeling et al., 2011; Parker and Abatzoglou, 2016). We do not yet know enough about the specific types of climate change impacts on crop quality to evaluate the usefulness of particular practices for diverse crops.

The same trends in climate will also contribute to changing ranges and behavior of plant pests (weeds, insects, and diseases), as well as beneficials (e.g., pollinators). Existing evidence suggests that individual pests, and the various biotic factors that regulate them, will respond differently to a changing climate, with both positive and negative impacts. As with the impacts on crop quality, we do not yet know enough about the impacts on specific pests and on particular crops to inform pest management practices, or to make projections of combined overall effects (Eigenbrode et al., 2017; Kirby et al., 2017). In addition, climate change and increased global commerce increase the possibility of invasive species, which can drastically change pest management regionally, nationally, or internationally (Lee et al., 2011; Leskey et al., 2012). Climate change is also projected to lead to warmer spring temperatures that will accelerate the timing of flowering, which could lead to a mismatch between flowering and availability of pollinators, thus impacting fruit setting (Houston et al., 2017).

Climate Mitigation Opportunities

Croplands emit and sequester multiple GHGs, including carbon dioxide (CO_2), nitrous oxide (N_2O), and small amounts of methane (CH_4). Soils across much of the region have lost carbon under cultivation. For example, dryland soils in the inland Northwest have lost an estimated 20–70% of their SOC since agricultural conversion (Puraskayastha et al., 2008; Brown and Huggins, 2012; Ghimire et al., 2015), a pattern seen elsewhere in the U.S. as well (Lal, 2004). The Columbia Basin is one important exception to this pattern, where irrigation and the associated increased plant productivity have contributed to higher total soil carbon under cultivation (Cochran et al., 2007). In both dryland and irrigated cropping systems, there is an opportunity for agricultural soils to sequester carbon by either reducing tillage or burning, or by increasing carbon inputs through crop residues, cover crops, or amendments (Paustian et al., 1997; Johnson et al., 2006).

Over the last 20 years, efforts to build SOC across much of the region have focused on encouraging the adoption of conservation tillage. These efforts have generated very important soil erosion reductions and soil health benefits (e.g., reduced bulk density, improved soil aggregation, water infiltration, and water holding capacity) over time, but experimental and modeling analyses suggest the potential climate mitigation impact is relatively modest (Brown and Huggins, 2012; Stöckle et al., 2012; Gollany et al., 2013; AgCC, 2016). Opportunities to store carbon are mostly from conversion to no-tillage in areas with greater precipitation, where productivity, and thus crop residue inputs, are higher. Stöckle et al. (2012) projected a change in SOC due to tillage of 0.26–0.49 Mg CO_2e ha^{-1} yr^{-1} over the first 30 years in the top 30 cm of soil from conversion to no-tillage in Pullman, Washington, an annual cropping area, with much smaller gains expected in drier and irrigated areas, or from conversion to reduced tillage.

In comparison, on a per-acre basis, the use of manures, biosolids, composts, and biochar may have greater potential for increasing SOC in the Northwest (Lazzeri et al., 2010; Cogger et al., 2013; AgCC, 2016), providing climate benefits as well as agronomic benefits. In a field experiment in eastern Washington State, biosolids application to a dryland grain-fallow system increased total soil carbon from 0.94 to 1.64% over 20 years (Cogger et al., 2013), while cover cropping in an irrigated system every other year raised soil organic matter from 0.6 to 1.2% over 13 years (Lazzeri et al., 2010). Biochar (a carbon-rich solid formed by pyrolysis of biomass) has garnered interest for a potential role in mitigating climate change (Woolf et al., 2010), and applications in corn in eastern Washington State have increased SOC (e.g., Bera et al., 2016), and raised pH (Streubel et al., 2011; Awale et al., 2017), an intriguing possibility given issues with soil acidification in some areas of the Northwest. However, costs, logistics of application, and other barriers such as pathogen concerns are sizeable (Galinato et al., 2011; AgCC, 2016), impacting the use of such soil amendments.

In addition to the carbon-based emissions, cropland soils (including those associated with livestock and poultry feed production) emit N_2O as a byproduct of the transformation of nitrogen carried out by soil microbes (Wrage et al., 2001; Zhu et al., 2013). Nitrous oxide emissions represent a significant challenge in the Northwest and elsewhere, as nitrogen is added to most cropland soils in fertilizers or manures, and negligible losses from an agronomic perspective can have a substantial impact from a GHG perspective (Post et al., 2012; Stöckle et al., 2012; Venterea et al., 2012). Because warmer, wetter soils are associated with high levels of N_2O emissions, there is a concern that emissions from agricultural soils may increase in the future (Venterea et al., 2012).

Despite ongoing advances (e.g., Waldo, 2016), measurement of N_2O emissions remains a methodological and scientific challenge (Henault et al., 2012; Venterea et al., 2012; Nicolini et al., 2013). Some existing experimental and modeling studies in eastern Washington State and southwest Montana have found N_2O emissions, as a percentage of nitrogen applied, that are lower than the current Intergovernmental Panel on Climate Change (IPCC) benchmark of 1% (0.1–0.9%; Cochran et al., 1981; Dusenbury et al., 2008; Haile-Mariam et al., 2008; Engel et al., 2010). However, other inland Northwest studies suggest emissions are more in line with, or even notably above, the IPCC benchmark (1.1–4.4%; Halvorson, 2010; Stöckle et al., 2012; Waldo, 2016).

Even with these methodological challenges, wider use of variable rate nitrogen application and of stabilized nitrogen fertilizers would likely reduce losses of reactive nitrogen, as existing research from other regions suggests that both can reduce N_2O emissions, including in semi-arid irrigated systems (Shoji et al., 2001; Sehy et al., 2003; Akiyama et al., 2010; Halvorson et al., 2011; Venterea et al., 2012). Both these practices aim to better match available nitrogen with crop needs, allowing for reductions in N-fertilizer inputs without negative impacts on crop yields. However, both practices tend to incur higher costs than traditional methods of nitrogen fertilization. Their broad-scale adoption, therefore, is dependent on the benefits to farmers outweighing increased costs.

Continuing improvements in process-based models (Stockle et al., 1994, 2003; Adam et al., 2015; Malek et al., 2016) and experimental work (Haile-Mariam et al., 2008; Brown and Huggins, 2012; Chi et al., 2016; Waldo et al., 2016) provide important insights and the capability to produce regionally-relevant estimates of mitigation potential of agricultural GHG reduction strategies. However, published estimates of the GHG reduction potential of the region are still incomplete due to the heterogeneity of the region's agroecosystems. For instance, there is very limited knowledge of the GHG impacts of the region's tree fruit, small fruit, and nursery, production systems; three cropping systems of significant geographic scale and economic impact.

Priorities for Adaptation and Mitigation in Cropland Agriculture

Based on the research and extension gaps that were identified during discussions at the Agriculture in a Changing Climate Workshop, the following priorities were identified for cropland agriculture in the Northwest U.S. over the next 5 years. These priorities are supported by a review of the current literature on remaining challenges and opportunities for climate change mitigation and adaptation in cropland agriculture. Each priority that emerged from the workshop is followed by a brief description of the supporting rationale and literature.

Cropping Priority A. Quantify vulnerabilities associated with the timing, amount, and inter-annual variability in water supply to support water-management decisions at multiple spatial and time scales.

Climate change is projected to lead to reduced snowpack and changes in timing of water availability, and is also expected to increase drought frequency, increasing water-related vulnerabilities. While changes in temperatures could also lead to new opportunities for individual farmers who have secure (senior) water rights, farmers' and water managers' water use decisions will affect junior water-right holders in the context of increased scarcity (Dang et al., 2016; Konar et al., 2016). In the Columbia River Basin, water use for pastures and hay has a large impact on aggregate water use and thus on shaping patterns of, and responses to, shortages (Rajagopalan, 2016). Development of adaptation strategies that can be used by individuals or irrigation districts is likely to be important. Such strategies may include improved irrigation efficiency, managed aquifer recharge and storage, micro-storage of irrigation water, use of reclaimed wastewater, and structures that facilitate water transfers to highest value uses during times of shortages. The effectiveness of different approaches may depend on the magnitude and timing of water supply vulnerabilities. As their implementation will require multiple years in some cases, quantifying potential water deficiencies and savings is an urgent need. Research and extension can also support development or improvement of tools that provide specific data and information for water-related decision-making, helping to promote more cost-efficient allocation of water (Dang et al., 2016).

Adaptations to climate change may also affect water demand through shifts in the crops and varieties grown, or through cover cropping or double cropping that takes advantage of lengthened growing seasons (Hall et al., 2016; Parker and Abatzoglou, 2016; Rajagopalan, 2016). Improved understanding of the effect these strategies have on water-related climate vulnerabilities will be important for the long-term profitability of irrigated crops—generally the higher-value products—in the region.

Cropping Priority B. Quantify expected climate change impacts on crop quality and crop pests (weeds, diseases, and insects), and evaluate strategies to address them, to support efforts to maintain quality of production.

To date, agricultural climate impact assessment research in the region has primarily focused on yield (quantity) effects. Workshop participants recognized a need to complement this with more information regarding the implications of climate change for crop quality (AgCC, 2016). Climate-related thresholds (e.g., consecutive days above important heat thresholds, accumulated chilling degree days, first and last frost dates) affect crop quality, either through direct impacts on the crop itself, or indirectly through influence on pests. These crop quality impacts should be investigated.

A need exists to assess climate change effects on pest pressure and to test control strategies for diverse locations throughout the Northwest. This will be challenging because species-specific pest and disease responses must be assessed for each crop of interest (AgCC, 2016). This need is particularly pressing for specialty crops, where crop protection costs are high and thresholds for effects are low.

Cropping Priority C. Establish credible estimates of carbon and nitrogen fluxes for Northwest agricultural systems to support innovation in and adoption of GHG reduction strategies.

Understanding current carbon and nitrogen fluxes and their variability can support GHG emissions reductions strategies. For example, in the Northwest, an extension of an analysis by Brown (2015) indicates that quantifying N_2O emissions is important to determining whether or not mitigation efforts could be accelerated through incentive mechanisms. The monetary incentive provided through existing GHG offset protocols is likely to not be large enough to induce changes in management if the lower end of the range of experimental emissions rates is used. However, if higher experimental measurements are used the incentive increases (e.g., $0.42–0.96 per hectare at an emissions factor of 0.2% vs. $2.50–5.89 per hectare at 2.9%, at a price of $50 per Mg CO_2 equivalent), especially when viewed in combination with the savings from reduced fertilizer expenses (Brown et al., this issue).

Cropping Priority D. Develop technical or other approaches to overcome existing barriers to increasing organic inputs in cropping systems, to support adoption of practices with substantial potential to increase carbon sequestration across the region.

Organic inputs to cropping systems can be increased through a variety of strategies, including increasing residues through choice of crop or variety, use of organic amendments, and integration of grazing livestock into cropping systems. Better understanding of the barriers that limit the use of organic soil amendments in different locations and types of cropping systems in the Northwest, and development of strategies to overcome these barriers (e.g., engineering biochar to add value through nutrients) could lead to more widespread use, increasing soil carbon sequestration and providing additional soil health benefits, even in the absence of a carbon market. Meanwhile, while integration of cropping and grazing systems is currently limited in the Northwest, an increasing number of innovative producers are grazing cover crops in both irrigated and dryland systems (Yorgey et al., 2017a,b).

Efforts to quantify the benefits provided by amendments through improved SOC (e.g., in the form of improved water holding capacity) could address these adoption barriers by providing motivation to farmers to invest in SOC-building strategies, especially in light of the recent emphasis on soil health by NRCS and other public and private agricultural advisors (AgCC, 2016). Understanding whether and under what conditions amendments may increase N_2O emissions is also a need as existing data have shown that this may sometimes occur (Collins et al., 2011; AgCC, 2016).

Cropping Priority E. Quantify under what conditions variable rate application and stabilized nitrogen fertilizers are most likely to decrease overall nitrogen use, and where that reduction is enough to offset increased costs, to support adoption of effective nitrogen management practices.

Variable rate nitrogen application and the use of stabilized nitrogen fertilizers were identified as priorities because of the likelihood that in some cases they can also provide short-term financial benefits to farmers, thus representing a win-win strategy. Variable rate nitrogen application, which aims to match fertilizer application to crop nitrogen needs as they vary within fields, has had variable impacts on overall nitrogen use. Based on experimental data (Mulla et al., 1992; Fiez et al., 1994; Huggins, 2010; Taylor, 2016) researchers have suggested that reductions of 10–35 kg ha^{-1} are achievable in low yielding areas of some but not all dryland cropping systems depending on the type of wheat grown, with low yielding areas varying, but in some cases representing 30% of field area (Brown et al., this issue). In addition to further research, extension efforts are also needed to support management of these technologies and assist farmers in evaluating performance (AgCC, 2016).

Enhanced efficiency nitrogen fertilizers reduce nutrient losses and better match availability with plant needs either by slowing release or by including additives that affect soil enzymatic or microbial processes. Price premiums (in the range of 10–40% in the late 2000s, Olson-Rutz et al., 2011) have been an important barrier to use of advanced fertilizer formulations in the Northwest and elsewhere. Prices had dropped significantly by early 2016, due to expiring patents and other factors, a change that makes these technologies more likely to be economically beneficial to producers (AgCC, 2016). Anecdotal evidence suggests that there is a need for decision-support to help farmers use them effectively (AgCC, 2016).

LIVESTOCK SYSTEMS IN A CHANGING CLIMATE

Climate Impacts and Vulnerabilities

While there have not been as many regional analyses of likely climate change-related impacts on livestock as for crops, existing studies suggest that higher temperatures projected for the twenty-first century are likely to cause heat stress for livestock, which will affect reproductive health, milk production, and can cause mortality (Key et al., 2014; Mauger et al., 2015). However, climate change impacts in the Northwest may be less detrimental than other regions of the country. Thus there are reasons to expect that the region may produce an increasing proportion of the nation's dairy and beef products in the future. For example, an economic analysis of the effects of climate change on milk production estimated that Washington State would experience a 0.4% loss in milk production from climate change by the end of the century, compared to Florida's projected 25% loss (Mauger et al., 2015). There may be opportunities to expand use of many heat stress reduction practices that are already implemented in the Northwest U.S. and other regions (e.g., Pressman, 2010; Brush et al., 2011; Key et al., 2014).

Historically, livestock production in the Northwest has benefited from a diversity of alternative forage resources, and from fewer and less severe droughts than other rangeland regions in the United States. However, it is important to recognize that drought risks may change in the future (Luce et al., 2016). Rangelands are particularly vulnerable to climate change because of their large land extent, sensitive ecology, inaccessibility to mechanical equipment, and relative low economic value. Climate change affects forage growth cycles and is likely to make spring grass available for grazing earlier in the season and ending earlier. Recent analysis suggests that Washington, Oregon, and Idaho are all likely to exhibit higher levels of rangelands vulnerability by 2060 (and beyond), among the higher for rangeland areas of the United States (Reeves et al., 2017). In addition, increased variability is expected to add significant challenges to implementing responsive grazing management plans and adapting effectively (Neibergs et al., 2017). Such planning could be important because, though strategies exist for coping with expected impacts and taking advantage of potential opportunities, their relative effectiveness in Northwest livestock systems will likely be system specific.

Mitigation Opportunities

In 2014, enteric fermentation in domestic livestock accounted for 22.5% of total U.S. CH_4 emissions, while manure management accounted for 8.4% of CH_4 emissions and 4.4% of N_2O emissions (EPA, 2014). Global research suggests that production system characteristics may affect GHG emissions (Eckard et al., 2010; Cottle et al., 2011; Smith et al., 2014), but the potential for such reductions in the Northwest remain uncertain.

Regular collection of manure prevents the significant GHG emissions that can result from anaerobic conditions developing within piles in the barn or feedlot pad (Sommer et al., 2007, 2013). However, only limited research has sought to quantify such GHG emissions in the Northwest (e.g., Brown et al., 2008). A review by Brown et al. (2008) suggested that improving manure management technology through improved composting, lagooning (manure storage in lagoons), and anaerobic digestion has significant potential to reduce livestock emissions. Composting can reduce GHG emissions, odors, and other air quality issues (Pattey et al., 2005). Liquid storage with a covered or aerated lagoon can have similar reductions in GHGs (Westerman and Zhang, 1997; VanderZaag et al., 2008). Application of manure to fields that is timed to coincide with crop or grass growth under mild temperatures and with minimum precipitation reduces GHG emissions and other air and water quality impacts (Ribaudo et al., 2003; Webb et al., 2010). Livestock producers adopting these and other mitigation practices to reduce emissions face challenges associated with determining which strategies are most effective for their unique system and are most likely to lead to net economic benefits over the long term.

Anaerobic digestion of livestock manure reduces GHG emissions and generates renewable energy by capturing CH_4 and CO_2 (Clemens et al., 2006; Holm-Nielsen et al., 2009; Mitchell et al., 2015). Recovery of nutrients from the resulting effluent further reduces the potential for nitrogen release as N_2O when applying the liquid to fields (Zeng and Li, 2006; Greaves et al., 2010), as well as for nitrogen (and other nutrients) to be released into water bodies. However, adoption of anaerobic digestion technologies has been slow across the U.S., despite their benefits. Contributing factors include unfavorable economics in light of current energy prices, ongoing regulatory uncertainty, and the fact that anaerobic digestion technology alone does not successfully alleviate nutrient-related concerns which are a higher priority for most dairies.

Follett et al. (2001) estimated that as much as 110 million metric tons of carbon could be sequestered per year on designated grazing land in the United States. Although, inland Northwest rangelands are generally arid, with low productivity, and susceptible to disturbance (and associated carbon loss) particularly as the climate changes (DiTomaso, 2000; Bradley et al., 2006; Neibergs et al., 2017), small changes to improve grazing management across millions of acres have the potential to increase or decrease total stored carbon in the region (Follett et al., 2001; Schuman et al., 2002; Booker et al., 2013; AgCC, 2016; Teague et al., 2016). In addition, applications of soil amendments (as discussed earlier in cropping systems) could increase carbon storage (Brown and Kurtz, 2010; Ryals and Silver, 2013), though questions remain about the economic feasibility of using soil amendments to increase SOC on Northwest rangelands. Experimental research on carbon sequestration in rangelands has been limited in the region (Briske et al., 2008), and the potential that such changes have to impact carbon sequestration in Northwest rangelands has yet to be quantified.

Priorities for Mitigation and Adaptation in Livestock Systems

Livestock Priority A. Share information on flexible drought management planning and on the effectiveness and cost of short- and long-term strategies for coping with heat and water stress to support adaptation.

Adapting livestock production to future climatic conditions will likely result from a combination of changes in planning (long-term) and changes in specific practices (both short- and long-term). Drought management plans may become increasingly important. This may entail a planned grazing process with high-density, short-duration grazing. This approach would allow for additional forage production during dry periods and would help producers to decide earlier whether they will need to sell animals if feed supply is insufficient (Kachergis et al., 2014). Selecting drought-tolerant feed species may also be an important adaptation strategy to reduce the impact of drought.

Short term adaptation strategies for heat stress include carefully monitoring ventilation systems, monitoring animal behavior for signs of heat stress, improving protocols for feeding animals in extreme weather, and adding more watering locations, shade structures, or other heat abatement systems (Pressman, 2010; Brush et al., 2011; Key et al., 2014). Many of these short-term adaptation strategies mentioned are already implemented on farms. Some producers are also making long-term investments in animal genetics, selecting breeds that respond relatively well to the dry and hot conditions, which are projected by climate models to occur more frequently (Place and Mitloehner, 2010).

Livestock Priority B. Increase adoption of strategies that build soil health and maintain ecosystem resilience to support adaptation of rangelands and other livestock systems to a changing climate.

Improved soil health across rangeland regions is critical to successful adaptation, and would also provide a mitigation benefit, even in the absence of incentive mechanisms. Current research suggests that much of the rangeland forage use in the Northwest is sub-optimal because of fixed turn-out and grazing end dates required by state and federal leases, leading to an inability to change grazing prescriptions in response to dynamic rangeland conditions (Neibergs et al., 2017). Thus, there is an opportunity to improve carbon storage and ecosystem function through improved technology-assisted matching of grazing to available forage resources (AgCC, 2016). Better matching of grazing management to forage resources in a dynamic planned grazing system could reduce the degradation of forage resources—associated with increased disturbance and carbon loss—increase productivity, and sequester carbon. The development and implementation of such strategies is critical given expected increases in rangeland vulnerability in the future.

The development of additional economically feasible models for integrated cropping and grazing systems provide another opportunity to support soil health in the region, with combined benefits for adaptation and mitigation. In integrated systems, ruminants increase SOC, biodiversity, and soil quality, which improves soil resilience during extreme wet and dry periods (Teague et al., 2016). In the areas of Washington and Oregon west of the Cascade mountains, growing cover crops for feed in rotation with annual crops such as corn silage (currently done on less than half of the acres in western Washington State), may significantly boost both local feed production and carbon sequestration (Olson et al., 2014; Poeplau and Don, 2015). Research to better understand barriers to integrating cropping and livestock systems in the Northwest, and collaborative efforts to develop practical integrated systems that overcome those barriers, would be beneficial (AgCC, 2016).

Livestock Priority C. Quantify GHG emissions associated with specific types of livestock operations, and evaluate animal production system characteristics that lead to reduced emissions in the Northwest, to facilitate their adoption.

Some of the most effective strategies for reducing the GHG emissions of livestock agriculture involve changes to the characteristics of animal production systems. Current research efforts are investigating choice of species and species mixing, and genetically-determined feed conversion and animal fertility rates (Eckard et al., 2010; Cottle et al., 2011; Smith et al., 2014) but there is a need to evaluate which of these strategies may be most relevant and feasible for the Northwest U.S. There is also potential for productivity improvements based on diet by switching to feed crops grown with minimal agricultural inputs (and therefore a smaller carbon footprint) and harvested in a manner that supports soil carbon storage (Beauchemin et al., 2009; Martin et al., 2010; Grainger and Beauchemin, 2011). Such strategies are likely to provide cost reductions for producers and facilitate adoption, even in the absence of carbon incentives.

Livestock Priority D. Update and share regional recommendations and decision support tools that support the appropriate use of existing technologies to plan and manage manure nutrients, reduce GHG emissions, and limit nutrient losses to soil, water, and air.

Limiting nutrient release from livestock systems, and the resulting negative soil, water and air quality impacts is a priority in several local areas of the Northwest with high concentrations of livestock (Mitchell et al., 2005; Baldwin et al., 2006; Leytem and Bjorneberg, 2009; USEPA, 2012). A robust manure nutrient management plan is an essential first step to reducing nutrient releases, and simultaneously reducing GHG emissions (Steed and Hashimoto, 1994; Van Horn et al., 1994; Rico et al., 2007; AgCC, 2016). In addition, manure management for intensive livestock systems will need to adapt to climate change in several ways. Adaptations to projected changes in timing, intensity, and frequency of rainfall events include increasing manure storage capacity and adjusting the timing of manure application (AgCC, 2016). Application setback distances may also play a role, though understanding is currently poor (e.g., Giddings, 1993). Timing of manure or fertilizer application may need to be adjusted to accommodate changes in timing of crop growth resulting from climate change. This points to a need for flexible regulation of the timing of manure application. Producers also require up-to-date recommendations about agronomic rates, potential risks and advantages of building new manure or water storage vessels, and redesigning outdoor pens to handle wetter early spring conditions.

Livestock Priority E. Develop cost reduction strategies and added value products that improve the economics for anaerobic digestion and manure nutrient recovery systems to support their adoption.

Continued research efforts are needed to improve the economic viability of anaerobic digestion systems by reducing costs and developing added-value products (Nasir et al., 2012; Mitchell et al., 2015; AgCC, 2016). Further development of emerging add-on technologies may also increase adoption rates by addressing producers' high priority concerns, such as nutrient recovery technologies that reduce impacts of high nutrient loads on water, air and other resources (Chen et al., 2005; Yorgey et al., 2014). Research should assess economic and non-economic benefits and challenges of these technologies at different scales across the Northwest. Improved, un-biased extension information about emerging technologies will also support industry and producer decision-making as external pressures change over time (AgCC, 2016).

DECISION SUPPORT SYSTEMS

Existing Use of Decision Support Systems and Their Potential

Agricultural decision-makers need targeted cropping and livestock system information that is easily integrated at the appropriate time and location to be useful. Decision support systems (DSS) are becoming a vehicle of choice to provide information in complex situations (Magarey et al., 2002; Samietz et al., 2007; Jones et al., 2010). Many existing agricultural decision support systems are aimed at dealing with time-sensitive information—such as forecasting when pests and diseases require various management interventions to prevent crop loss—and are often paired with short-range weather forecasts to enable users to respond. Data visualization tools can complement these DSS, allowing users to peruse weather and climate information, and in some cases also include derivative variables of particular importance to agriculture (e.g., growing degree days, chilling hours).

With this ongoing attention to DSS, there has been interest in using decision support systems to help producers adapt to climate change (**Table 2**). For the purpose of this paper, we refer to such DSS as climate change-related DSS. Climate change-related DSS need to incorporate insights learned from other types of DSS in order to be successful. For example, investing in validation of DSS outputs through testing model projections against empirical data is critical to ensuring credibility of results. This is important because producers have a long memory, and lack of validation and subsequent model failure would set back adoption of the system dramatically (AgCC, 2016).

Like non-climate related DSS, climate change-related DSS requires a collaborative and interdisciplinary approach to account for the complexity of solutions and to provide a suite of options. Non-climate related DSS are often developed for a relatively narrow purpose; for example, forecasting some part of the life history of an insect important for management, or predicting an epizootic for a particular plant disease. The users of these DSS are generally trying to deal with a complex set of problems that may occur at similar or different times of the year. Therefore, from the user perspective, it is important for the models included in the DSS to interact in some fashion. Experience has shown that for a DSS to be deemed usable and adopted by decision-makers, it must incorporate a significant number of models so that users come to the DSS over a significant fraction of the growing season (Jones et al., 2010). This sort of DSS essentially opens a new communication channel that allows a more efficient transfer of general (e.g., pest management guidance) as well as specific (model-based) information.

Development of climate change-related DSS has some distinct challenges. While many non-climate related DSS use information from weather forecasts, most ignore the inherent uncertainty and focus on a single result (e.g., forecasted high for tomorrow of 72°F). By contrast, seasonal climate forecasts (e.g., outlooks for the next several months) often involve a range of possible outcomes and uncertainty that a user of the climate change-related DSS may incorporate into their decision-making process. Likewise, longer-term climate change projections involve a large amount of data that should not be distilled into a single result, but instead should be viewed probabilistically, with uncertainties relating to climate change projections clearly communicated to the user (Wright-Morton et al., 2017). The construction of these tools is made more complex due to the greater diversity of potential clientele, ranging from agricultural producers to government agency users and researchers, as well as the varied time-scales of user interest.

Ongoing maintenance is essential to the long-term success of any DSS, including climate change-related DSS. This challenge requires creative and intentional planning to be successful. Funding agencies are generally eager to fund tool development, but much less willing to fund the maintenance of a tool or system. Existing successful DSS in the Northwest such as WSU-DAS or AIRPACT (Air-quality forecasting for the Pacific Northwest, lar.wsu.edu/airpact) have generally relied on multiple funding sources for ongoing programming and maintenance, including institutional support (e.g., from the hosting university or agency users), user fees, and support of the existing system made possible through ongoing expansion (AgCC, 2016). Other approaches that have been taken include voluntary support from users (so far unsuccessful to our knowledge), and selling advertising space (so far unsuccessful, but with potential). Partnerships with industry may also be relevant for accessing data and ensuring financial

TABLE 2 | Examples of existing and developing DSS relevant to the Northwest that include a climate or climate change aspect or have potential to include these aspects.

Tool	Description
COMET-Farm (http://cometfarm.nrel.colostate.edu/) and COMET-Planner (http://www.comet-planner.com/)	A carbon and GHG accounting system for whole farms and ranches in the US. Planner enables users to evaluate potential carbon sequestration and greenhouse gas reductions from adopting NRCS conservation practices
AgBiz Climate and suite of AgBizLogic tools (http://www.agbizlogic.com)	Economic, financial, and environmental decision tools for businesses that grow, harvest, package, add value, and sell agricultural products
WSU-Decision Aid System (DAS) for tree fruits (http://www.decisionaid.systems)	Integrates horticultural, insect and disease models to provide current management recommendations to Washington State tree fruit growers
Northwest Climate Toolbox (https://climatetoolbox.org/)	Synthesizes agriculturally relevant recent and projected climate information, allows users to query specific locations, climate scenarios, models and time horizons
Cattle heat stress alert and forecast (https://www.ars.usda.gov/plains-area/clay-center-ne/marc/docs/heat-stress/cattle-heat-stress-forecast/)	Uses National Weather Service 7-day forecast information to forecast animal heat stress
Dairy CropSyst (http://modeling.bsyse.wsu.edu/rnelson/Dairy-CropSyst/index.html)	A whole farm emissions and nutrient fate modeling tool that can support dairy decision making, with a focus on manure management
OFoot (https://ofoot.wsu.edu/)	A calculator for estimating the carbon footprint of organic farms

Some are developed specifically for the Northwest, while others are national in scope. The USDA Northwest Climate Hub (https://www.climatehubs.oce.usda.gov/northwest), provides links to many of these tools, and will be updated over time.

sustainability, though issues related to proprietary information and transparency of data collection and use need to be addressed. Diversifying and customizing the DSS to a range of end-users may be an important strategy, as it opens up the potential for multiple complimentary revenue streams.

Depending on their purposes, specific tools within a DSS may require weather or climate data at various spatial and temporal resolutions. Existing climate and non-climate related DSS cope with a variety of challenges related to use of individual datasets (including data quality, spatial and temporal coverage, resolution, and data biases). Implementing quality control procedures and managing these challenges is a key ongoing cost of managing DSS over time. Even with recent improvements, there are challenges in maintaining seamless flow of real-time data and forecasts, and some level of continual maintenance is required.

For this and other reasons, collaboration and centralized infrastructure may also be a key strategy for keeping development and maintenance costs low over time. Expansion to new geographic areas or commodities would be most cost-effective if it takes advantage of a wide variety of existing infrastructure, including environmental/forecasting subsystems, routines for setting up user profiles, data display and manipulation, access to management recommendations, and ancillary databases for miscellaneous purposes. Successful collaboration and maintenance lowers programming costs, allowing for more efficient focus on development of specific models that provide the decision-support outputs.

Priorities for Decision Support Systems to Inform Climate Change Mitigation and Adaptation

As described above, lessons learned in developing and using traditional decision support systems must be incorporated into the development of climate change-related DSS to be successful. The priorities for such development described below arose from discussions of those lessons in the literature and during the Agriculture in a Changing Climate Workshop.

DSS Priority A. Integrate climate change-related DSS with existing DSS tools and integrate financial planning components, so producers can evaluate the economics of potential management actions and investments.

A holistic approach is vitally important when developing climate change-related DSS. Developers of climate change-related decision support systems should consider incorporating multiple models to improve the tool's ability to walk producers through a variety of factors that may be affected by climate change (e.g., crop phenology, insect maturation, disease risk). Developers of climate change-related DSS should consider collaborating with providers of traditional DSS that producers already know and use. There is value in providing users with climate change-related information at online locations where they already go for decision support, such as pest management DSS (McNie, 2012; Kirchhoff et al., 2013). Integrating climate change-related DSS with other agricultural DSS creates opportunities to engage users who may not seek out climate change-related tools on their own, or who are skeptical about climate change (Feldman and Ingram, 2009; Akerlof et al., 2012). Integrated tools enable producers to consider climate as one of many risks that they need to plan for and manage (Howden et al., 2007; McNie, 2012; Kirchhoff et al., 2013).

The utility of climate change-related DSS would be enhanced by including models that evaluate the economics of different management strategies in addition to modeling agronomic impacts. Climate change-related DSS could thereby help producers incorporate climate change considerations into investment decisions, such as perennial crop plantings, equipment purchases, land purchases, and long-term leases (Allen et al., 2017; Capalbo et al., 2017; Kanter et al., in press), by helping them analyze costs, outcomes, and tradeoffs of alternative decisions. It is important that producers have access to climate-related DSS that allow them to make more efficient use of capital as well as inputs, as in many cases investment decisions have longer-term outcomes, and thus incorporating climate considerations is likely to improve readiness for future changes.

DSS Priority B. Develop multi-scale climate change-related decision support systems that focus on aggregate-scale as well as individual (farm-scale) decision-making, to help decision-makers at broader scales incorporate climate change.

Many of the available agricultural DSS are focused on individual producer-level decisions. These systems generally need data that have the highest spatial resolution and relatively short forecast duration (e.g., 2–4 weeks) to help make decisions regarding different management options. However, decisions are also made at larger scales, including irrigation district, watershed, or other political boundaries. Decisions made at each scale are conditional on those made at other scales and affect each other through feedbacks.

There are considerably fewer users at the aggregate scales, primarily regulators, or policy makers. However, the effects of poor decisions by this group can be extensive, and may result in serious economic impacts to individual producers or managers. There will also likely be higher development and support costs per user for aggregate-scale DSS, both because of fewer users, and because of the higher complexity of aggregate models. Yet these users tend to have access to more significant financial resources. Targeting these aggregate-scale decision-makers as users of climate-related DSS could lead to broader incorporation of climate change considerations in larger scale planning activities. Multi-scale tools may also help the aggregate-scale decision-makers visualize and evaluate the farm-scale impacts of their broader scale decisions (and vice versa).

DSS Priority C. Develop a centralized, quality-controlled source of input weather and climate data at multiple temporal scales so DSS developers can focus on the decision support aspect to directly inform adaptation decisions.

The majority of currently available climate projections are aggregated to a time-scale that has limited utility for supporting farm management decisions (Lemos et al., 2012; Weaver et al., 2013; Newsom et al., 2016). Many climate change projections are focused on a 20–30 year time-scale that are useful for policy and infrastructural investment purposes, but not for most farm management and investment decisions, which typically require shorter (2–10 year, or even seasonal) forecasts (Allen et al., 2017). In addition, climate change projections often focus on changes in average conditions, rather than extremes (e.g., heat waves, drought) that tend to more directly impact agricultural production (Lemos et al., 2012; Kirchhoff et al., 2013; Weaver et al., 2013). If ongoing scientific advances enable reliable seasonal forecasts and decadal climate prediction, as well as projections of changes in the frequency and intensity of extreme events, then their incorporation into climate-related DSS would likely make them more valuable to producers for farm-level planning and management (AgCC, 2016), especially if climate change makes it more difficult for producers to rely on experience to inform their expectations.

The development of climate change-related DSS would be greatly accelerated and considerably cheaper if there were a centralized source of quality-controlled weather data and climate forecasts. A central repository would also improve DSS quality by improving access to independent datasets for filling in missing data and for validation efforts. To illustrate the potential cost savings, it is estimated that 70% of the effort required to expand the Washington State University-Decision Aid System (WSU-DAS) for tree fruits from Washington State to British Columbia will be the development of the environmental monitoring/forecast system, with only 30% of effort for adapting the DSS to the management differences (AgCC, 2016). Achieving consistency and integration between one or more weather and climate datasets that are of interest within a climate change-related DSS can add to these challenges, as datasets will likely combine historical observations and multiple climate change projections.

Data should be available with a simple interface that would allow users to quickly access the desired climatic parameters for a particular location and time period (both historical and forecast), as well as automated collection of the data by web-based DSS. Users (DSS developers) should also be provided with explanations that would help them understand the limitations of the data and assumptions. For example, in climate projection data sets, changes in temperature are typically more pronounced than changes in precipitation, which needs to be considered when DSS developers are using the data as inputs to run biological models, or for deriving other variables.

PARTNERSHIPS AND COMMUNICATION AMONG RESEARCHERS AND DECISION-MAKERS

Existing Partnerships and Their Value

Recent decades have seen rapidly expanding efforts to conduct research that directly informs policies and the decisions made by agricultural producers, yet significant barriers remain in the pursuit of usable science focused on climate change and agriculture (Lemos et al., 2012; Kirchhoff et al., 2013; Wibeck, 2014). Active partnerships already exist in the Northwest U.S. among individuals working at many points along the research-extension-practice continuum on specific topics, in particular geographies, or on specific crops or production systems (AgCC, 2016). There is a need for the research and extension community to continue developing strategies for effective collaboration and communication with stakeholders, who have diverse needs and expertise (Moser and Ekstrom, 2010; Akerlof et al., 2012; Wibeck, 2014; AgCC, 2016). Existing literature suggests effective mechanisms for researchers to engage with agricultural decision-makers, and for building the necessary extension capacity—including that of conservation district staff, private-sector technical service providers, and others—to deliver actionable climate change information (McNie, 2012; Kirchhoff et al., 2013; Wibeck, 2014; Prokopy et al., 2015a; Roesch-McNally et al., 2017). In order to produce relevant tools and research, scientists need to be well-versed in the concerns and challenges that regional producers are facing and how those producers make decisions (McNie, 2012; Kirchhoff et al., 2013; Weaver et al., 2013; Allen et al., 2017).

Agricultural producers already manage multiple risks—economic, production-based, environmental, weather—however, managing for climate change-related risks is uniquely challenging because impacts are uncertain, variable over space and time, and often perceived as being only of concern in the distant future (Moser and Ekstrom, 2010; Leiserowitz et al., 2011; Akerlof et al., 2012). In some cases, discussions of climate change with agricultural producers has been complicated both by the politicized nature of the discussion (McCright and Dunlap, 2011), and because decision-makers may discount climate science as political rhetoric (Leiserowitz et al., 2011). These complications pose added obstacles for moving toward proactive, purposeful responses to long-term climate change risks, balancing the trade-offs and finding approaches for which the benefits outweigh the costs, for both individual producers and society.

Fortunately, there are increasing opportunities in the Northwest for effective collaboration among climate and agriculture researchers, agricultural professionals, producers, and other decision-makers who can use research results and decision support systems to inform their decisions. Northwest agricultural professionals recognize the effects of climate change as a priority research area (Zimmerman et al., 2014; AgCC, 2016). Interest in the results of agriculture and climate change research may also be growing in response to unprecedented regional climate patterns from 2014 through 2016 (AgCC, 2016). Workshop participants from different backgrounds—including researchers, agricultural professionals, industry representatives, and producers—voiced a sense of readiness in the Northwest to communicate openly to address climate change impacts through science, management, and policy channels (AgCC, 2016). There is also clear interest among scientists, producers and policy makers in working collaboratively across institutions to develop new technologies to monitor and manage agricultural systems (AgCC, 2016). Regional priorities for research and extension partnerships and communication in the Northwest U.S. are consistent with a nationwide trend to increasingly value and emphasize knowledge co-production and actionable climate science for natural resource decision-makers (Sarewitz and Pielke, 2007; McNie, 2012; Kirchhoff et al., 2013; Weaver et al., 2013).

Priorities for Partnerships and Communication Among Researchers and Decision-Makers

Specific recommendations for fostering the necessary collaboration and co-production of agriculture and climate change research in the Northwest U.S. emerged from discussions at the Agriculture in a Changing Climate Workshop, and are articulated in the following priorities.

Partnerships Priority A. Continue to build a robust network of diverse agriculture professionals and researchers that collaboratively identify research priorities and management-relevant questions, and integrate results into useful decision support systems.

The state of knowledge about climate change impacts and mitigation is rapidly evolving, and new concerns and information needs continue to emerge among agricultural decision-makers. In addition, producers' trusted sources of information are rapidly diversifying, including family, friends, neighbors, crop consultants, and input suppliers (Haigh et al., 2015; Prokopy et al., 2015a; Wright-Morton et al., 2016), as well as a growing use of web-based resources. Ongoing collaborations among researchers and stakeholders are therefore essential in order to (a) conduct relevant research and to develop effective climate change-related decision support systems, and (b) to make them available to users through the right channels, and (c) with appropriate training and support to facilitate their effective use. A clearinghouse for agriculture and climate change research, tools, and news would meet the need for such ongoing collaboration. The growing Agriculture Climate Network and its cornerstone website (www.agclimate.net) that shares and discusses agriculture and climate change research topics and resources in the Northwest U.S. represents one effort to foster such a robust network. This network is supported by organizations and programs that also provide additional climate science and tools, such as the Northwest Climate Hub (https://www.climatehubs.oce.usda.gov/northwest) and the Pacific Northwest Climate Impacts Research Consortium (http://pnwcirc.org/circ).

Partnerships Priority B. Partner along the research-extension-practice continuum to demonstrate the overall economic and environmental costs and benefits of climate change adaptation and mitigation strategies, to accurately inform individual adoption decisions.

Agricultural systems are complex, and producers are generally experienced in integrating many different considerations into a single decision (Mase and Prokopy, 2014). Often, a focus on short-term improvements and regulatory actions can have unintended negative impacts on other parts of the production system or the environment. Quantifying a holistic array of environmental and economic costs and benefits (which requires better incorporation of economic and social sciences) is one important strategy for improving research at the intersection of management and decision-making.

It is not realistic to expect producers to be motivated by mitigation strategies that have an overall cost. Costs and benefits of adaptation and mitigation strategies should be assessed and demonstrated at short-, mid-, and long-term time scales, and across the diverse agricultural systems of the Northwest. This will allow stakeholders to identify and consider those strategies that will be beneficial to them. In addition, producers may decide not to follow an adaptation or mitigation approach not because of a lack of scientific support, but because they are uncertain about the economic implications or the logistical burden of changing their operations. Ultimately, on-the ground demonstration of practice effectiveness is often needed before a producer is willing risk new methods or make significant investments on their farm (AgCC, 2016).

Partnerships Priority C. Communicate the limits of farm-level adaptation strategies, as well as important thresholds or tipping points at which climate change impacts may become more detrimental, to help decision-makers understand vulnerabilities.

A balanced approach is needed in communicating the potential effects of climate change. This approach should acknowledge the potential for opportunities for Northwest agricultural producers, and research indicating that individual farm-level adaptation may be adequate for many crops. However, it should also acknowledge that uncertainty still exists in terms of the magnitude of change in climatic variables, and that climate change may proceed more quickly than indicated by the scenarios currently used in many existing climate impacts studies for agriculture. In addition, vulnerabilities still exist, particularly due to impact of extreme events such as droughts, floods, and heat waves.

There are few published studies that examine the effectiveness and limits of individual farm-level adaptation strategies, such as changing varieties, selecting alternative crops, or building soil carbon storage (Stöckle et al., 2010). For some climate change-related risks (e.g., water shortages, flooding), effective responses may be required beyond the farm level. There is a need to ensure that—at a minimum—management and policy decisions implemented in the near term do not undermine farmers' ability to cope with more severe climate change impacts in the future (Howden et al., 2007; Roesch-McNally et al., 2017).

CONCLUSION

Climate change impacts on agriculture in the Northwest are projected to be generally milder than in many other agricultural regions of the country and the world given that the region's historical climate is relatively cool. Thus for some crops, moderate warming may be beneficial. Additionally, the region's cropping systems have a significant amount of resiliency built in to address historical inter-annual climate variability. This relative level of "regional climate change insulation" may lead to improved global market opportunities for some Northwest producers in the future.

Climate change, however, will likely create additional sustainability challenges for agriculture in the Northwest. For example, increased reliance on Northwest dairies for the United States' national milk production could exacerbate issues of water availability and manure management in some areas of the region. It could also increase the need to import feed, with associated import of nutrients to the region, contributing further to nutrient-related air and water quality concerns. Another significant concern is that climate change may cause farmers to increase fallowing as a risk mitigation strategy in the dryland crop production areas of the inland Northwest. This could threaten decades of progress made in reducing soil erosion, and make maintaining SOC more challenging (Kaur et al., 2017; Morrow et al., 2017). Similarly, some strategies to limit emissions of N_2O could increase losses of nitrogen as ammonia or nitrate. Investing in the necessary research and extension to understand these sustainability challenges, quantify trade-offs, and test and evaluate the cost and effectiveness of potential responses will provide the scientific foundation to inform producer responses as well as policies and incentives that support sustainable agricultural production over the long term.

Other agricultural regions in the United States may face more severe impacts from a changing climate, which may pose different challenges and raise different environmental concerns to those that are the focus in the Northwest. However, as climate change progresses, it is important to understand thresholds in environmental sustainability, the limits of farm-level adaptation, and the points beyond which easily accessible adaptation strategies will no longer be effective in each production region. Building from the example above on soil erosion, previously effective strategies in the Northwest and elsewhere—such as adoption of no-till farming—may not be sufficient to overcome the new challenges posed by a changing climate, requiring transformative thinking and the development of new management approaches or genetic improvements not yet envisioned.

We have synthesized the perspectives shared at the Agriculture in a Changing Climate Workshop (AgCC, 2016) and have provided specifics about research and extension priorities based on a review of agriculture and climate change-focused literature. Knowledge gaps, remaining challenges, and existing opportunities have guided the definition of research and extension priorities that are expected to help the Northwest's agricultural sector adapt to current and future climate change and contribute to mitigation efforts.

Multiple, interrelated challenges exist for funding entities, researchers, extension professionals, and agricultural advisors pursuing these priorities. Agricultural systems in the region are highly variable, so adaptation or mitigation practices that are successful for one location or production system may not be successful in another. Different decision-makers—from policy-makers to producers—require information at different scales. Also, efforts to address these priorities require an understanding of the complexity and interconnected nature of climate systems, agroecosystems, and society. Where possible, this article anticipates these challenges and suggests effective strategies that would lead to research that informs agricultural decision-making at multiple levels. The specific research results obtained by pursuing these priorities will be most directly informative within the Northwest region and its specific production systems, however, there are many lessons that can be applied elsewhere related to effective approaches to inform climate change adaptation and mitigation in agricultural systems.

There are many challenges to the viability and sustainability of agricultural systems in the Northwest U.S., including changing national and global trade opportunities, labor issues, and competing land use priorities (Allen et al., 2017). Climate change impacts intersect with these existing challenges in multiple ways. Managing agricultural systems to mitigate and adapt to climate change presents new and complex issues for agricultural decision-makers, yet there are good reasons to be cautiously optimistic about the potential for increasingly sustainable and resilient agricultural systems in this region. The agricultural industry is experienced at adapting to climatic variability and managing multiple risks. This experience in risk management, coupled with the relatively moderate impacts expected in the Northwest, suggest that proactive and informed producers can likely adapt to future changes and continue to sustainably provide agricultural products to the region and the country. The efforts of producers must be supported by the work of agriculture and climate change researchers from diverse disciplines (and their supporting and funding institutions). These research and extension priorities provide a roadmap for continuing to invest strategically in collaboration and knowledge-sharing designed to produce actionable science, to build capacity and facilitate the use of such science. By pursuing these priorities we can move toward implementing key adaptation and mitigation strategies appropriate to the unique production systems of the Northwest.

AUTHOR CONTRIBUTIONS

GY: Lead author responsible for conference planning/design of collaborative process, major text outline and writing, coordination and editing of manuscript. SH: condensing cropping systems contributions, major manuscript editing. EA: Partnerships contributions, coordination of livestock systems section, major manuscript editing. EW and NE: Conference planning committee, livestock contributions. VJ: Key conference planner decision support systems contributions. BS: Primary conference organizer and coordinator, key conference planner/design of collaborative process, text contributions. KR and JA: Decision support systems contributions. GR: partnerships contributions. BV: Conference planning committee. HC: Conference planning committee, cropping systems contributions. LH: Conference planning committee, economics/decision support contributions. TE: Livestock contributions. CK: Key conference planner/design of collaborative process, major manuscript editing. All: manuscript review and editing.

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Agro-Ecological Class Stability Decreases in Response to Climate Change Projections for the Pacific Northwest, USA

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Climate change will impact bioclimatic drivers that regulate the geospatial distribution of dryland agro-ecological classes (AECs). Characterizing the geospatial relationship between present AECs and their bioclimatic controls will provide insights into potential future shifts in AECs as climate changes. The major objectives of this study are to quantify empirical relationships between bioclimatic variables and the current geospatial distribution of six dryland AECs of the inland Pacific Northwest (iPNW) of the United States; and apply bioclimatic projections from downscaled climate models to assess geospatial shifts of AECs under current production practices. Two Random Forest variable selection algorithms, VarSelRF and Boruta, were used to identify relevant bioclimatic variables. Three bioclimatic variables were identified by VarSelRF as useful for predictive Random Forest modeling of six AECs: (1) Holdridge evapotranspiration index; (2) spring precipitation (March, April, and May); and (3) precipitation of the warmest 4-month season (June, July, August, and September). Super-imposing future climate scenarios onto current agricultural production systems resulted in significant geospatial shifts in AECs. The Random Forest model projected a 58 and 63% increase in area under dynamic annual crop-fallow-transition (AC-T) and dynamic grain-fallow (GF) AECs, respectively. By contrast, a 46% decrease in area was projected for stable AC-T and dynamic annual crop (AC) AECs across all future time periods for Representative Concentration Pathway (RCP) 8.5. For the same scenarios, the stable AC and GF AECs showed the least declines in area (8 and 13%, respectively), compared to other AECs. Future spatial shifts from stable to dynamic AECs, particularly to dynamic AC-T and dynamic GF AECs would result in more use of fallow, a greater hazard for soil erosion, greater cropping system uncertainty, and potentially less cropping system flexibility. These projections are counter to cropping system goals of increasing intensification, diversification, and productivity.

Keywords: climate change, bioclimatic variables, cropping systems, fallow, agro-ecosystem

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INTRODUCTION

Changing climatic conditions have resulted in substantial shifts in the geographic range of plant and animal species in natural ecosystems (Gonzalez, 2001; Wilson et al., 2005; Pauli et al., 2007; Chen et al., 2011) and are predicted to continue in the future (Schrag et al., 2008; Lawler et al., 2009; Monadjem et al., 2013). Likewise, single or multiple crop agro-ecosystems within a biophysical and socio-economic context have been affected by changing climatic variables (Kumar et al., 2013; Zhang et al., 2013). It follows that shifts in the geographic suitability of crop species/systems would occur in response to a changing climate (Evangelista et al., 2013; Ovalle-Rivera et al., 2015).

Assessing potential impacts of climate change on agro-ecosystems would benefit from classification systems that are dynamic and reflective of differences in the spatial distribution of land use/cover over time. Considering this goal, a new agro-ecosystem classification system, identified as dynamic agro-ecological classes (AECs) was developed for the dryland cropping region of the inland Pacific Northwest (iPNW; Huggins et al., 2014b). The AECs deviate from existing frameworks that classify agro-ecosystems based strictly on environmental drivers (e.g., soil, climate, and physiography) with relatively static boundaries, such as agro-climatic zones (Douglas et al., 1992), Ecoregions (US-EPA, Omernik and Griffith, 2014), and Major Land Resource Areas (USDA-NRCS, 2006). The AECs are based on the actual annual land use/cover derived from the Cropland data layer (USDA-NASS, 2008–2015). This classification approach for defining AECs provides the opportunity to quantify and test hypotheses regarding the drivers of spatio-temporal changes in cropping systems.

Currently, dryland cropping systems of the iPNW are fundamentally influenced by climatic gradients of temperature and precipitation (Schillinger et al., 2006). The dominant rotation practiced in regions with the lowest annual precipitation and highest annual temperatures is winter wheat–summer fallow which corresponds to the grain fallow class of AECs (Huggins et al., 2014b). This 2-year rotation includes a year of fallow to increase stored soil water that further ensures successful production of winter wheat. Grain-fallow systems become less prevalent in wetter portions of the iPNW where annual cropping systems dominate. Consequently, cropping system intensification progresses from the grain-fallow AEC with >40% annual fallow to the annual crop-fallow transition AEC (>10 to ≤40% annual fallow) and the annual cropping AEC (≤10% annual fallow). As climatic gradients influence crop choices and the use of fallow across the iPNW, we hypothesize that bioclimatic variables may explain significant geographic variations in AECs. In turn, a geospatial model of AECs based on bioclimatic variables may be used to project potential shifts in regional AECs under future climate scenarios.

Ecological studies that have assessed species distribution and projected changes in response to future climates often use and compare a variety of methods. These methods include generalized additive models (Estes et al., 2013), generalized linear models (Pompe et al., 2008), Artificial Neural Networks (Rasztovits et al., 2012), Random Forest (Schrag et al., 2008; Lawler et al., 2009; Chang et al., 2014; Langdon and Lawler, 2015), and maximum entropy modeling (MaxEnt; Monadjem et al., 2013; Clark et al., 2014; Ren et al., 2016). Here we use Random Forest modeling to assess potential regional shifts in AECs for the iPNW.

Our objectives are the following: (1) identify bioclimatic predictors which can discriminate among current AECs using two different Random Forest variable selection methods; (2) assess the predictive capacity of the geospatial models for current AECs using bioclimatic variables; (3) use future climate scenarios to predict changes in identified bioclimatic variables; (4) model regional shifts in AECs that would result if future climate scenarios were imposed on current agricultural systems; and (5) interpret the relevance of any AEC shifts in terms of sustainable agricultural intensification, vulnerability to resource degradation, and priorities for agricultural research.

MATERIALS AND METHODS

Current Climate, Bioclimatic Variables, and AECs

The iPNW study region covering the lower elevations across eastern and central Washington, north-central Oregon, and northern Idaho has an extent of 9.4 million ha and is comprised of three dryland agroecosystem classes (AECs): (1) annual crop (AC); (2) annual crop-fallow-transition (AC-T); and (3) grain fallow (GF; Huggins et al., 2014b). The climate is generally Mediterranean-like (Schillinger et al., 2006), with cold, wet winters and warm to hot, dry summers. Annual average precipitation varies across the region with around 150 mm in lee of the Cascade Range in central Washington to more than 1,400 mm across the eastern portion of the study region in northern Idaho. Bioclimatic variables are derivatives of temperature and precipitation and variables considered biologically important for Mediterranean climates have been identified (Peinado et al., 2012). Here, we use 44 previously identified bioclimatic variables for empirical modeling (**Table 1**). Not included are potential future effects of elevated atmospheric CO_2 levels on bioclimatic variables.

Cropland data layer derived AECs for dryland annual crop, annual crop-grain fallow-transition and grain fallow in raster layers (30 × 30 m resolution) were used for each of the years 2007–2014 (Huggins et al., 2015). The rasterized AEC information from 8 years were further combined into one map layer by categorizing each dryland AEC into two subclasses using the raster calculator tool in ArcGIS (version 10.3.1, ESRI, 2011): (1) stable dryland AECs, where pixels were consistently the same dryland class for 2007–2014 and; (2) dynamic dryland AECs, where pixels changed classes during the 8-year period (Huggins et al., 2015). Identifying stable and dynamic AEC subclasses resulted in the development of a classification comprised of six AECs. The resultant AEC layer was then brought to a coarser scale of 4 × 4 km, using the zonal statistics and cell statistics tool in ArcGIS (**Figure 1**).

Gridded climate data from years 1981–2010 was obtained from Abatzoglou (2013). Daily maximum temperature,

TABLE 1 | Bioclimatic variables derived from climate data.

Name	Units	Bioclimatic variable description
ARI	Unitless	Aridity index (ARI = TEV/P)
BIOT	°C	Holdridge annual biotemperature
COI	°C	Continentality Index (COI = Tmax – Tmin)
HBIO	Unitless	Holdridge evapotranspiration index (HBIO =HEV/P)
HEV	mm	Holdridge potential yearly evapotranspiration
Hm	mm	Humid months; months in which P ≥ 2T
M	°C	Average maximum temperature of the coldest month
m	°C	Average minimum temperature of the coldest month
OEI	Unitless	Ombro-Evapotranspiration Index (OEI = 10 (Pp/TEV))
OTI	mm/°C	Ombrothermal index (OTI = Pp/Tp)
OTI_2	mm/°C	Ombrothermal index of the two driest consecutive months of the year
OTI_3	mm/°C	Ombrothermal index of the three driest consecutive months of the year
OTI2w	mm/°C	Ombrothermal index of the two warmest consecutive months of the year
P	mm	Yearly average precipitation
Pau	mm	Autumn precipitation (September + October + November)
%Pau	%	Percentage autumn precipitation
Pcm1	mm	Precipitation of the warmest four months in the year
%Pcm1	%	Percentage precipitation of the warmest four months
Pcm2	mm	Precipitation of the four months before Pcm1
%Pcm2	%	Percentage precipitation of the four months before Pcm1
Pcm3	mm	Precipitation of the four months after Pcm1
%Pcm3	%	Percentage precipitation of the four months after Pcm1
Phm	mm	Total precipitation for the humid months
%Phm	%	Percentage precipitation of the humid months
%Pj-s	%	Percentage precipitation from June to September
Pp	mm	Positive precipitation; total precipitation of those months whose mean temperature is higher than 0°C
Ps2	mm	Precipitation of the two warmest consecutive months of the year
Psp	mm	Spring precipitation (March + April + May)
%Psp	%	Percentage spring precipitation
Psu	mm	Summer precipitation (June + July + August)
%Psu	%	Percentage summer precipitation
Pwi	mm	Winter precipitation (December + January + February)
%Pwi	%	Percentage winter precipitation
SEPI	Unitless	Seasonal precipitation index (SEPI = (%Pwi + %Psp)/(%Psu + %Pau))
T	°C	Mean yearly temperature
TEV	mm	Thornthwaite yearly evapotranspiration
THI	°C	Thermicity Index (THI = 10 (T + m + M))
Tmax	°C	Mean temperature of the warmest month
Tmin	°C	Mean temperature of the coldest month
Tn	°C	Negative temperature; sum of the mean monthly temperatures of those months whose mean temperature is lower than 0°C
Tp	°C	Positive temperature; sum of the mean monthly temperatures of those months whose mean temperature is higher than 0°C
Ts2	°C	Mean temperature of the two warmest consecutive months of the year
Tsu	°C	Summer mean temperature (June + July + August)
GDD	Degree day	Growing degree days from Jan 1st to May 31st

minimum temperature, and accumulated precipitation at a 4 × 4 km resolution were aggregated to monthly time scales. We also extracted downscaled climate projections from 17 global climate models participating in the Fifth Coupled Model Inter-comparison Project (CMIP5) that have been evaluated for credibly simulating characteristics of regional climate (Rupp et al., 2013). Climate projections were downscaled using the Multivariate Adaptive Constructed Analogs approach (Abatzoglou and Brown, 2012) using the baseline training dataset of Abatzoglou (2013) to provide compatibility between current and future climate data. The 17 GCMs considered in evaluating predictive model performance were: bcc-csm1-1, BNU-ESM, CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2G, GFDL-ESM2M, inmcm4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM3, and NorESM1-M. Climate network common data form (netcdf) layers (4 × 4 km resolution) were brought into ArcGIS and converted to raster layer using "Make netcdf to raster" tool and then to point dataset using "raster to point" tool. Conversion to point layer facilitated generation of latitude and longitude for each point, at the center of 4 × 4 km pixel, thus aiding the extraction of AEC information for each point in ArcGIS and extraction of present and future climate netcdfs of precipitation, maximum, and minimum temperature data in R (R Core Team, 2015).

A total of 44 bioclimatic variables (**Table 1**) were calculated using actual historical climate data (1981–2010) for precipitation, maximum, and minimum temperature. In addition, annual historical climate data derived from 17 Global climate models (GCM) for years 1981–2005 (Abatzoglou and Brown, 2012; Taylor et al., 2012) were used to calculate the same bioclimatic variables (**Table 1**). Reducing the data dimensionality from 44 to a few key variables was accomplished using two different wrapper variable selection algorithms: VarSelRF (Variable Selection using Random Forests; Diaz-Uriarte, 2014) and Boruta (Kursa and Rudnicki, 2010). VarSelRF, a minimal optimal approach, performs selection by retaining a compact subset of variables with improved classification performance based on "Out of Bag" (OOB) error and also allows computation of variable importance (VarSelRF R package, R Core Team, 2015). Boruta, an all relevant variable selection approach, identifies all relevant variables, and

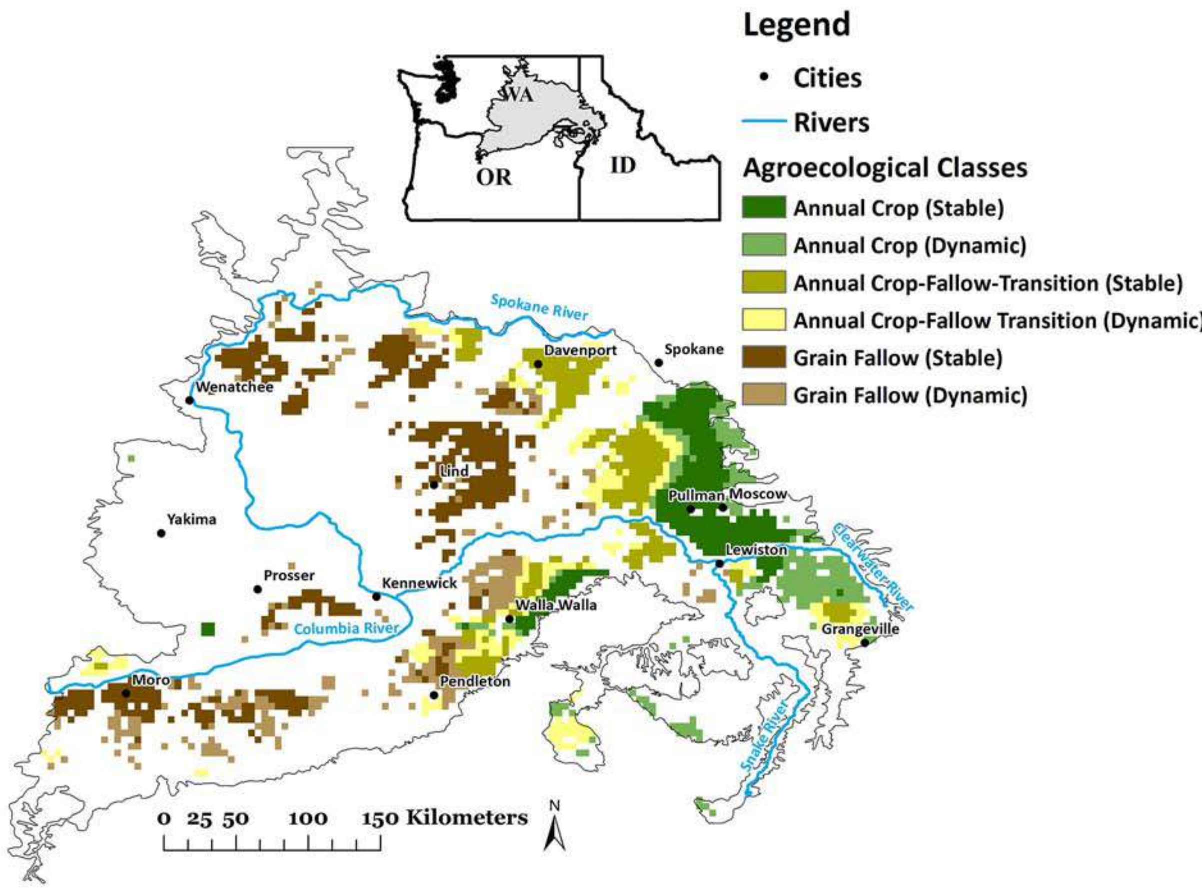

FIGURE 1 | Agro-ecological classes (AECs) for years 2007 through 2014 at 4-km resolution.

models them collectively to examine any underlying mechanisms in addition to being a predictive model (Boruta R package, R Core Team, 2015).

Observed bioclimatic variables and AECs (**Figure 1**) were used as input to R for variable selection using Boruta and VarSelRF algorithms and the process was repeated 30 times on split: training (70%) and test (30%) data sets, with different seed sets for each run. This step is based on the procedure used in the evaluation process of feature/gene selection (Fortino et al., 2014; Guo et al., 2014). The goal was to identify the variables that contributed the most to model performance in the selection process, which were selected repeatedly during 30 iterations. The motive behind partitioning the data as training (70%) and test (30%) was to understand the effect of selecting random subsets of data (training) on the ranking of variables and, as important variables were identified, the test set also provided an opportunity to independently quantify model performance.

Selection algorithms were used with their default parameters. The Boruta and VarSelRF algorithms facilitated selection of different sets of variables using performance metrics of z-score (which only identifies a variable as "important" or "unimportant") and accuracy (estimated using OOB error), respectively. The variables selected by the two methods were then used to model AECs using Random Forest. The Random Forest predictive models were built using the "train" function available in the "caret" package of R and performance statistics such as overall accuracy and kappa were determined for the test dataset during 30 iterations by training the model on a different training set (70%) each time, as well as on the full dataset with 10-fold five times cross validation. Performance statistics (overall accuracy and kappa) of predictive models were also estimated using historical GCM data (1981 through 2005). The Kruskal-Wallis-Test, non-parametric, was conducted using the "kruskal" function in R (package "agricolae"; de Mendiburu, 2015) to statistically compare selected Random Forest models and the selected variables of the final Random Forest model trained on all six dryland AECs. The performance of predictive Random Forest models was further evaluated for each AEC by computing confusion matrix statistics (accuracy and reliability) for each AEC. The same methods of variable selection using VarSelRF model training and evaluation were repeated to produce separate, reduced variable Random Forest models for each of the three main dryland AECs. Here, the stable and dynamic subclasses of each

AEC were combined into one AEC to produce three main AECs.

Global Climate Models, Prediction of Future Bioclimatic Variables, and AEC Shifts

Future climate data were derived from 17 GCMs for time periods 2030 (2015–2045), 2050 (2035–2065), and 2070 (2055–2085) and for two Representative Concentration Pathway (RCP) scenarios (RCP-4.5 and RCP-8.5). Downscaled climate data were used to calculate bioclimatic variables identified as important for discriminating among current AECs. Using the current spatial structure of each AEC, spatial average and coefficient of variation (%) of the identified bioclimatic variables were computed under present (1981–2010) as well as future time periods and scenarios (2070 for RCP 4.5 and 8.5).

The selected Random Forest predictive models, trained on current distributions for all six AECs and separately for each of the three main AECs, were used to determine changes in dryland AECs for different climate change time periods and RCP scenarios. This step was conducted in "R" using the "predict" function available in the "caret" package (Kuhn, 2015). Here, future climate scenarios were superimposed on current AEC production outcomes to assess how climate projections would impact the current aerial extent and spatial distribution of AECs. The 17 GCMs resulted in 17 AEC prediction outcomes for each latitude-longitude which were then consolidated into one value by selecting the AEC which had been predicted the maximum number of times.

RESULTS

Modeling AECs

Selection of Bioclimatic Variables and Random Forest Modeling of Current AECs

The Boruta algorithm selected all 44 bioclimatic variables as important for Random Forest modeling of AECs and the resultant model had an overall accuracy using present meteorological data of 76% (**Table 2**). In contrast, the VarSelRF method indicated that three bioclimatic variables, (Holdridge evapotranspiration index (HBIO), spring (Mar–May) precipitation (Psp), and precipitation of the warmest 4-months, Jun–Sep (Pcm1), modeled all six current AECs with an accuracy of 67% compared to 75% when using all 44 variables (Data not shown). Cross validation performance statistics of the Random Forest model using 44 variables had a slight but significantly greater overall accuracy and kappa for the historical GCM data compared to the reduced model of the VarSelRF method (**Table 2**). Models of the six current AECs using historical GCM data had an overall accuracy and kappa that were lower than models using present meteorological data (**Table 2**).

The performance of reduced predictive Random Forest models for each of the three major AECs was superior to the all- and three-variable predictive models for the six AECs (**Table 2**). Cross validation performance statistics were greatest for the GF AEC where the overall accuracy for the Random Forest model using present data was 93%, followed closely by AC (91%) and AC-T (89%) (**Table 2**). In order of importance, the bioclimatic variables selected by Random Forest modeling of the AC AEC were (1) Holdridge evapotranspiration index, (2) autumn precipitation (Sep–Nov) (Pau), and (3) Aridity Index; for the AC-T AEC, (1) precipitation of the warmest 4-months, Jun–Sep (Pcm1), (2) Holdridge evapotranspiration index, (3) Aridity Index, and (4) precipitation of the 4-month season before Pcm1 (Feb–May) (Pcm2); and for the GF AEC, (1) Holdridge evapotranspiration index, (2) precipitation of the warmest 4-months, Jun–Sep, and (3) Aridity Index (**Table 2**). The performance metrics of the individual three variable predictive Random Forest models using historical GCM data did not deviate substantially from those using present meteorological data (**Table 2**).

Cross validation accuracy and reliability of Random Forest modeling for the six AECs were higher using all bioclimatic variables compared to the three variable Random Forest model (**Table 3**). Accuracy of a class is the percent of correctly classified pixels out of the actual number of pixels, whereas reliability of a class is the percent of correctly classified pixels out of the predicted number of pixels. Accuracy and reliability ranged from 48 to 89% and were generally greater for stable than dynamic AECs for the six AEC models. Irrespective of the Random Forest model used for all six AECs, predictive accuracy and reliability were highest for the stable GF class averaging 86% and lowest for the dynamic AC-T averaging 55% (**Table 3**). The accuracy and reliability of the Random Forest models for each of the three individual AECs were notably greater than that of the six AEC Random Forest models and averaged 89% for AC, 87% for AC-T, and 93% for GF (**Table 3**).

Currently, stable AECs are 59% and dynamic AECs 41% of the total geographical distribution of dryland cropping systems (**Table 3**). The GF AEC currently has the largest area at 42%, followed by AC-T at 30% and AC at 28%. Spatially, dynamic AECs occur at the boundary of stable AECs (**Figure 1**). Here, non-parametric one-way ANOVA (Krushkal Wallis) showed significant differences in HBIO, Psp, and Pcm1 among all six AECs, except stable and dynamic AC-T (**Table 4**). HBIO means ranged from a low of 0.89 for dynamic AC-T to a high of 2.13 for stable GF. The stable GF had the lowest and dynamic AC-T the highest Psp and Pcm1. In addition, bioclimatic variability (CV) was higher for variables in dynamic compared to stable AECs (**Table 4**). Geospatial contours of HBIO, one of the most useful predictors, and current AECs showed similar patterns with division between AC and AC-T occurring about where HBIO was 1, while division between AC-T and GF occurred where HBIO was 1.5 (**Figure 2**).

Projected Changes in Bioclimatic Variables and Modeled Shifts in Current AECs

Increases in HBIO are projected under RCP 4.5 and 8.5 by 2070 (**Table 4**, **Figure 2**). Projected increases in Psp and declines in Pcm1 are anticipated across the iPNW. Both HBIO and ARI (different methods of calculating evapotranspiration and then dividing by precipitation) are predicted to increase and were selected as important for

TABLE 2 | Bioclimatic variables selected by Random Forest (RF) modeling of six and three agro-ecological classes (AECs).

Variable selection algorithm	Variables† (variable importance)	AECs‡	Present§ overall accuracy (%)	Present kappa	Historical¶ GCM overall accuracy (%)	Historical GCM kappa
Models for all six stable and dynamic AECs						
Boruta	All 44 variables	All	76	0.70	69a*	0.62a*
VarselRF	HBIO (99.2) + Psp (92.2) + Pcm1 (76.6)	All	69	0.62	64b	0.56b
RF models for each of the three major AECs						
VarselRF	HBIO (84.7) + Pau (43.9) + ARI (33.1)	AC	91	0.79	90	0.75
	Pcm1 (47.8) + HBIO (41.6) + ARI (35.1) + Pcm2 (34.0)	AC-T	89	0.74	86	0.67
	HBIO (55.4) + Pcm1 (36.6) + ARI (26.6)	GF	93	0.86	91	0.83

Numbers in columns with different letters are statistically different at $p < 0.05$ level of significance using non parametric one-way ANOVA (Krushkal Wallis) test.

† *HBIO, Holdridge evapotranspiration index (unitless); Psp = spring precipitation (March-May), mm; Pcm1 = precipitation of the warmest four-month season in the year (June-September), mm; Pau = autumn precipitation (September-November), mm; ARI = Aridity index (unitless); Pcm2 = precipitation of the four-month season before Pcm1 (February-May), mm.*

‡ *All = six stable and dynamic AECs; AC, stable and dynamic annual crop AECs; AC-T, stable and dynamic annual crop-fallow transition AECs; GF, stable and dynamic grain-fallow AECs.*

§ *Meteorological data from 1981 to 2010.*

¶ *Meteorological simulations generated by 17 GCMs (Global Climate Models) from 1981 to 2005.*

TABLE 3 | Agro-ecological classes (AECs) in present time period and cross validation accuracy and reliability of full and reduced variable Random Forest (RF) models for six and three AECs.

		Annual crop	Annual crop-fallow-transition	Grain fallow
Current AECs (number of 4 x 4 km pixels)	Stable	276	271	455
	Dynamic	205	235	262
Full (44 variable) RF model for six AECs				
Accuracy† (%)	Stable	78	75	84
	Dynamic	78	62	66
Reliability‡ (%)	Stable	86	77	89
	Dynamic	68	57	62
Reduced (three variable) RF model for six AECs				
Accuracy (%)	Stable	76	69	88
	Dynamic	59	48	55
Reliability (%)	Stable	68	66	84
	Dynamic	69	54	59
Reduced (three or four variables) RF models for each of the three major AECs				
Actual classified pixels (number)	Presence	481	506	717
	Absence	1223	1198	987
Accuracy (%)	Presence	85	80	91
	Absence	94	93	95
Reliability (%)	Presence	85	82	92
	Absence	94	92	94

† *Accuracy of a class is defined as the percent of correctly classified pixels of that class out of its total actual/true number of pixels.*

‡ *Reliability of a class is defined as the percent of correctly classified pixels of that class out of its total pixels in the predicted classification.*

individual Random Forest modeling of the three major AECs, although HBIO showed greater predicted responses to climate change than ARI (**Table 4**). Increases in seasonal precipitation were predicted for AC and AC-T; Pcm2 increases were particularly important in AC-T, while Pau increased modestly for AC. In contrast, decreased Pcm1 was predicted for GF (**Table 4**).

A 46% decrease in area for dynamic AC and stable AC-T occurs if future climate scenarios of RCP 8.5 were imposed upon current production systems using the six AEC model (**Table 5**). Areas of stable AC and GF would decline more modestly (8 and 13%, respectively). In contrast, area would increase by 58 and 63%, respectively, for dynamic AC-T and GF. These results are depicted spatially in **Figure 3** for 2070, RCP 8.5, and in comparison with present AECs (**Figure 1**), show dynamic AC-T and GF replacing dynamic AC and stable AC-T, GF, and AC. Coefficients of variation (CVs) of projected areas tended to be higher for dynamic compared to stable AECs and, with a few exceptions (stable AC-T, under RCP 4.5 and 8.5), generally increased as the twenty-first century progressed (**Table 5**).

In general, predictions for the main three AECs followed the same trends as the six AEC models, with the area under AC declining by 17%, AC-T increasing modestly (2%), and with more substantial area increases predicted for GF (15%) across all time periods of RCP 8.5 (**Table 5**). Here, CVs were generally lower under all future climate scenarios than for the six AEC models and did not have a strong tendency to increase with time. Spatial representations of the three main AEC Random Forest models for present day and a future scenario (2070 and RCP 8.5) generally indicate future areas under AC-T encroaching on present day AC while GF replaces AC-T (**Figure 4**).

TABLE 4 | Spatial average and coefficient of variation (CV%) of bioclimatic variables used with Random Forest (RF) models for present time period (1981–2010) and their future (2070) predictions under two representative concentration pathway (RCP- 4.5 and 8.5) scenarios derived from 17 global climate models.

Variables† (Units)	RCP‡	Time period	Annual crop		Annual crop-fallow-transition		Grain fallow	
			Stable (CV%)	Dynamic (CV%)	Stable (CV%)	Dynamic (CV%)	Stable (CV%)	Dynamic (CV%)
RF modeling of all six AECs								
HBIO (unitless)	n.a.§	Present	0.95d* (19)	0.89e (27)	1.28c (14)	1.31c (22)	2.13a (17)	1.86b (22)
	4.5	2070	1.16 (17)	1.10 (25)	1.53 (13)	1.57 (20)	2.48 (16)	2.19 (21)
	8.5	2070	1.25 (17)	1.20 (23)	1.64 (12)	1.68 (19)	2.61 (15)	2.30 (21)
Psp (mm)	n.a.	Present	162b (16)	176a (17)	126c (20)	133c (26)	74e (19)	100d (26)
	4.5	2070	175 (16)	191 (18)	136 (19)	143 (27)	79 (19)	105 (26)
	8.5	2070	183 (16)	199 (18)	142 (19)	149 (27)	82 (19)	110 (26)
Pcm1 (mm)	n.a.	Present	104b (15)	124a (19)	81c (22)	87c (39)	48e (17)	59d (25)
	4.5	2070	100 (15)	120 (19)	78 (22)	83 (39)	46 (18)	56 (25)
	8.5	2070	102 (14)	122 (19)	80 (22)	85 (38)	47 (18)	57 (26)
			Presence (CV%)	Absence (CV%)	Presence (CV%)	Absence (CV%)	Presence (CV%)	Absence (CV%)
RF modeling of each of the three major AECs								
HBIO (unitless)	n.a.	Present	0.93 (22)	1.73 (29)	1.30 (18)	1.59 (40)	2.03 (20)	1.12 (26)
	4.5	2070	1.13 (21)	2.03 (27)	1.55 (17)	1.88 (38)	2.38 (19)	1.35 (24)
	8.5	2070	1.23 (20)	2.15 (26)	1.65 (16)	1.99 (37)	2.50 (18)	1.45 (23)
ARI (unitless)	n.a.	Present	1.08 (19)	1.90 (27)	1.45 (16)	1.76 (37)	2.21 (19)	1.27 (23)
	4.5	2070	1.17 (19)	2.05 (27)	1.57 (16)	1.90 (37)	2.39 (18)	1.38 (22)
	8.5	2070	1.22 (19)	2.13 (27)	1.64 (16)	1.98 (37)	2.48 (18)	1.44 (22)
Pcm1 (mm)	n.a.	Present	n.a.	n.a.	84 (32)	76 (45)	52 (24)	98 (29)
	4.5	2070	n.a.	n.a.	81 (32)	73 (45)	50 (24)	94 (29)
	8.5	2070	n.a.	n.a.	82 (31)	75 (45)	51 (24)	96 (28)
Pcm2 (mm)	n.a.	Present	n.a.	n.a.	166 (20)	152 (40)	n.a.	n.a.
	4.5	2070	n.a.	n.a.	182 (20)	168 (40)	n.a.	n.a.
	8.5	2070	n.a.	n.a.	190 (20)	175 (40)	n.a.	n.a.
Pau (mm)	n.a.	Present	142 (18)	90 (25)	109 (15)	102 (37)	n.a.	n.a.
	4.5	2070	146 (17)	95 (24)	114 (13)	107 (35)	n.a.	n.a.
	8.5	2070	147 (17)	98 (22)	117 (13)	109 (34)	n.a.	n.a.

*Numbers with different letters are statistically different at $p<0.05$ level of significance using non parametric one-way ANOVA (Krushkal Wallis) test.

† HBIO, Holdridge evapotranspiration index, unitless; Psp = spring precipitation (March-May), mm; Pcm1, Precipitation of the warmest four months (Jun-Sept), mm; ARI, Aridity index, unitless; Pcm2, Precipitation of the four months before Pcm1 (Feb-May), mm; Pau, Autumn precipitation (Sept-Nov), mm.

‡ RCP, Representative concentration pathway.

§ n.a., Not applicable.

DISCUSSION

Identification of Bioclimatic Predictors Useful for Discriminating among Current AECs

Our study emphasizes the use of bioclimatic variables as they contribute to the geographic distributions of species and are used in modeling species occurrence (Watling et al., 2012). The HBIO was identified as an important bioclimatic variable for AEC modeling and prediction of all six dryland AECs as well as each of the three main AECs. Computationally, HBIO is an annual average of monthly temperatures within a range of 0–30°C, which is multiplied by a constant (58.93; Holdridge, 1967) to give Holdridge evapotranspiration (ET) and then divided by annual precipitation. HBIO, an important variable in the Holdridge life zone classification, is defined as potential evapotranspiration ratio and as mentioned, is dependent on annual precipitation and annual bio-temperature, the other two important variables used in the classification. The Holdridge life zone classification model represents the relation between climate and vegetation pattern and has been used in climate change studies to investigate the impact of changing climate on species distributions in different ecosystems (Cameron and Scheel, 2001; Enquist, 2002). Values of HBIO < 1 indicates conditions of water sufficiency while HBIO > 1 suggests conditions of water insufficiency or deficiency for all plant and animal life forms (Savage, 2002). In the present study, the average HBIO of stable and dynamic AC AECs were <1, while the remaining AECs, which all rely on fallow, had an HBIO > 1 (**Table 4**). Thus, empirically, HBIO emerged as an important bioclimatic variable for driving future changes in the extent and spatial distribution of AECs (**Figures 1–3**). Similarly, when considering 44 bioclimatic variables for each

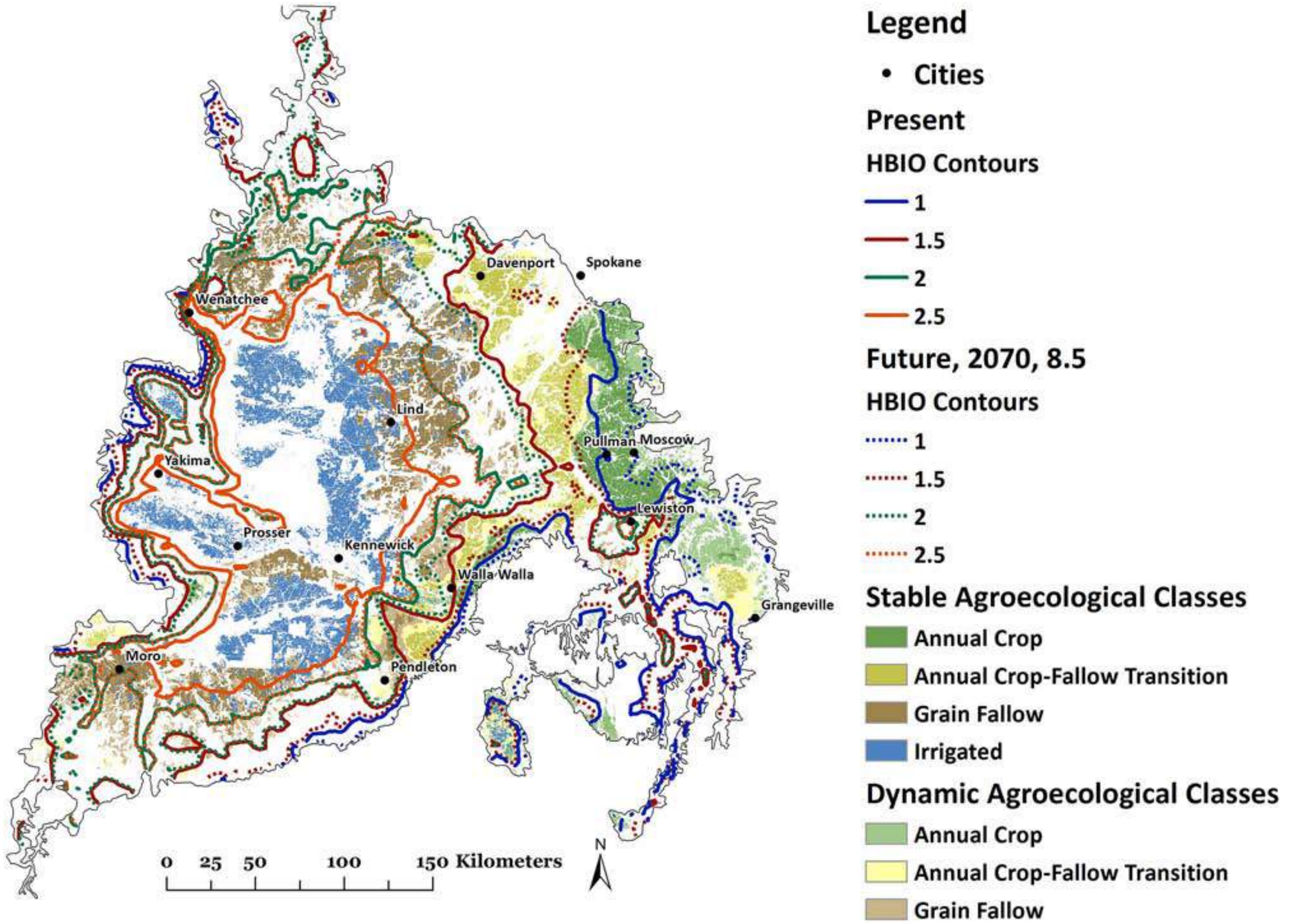

FIGURE 2 | Geo-spatial depiction of current Agro-ecological classes (AECs) and Holdridge Evapotranspiration index (HBIO) in present (1981–2010) and future climate scenario (2070, Representative Concentration Pathway, RCP-8.5).

of the three major AECs, ET indices, namely HBIO, and ARI (Thornthwaite ET index; defined as ratio of Thornthwaite ET to annual precipitation), were identified as the most important driving variables for AEC modeling.

Our analyses do not consider potential beneficial effects of rising carbon dioxide (CO_2) levels on crop physiology including increases in water-use efficiency (WUE) and overall crop yield (Stöckle et al., 2010). Ramírez and Finnerty (1996) reported decreased potential evapotranspiration (PET) under elevated CO_2 conditions and a resultant increase in WUE. Therefore, HBIO, although a bio-temperature based estimate of PET, could decrease with greater levels of atmospheric CO_2, potentially compensating for increased HBIO resulting from warming. Significant increases in soil water availability (via reduced stomatal conductance) under elevated CO_2 levels (Lu et al., 2016) could also compensate for negative impacts reported here, particularly the use of annual fallow. Palmquist et al. (2016), however, projected increases in actual evapotranspiration, dry days, and large reductions in available soil water during summer due to climate change for the western U.S. including our study region. Here, potential ameliorating effects of elevated CO_2 levels were not considered. Nonetheless, offsets of positive influences of elevated CO_2 levels due to negative effects of increased temperatures on crop physiology and growth have also been reported (Reddy et al., 2002; Zavaleta et al., 2003). Ko et al. (2012) simulated that negative effects of increased temperature would dominate the positive effects of rising CO_2 levels on crop yields in dryland cereal-based rotations of the U.S. Central Great Plains. Consequently, a thorough understanding of positive and negative feedback mechanisms from climate-vegetation interactions including CO_2 levels remains elusive.

Previous studies have used annual precipitation as an important delineator to classify dryland cropping systems of the iPNW (Douglas et al., 1988, 1992). In the present study, however, spring precipitation (Psp) and precipitation during the warmest 4 months (Pcm1) were identified as more important empirical predictors of AECs than annual precipitation. From a crop production and soil water storage perspective, most of the annual precipitation occurs from November to May and is important for all dryland AECs of the iPNW (Schillinger et al., 2008). Also relevant, however, are quantities of spring and early summer rainfall (April–Jun) which coincide with

TABLE 5 | Agro-ecological class (AEC) (number of 4 × 4 km pixels) for present time period and predicted number, average and coefficient of variation (CV%), under three future time periods and two representative concentration pathway (RCP-4.5 and 8.5) scenarios derived from 17 global climate models using Random Forest (RF) models for six and three AECs.

Time period	Annual crop		Annual crop-fallow-transition		Grain fallow	
	Stable (CV%)	Dynamic (CV%)	Stable (CV%)	Dynamic (CV%)	Stable (CV%)	Dynamic (CV%)
RF model for six AECs						
Present	276	205	271	235	455	262
RCP-4.5						
2030	258 (23)	138 (38)	213 (25)	298 (50)	466 (11)	331 (43)
2050	259 (28)	116 (49)	164 (38)	344 (48)	443 (19)	377 (42)
2070	272 (18)	108 (54)	138 (41)	382 (40)	393 (28)	412 (47)
RCP-8.5						
2030	230 (35)	141 (51)	182 (32)	328 (46)	467 (18)	356 (48)
2050	269 (22)	101 (60)	141 (45)	363 (48)	388 (28)	443 (46)
2070	264 (22)	92 (70)	118 (49)	423 (49)	328 (32)	480 (52)
	Presence (CV%)	**Absence (CV%)**	**Presence (CV%)**	**Absence (CV%)**	**Presence (CV%)**	**Absence (CV%)**
Separate RF models for each of the three major AECs						
Present	481	1223	506	1198	717	987
RCP-4.5						
2030	436 (20)	1268 (7)	495 (21)	1209 (9)	799 (16)	905 (14)
2050	439 (20)	1265 (7)	488 (20)	1216 (8)	816 (16)	888 (15)
2070	420 (21)	1284 (7)	502 (19)	1202 (8)	805 (18)	899 (16)
RCP-8.5						
2030	392 (18)	1312 (6)	494 (22)	1210 (9)	800 (19)	904 (17)
2050	386 (31)	1318 (9)	497 (23)	1207 (9)	842 (19)	862 (18)
2070	415 (32)	1289 (10)	557 (26)	1147 (12)	832 (26)	872 (24)

anthesis and grain filling of winter and spring crops (Schillinger et al., 2008). Our study indicates that seasonal precipitation and temperature significantly contributed toward differentiating among AECs. These results have production relevance as decisions regarding spring flex-cropping options (whether to produce a spring crop or to fallow) would be based on winter precipitation rather than spring and summer rainfall. Consequently, more uncertainty would be associated with flex-cropping options, potentially promoting the use of annual fallow.

Predictive Capacity of AEC Models

There are numerous empirical approaches available to understand species distributions and analyze climate-species relations. In the present study, we used "Random Forest," reported as a higher performance algorithm than other empirical approaches (Cutler et al., 2007; Schrag et al., 2008). Watling et al. (2012) did not report significant differences in prediction results using Random Forest with two different sets of variables (bioclimatic and monthly variables). Similarly, with our dataset, using Random Forest to predict current AECs resulted in comparable overall accuracy and kappa with cross validation on different sets of selected variables using two different variable selection methods. Elsewhere, the Random Forest approach has been successfully applied in various fields of research ranging from micro-array data analysis (Díaz-Uriarte and Alvarez de Andrés, 2006), hyper-spectral data analysis (Adam et al., 2012; Poona and Ismail, 2014), current species distribution studies, as well as in predicting distributions with changing future climate (Schrag et al., 2008; Watling et al., 2012; Langdon and Lawler, 2015). Random Forest belongs to the algorithmic modeling culture (Breiman, 2001) in statistical modeling where the data mechanisms are complex and not known. Therefore, Random Forest modeling results can be difficult to interpret and to identify underlying causal mechanisms. Nonetheless, Random Forest is gaining popularity over other empirical approaches for the following reasons: (1) it is non-parametric in nature and does not assume data distribution; (2) it is an ensemble classifier, its results are aggregated over the number of classification trees built/defined in the algorithm, and it avoids overfitting; and (3) the Random Forest algorithm is computationally more efficient and deals well with correlation and high-order interactions between input variables. For many datasets, utilizing Random Forest has proved to be highly accurate compared to other classifiers (Fernández-Delgado et al., 2014).

Performance of Random Forest as a predictive model was comparable with present meteorological as well as GCM data even with the reduction from 44 to 3 variables, which corroborated the high performance of the Random Forest

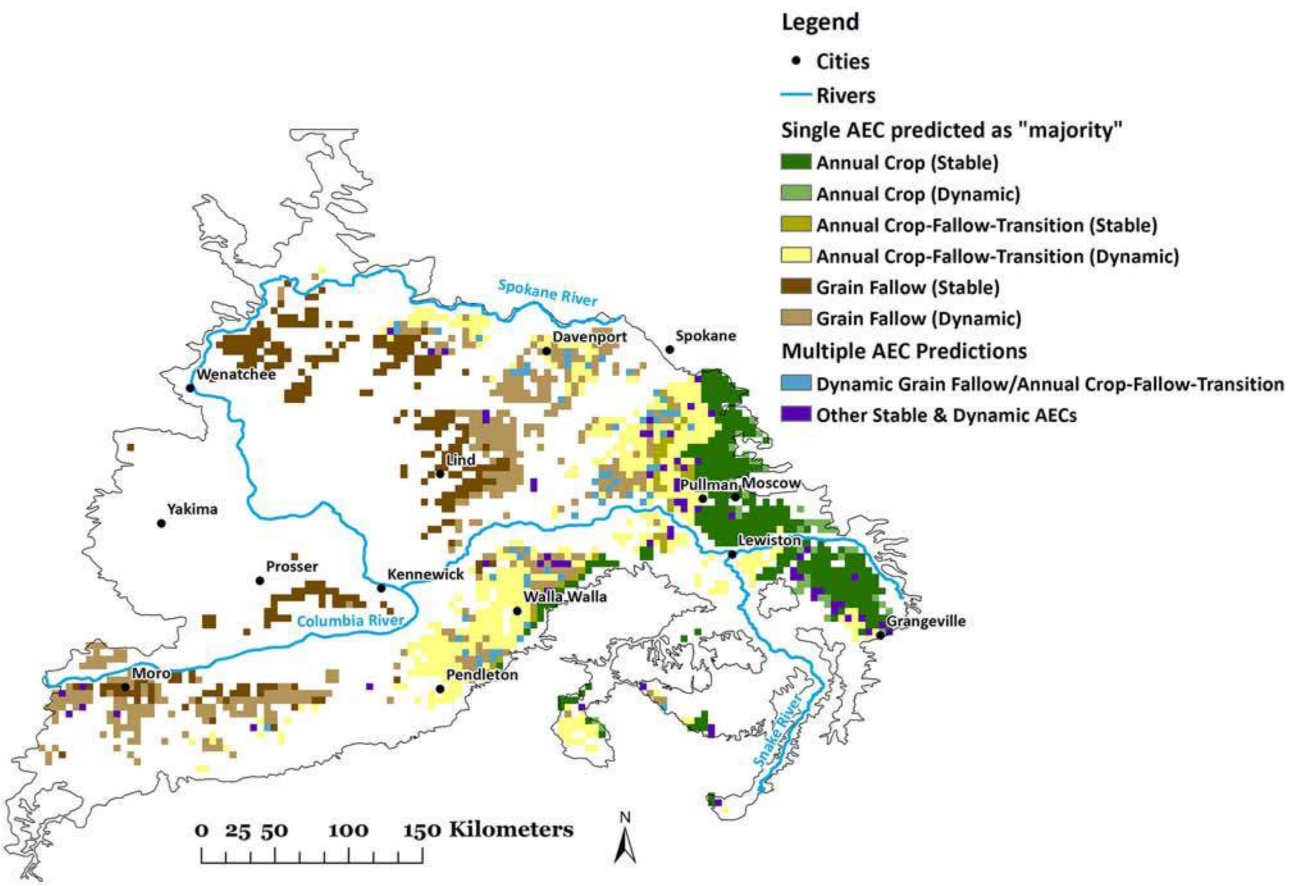

FIGURE 3 | Projected geo-spatial distribution of six (stable and dynamic) agro-ecological classes (AECs) using combined Random Forest (RF) model of bioclimatic variables for six AECs under future climate scenario (2070, Representative Concentration Pathway, RCP-8.5).

algorithm (**Table 2**). The only limitation of using the reduced Random Forest model with three variables was that this might decrease the possible combinations which would otherwise be used by Random Forest to improve AEC classification accuracy. In predictive modeling, however, a less complex and parsimonious model that uses a few important and relevant variables with high explanatory power is easier to interpret than a model with many variables as long as overall accuracy is not too impaired and the less complex model is also able to capture the intricacies of the patterns and distributions modeled (Evans et al., 2011). In our research, the 44 (all variables) Random Forest model had greater accuracy and reliability than the three variable model, but there was little loss in performance by reducing the number of variables from 44 to 3 (**Table 2**). Therefore, we proceeded with the VarSelRF selection method to reduce model dimensionality as well as redundancy to facilitate interpretation (Murphy et al., 2010) for all subsequent Random Forest modeling of AECs, and also to avoid model overfitting, which occurs in complex models with increased model variance (Hastie et al., 2009; **Table 3**).

The range in accuracy and reliability for the three variable Random Forest model was much greater for stable than dynamic AECs (**Table 3**) indicating more uncertainty would occur in prediction of dynamic AECs when imposing future predicted changes in bioclimatic drivers. Contributing to the uncertainty of dynamic AEC prediction was the scattered spatial distribution (e.g., Thuiller et al., 2003) of dynamic AECs compared to the more compact distribution of stable AECs (**Figures 1**, **4**). In turn, this contributed to higher CVs of selected bioclimatic variables within dynamic compared to stable AECs (**Table 4**). The relatively poor Random Forest model performance of the dynamic AECs led to modeling each of the three major AECs where stable and dynamic AECs were combined. Here, Random Forest modeling of the three major AECs separately improved overall Random Forest model accuracy from 69% to up to more than 93% (**Table 2**) and further identified the difficulty in using only bioclimatic variables in one Random Forest model to differentiate between stable and dynamic subclasses of major AECs. Thus, modeling three major AECs separately highlighted the role of bioclimatic variables and identified the need to include additional variables (e.g., soil, seasonal weather, and economic) if greater AEC model accuracy is required. The overall high accuracy (89–93%) of Random Forest modeling of the major AECs using only a few (3–4) bioclimatic

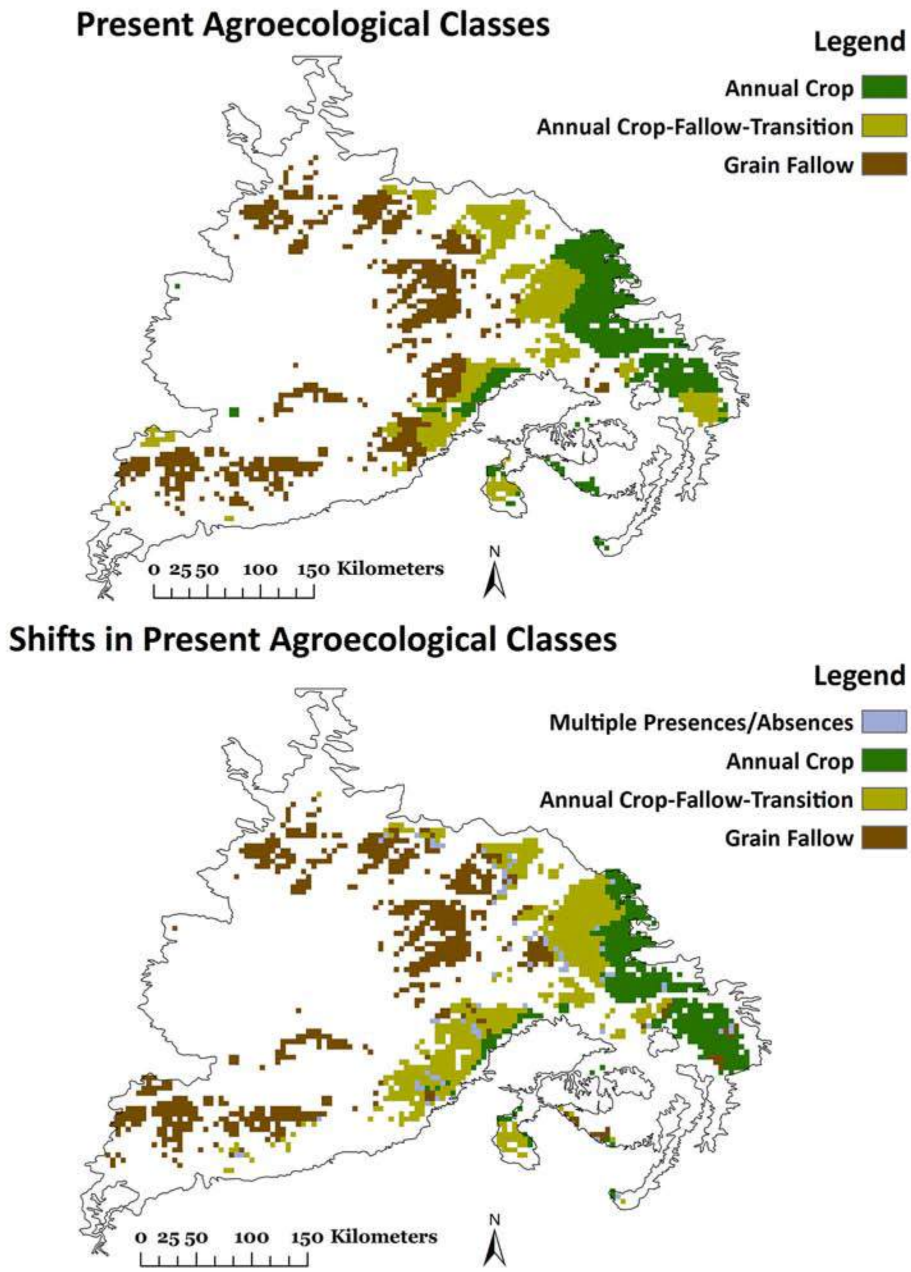

FIGURE 4 | Projected geo-spatial distribution of three agro-ecological classes (AECs) using three individual Random Forest (RF) models of bioclimatic variables under future climate scenario (2070, Representative Concentration Pathway, RCP-8.5).

variables was surprising as other socio-economic and biophysical factors contribute to current AEC outcomes (**Figures 1**, **4**). It is important to recognize that the current AECs are derived from the Cropland datalayer (USDA-NASS, 2008–2015) and represents the land use/cover derived from the integration of biophysical and socio-economic factors. Our results, however, emphasize the fundamental importance of climatic variables in driving AEC outcomes and the potential for climate change to shape future AECs.

Regional Shifts in Current AECs under Future Climate Scenarios

It is important to recognize that our analyses simply impose future projections of relevant bioclimatic variables in modeling geo-spatial shifts of AECs under current production factors, including existing levels of atmospheric CO_2. The modeled changes in AECs indicate that cropping systems would be less stable and employ more annual fallow, thereby decreasing cropping system intensification. Currently, the GF AEC is the least flexible and diverse cropping system with few economic options with respect to crop choice, consisting primarily of winter wheat followed by annual fallow in short, 2-year rotations. Consequently, the GF AEC is the most vulnerable to extremes in weather or variations in markets, farm input costs, government policies and other sources of uncertainty. In contrast, the AC AEC has the most crop diversity and is relatively less vulnerable to future uncertainties, although improvements would be beneficial (Huggins et al., 2015).

Collectively, these results suggest a reduction in cropping intensity, potentially reduced yields (more fallow) and diversity, and increased area where cropping systems are less stable under climate change. These conclusions contrast sharply with results reported for the same region using process-oriented cropping system modeling that includes increasing future levels of CO_2 (Karimi et al., 2017; Stöckle et al., 2017). Here, crop yields are simulated to increase under the same climate change scenarios presented here with the conclusion that there will be less annual fallow. Challenges of biophysical modeling of cropping systems, however, include determining what factors determine the geospatial extent and location of a given cropping system. This challenge becomes more acute if cropping systems are projected to become more dynamic as in our study. Many factors other than crop yield, such as social-economic, yield stability and risk, disease, weed and pest pressure, are not fully integrated into crop models to determine the cropping system that would be used by producers. Here, projected yield increases may not necessarily result in less fallow and could actually be associated with more fallow to aid the stability of higher yields. Furthermore, if higher yields are associated with more area under annual fallow, then the overall crop yields of the region could decline. Our analyses use the cropping systems derived from the Cropland data-layer (USDA-NASS, 2008–2015) which are geo-spatial outcomes of producer decisions resulting from the integration of all contributing bio-physical and socio-economic factors. We contend, therefore, that future research will need to explore and develop production systems that promote intensification and diversification in the face of adverse climate change.

Relevance of AEC Shifts for Sustainable Agriculture

Processes affecting soil resources in dryland cropping systems of the iPNW include soil erosion through the action of wind, water, and tillage (McCool et al., 1998; Saxton et al., 2000; Sharratt et al., 2012), declining levels of soil organic matter (SOM; Rasmussen et al., 1989; Purakayastha et al., 2008), increasing soil acidification (Mahler et al., 1985; Brown et al., 2008), and decreasing soil biological activity and diversity (Elliott and Lynch, 1994). Currently, these degradation processes threaten the sustainability of the region's dryland cropping systems (McCool et al., 2001). Winter wheat following annual fallow combined with conventional tillage that leaves little protective surface crop or residue cover is particularly prone to soil erosion. Potential increases in HBIO and shifts toward more annual fallow due to climate change (**Table 5**) could increase the regional hazard of soil erosion. This could occur despite potential off-setting factors, such as increased crop biomass production due to CO_2 fertilization effects (Sharratt et al., 2015). Annual soil losses due to soil erosion by wind and water currently range from 1 to 50 Mg ha^{-1} (Nagle and Ritchie, 2004; Kok et al., 2008; Sharratt et al., 2012). Rates of soil erosion below established USDA annual soil loss tolerance limits of 2.2–11.2 Mg ha^{-1} (Renard et al., 1997) are likely required to meet agricultural sustainability goals (Montgomery, 2007) and could be achieved with continuous no-tillage under annual or perennial cropping systems that limit annual fallow (Huggins and Reganold, 2008; Huggins et al., 2014a).

Negative impacts of annual fallow on SOM, primarily due to decreased crop inputs, factors enhancing biological decomposition (e.g., tillage, water, and temperature), and increased vulnerability to soil erosion, are well-documented (Campbell et al., 1999; Liebig et al., 2006; Gan et al., 2012). Declining SOM associated with increasing regional climate ratios as projected by future climate change in the iPNW (Morrow et al., 2017) would further promote soil degradation processes by negatively impacting aggregate stability and microbial communities and their functions (Allen et al., 2011; Maestre et al., 2015). Annual fallow has been reported to adversely influence microbial biomass and activity (Steenwerth et al., 2002; Pankhurst et al., 2005) as well as obligatory symbiotic organisms such as arbuscular mycorrhizal fungi (Thompson, 1987; Pankhurst et al., 2005). The primary objective of annual fallow is to stabilize crop yields under conditions of low or widely varying precipitation (Greb et al., 1974). Annual fallow has been widely practiced across agricultural areas of the western United States and Prairie Provinces of Canada (Nielson and Calderon, 2011). In the iPNW, 2-year winter wheat–annual fallow rotations have dominated low annual precipitation areas with dryland cropping since the 1890s as this rotation is less risky and more profitable (Schillinger et al., 2006). Therefore, overcoming projected increases in annual fallow that would further threaten the regions agricultural sustainability under climate change will likely require diverse strategies that engage socio-economic as well as biophysical dimensions (Peterson et al., 1996; Pan et al., 2016; Maaz et al., in press).

Agricultural strategies to reduce or eliminate annual fallow and its adverse effects include: (1) conservation tillage practices; (2) intensification and diversification of cropping systems; (3) elimination of crop residue removal via residue burning or harvest; (4) use of soil amendments such as manures and bio-solids; and (5) policies that enhance the short-term economics of alternative crops and fallow replacement. Precipitation-use efficiency, under cropping systems with annual fallow, ranges from 10 to 40% (Peterson et al., 1996; Farahani et al., 1998). Reviewing the literature, Hatfield et al. (2001) concluded that increases in WUE of 25–40% could be achieved through conservation tillage and cropping system intensification in semiarid environments. Peterson et al. (1996), however, stated that despite improvements in WUE or environmental factors, adoption of intensified cropping systems depended more on favorable economic outcomes and government programs. In the iPNW, various alternative crop and opportunity (flex) crop options have been explored such as canola (Pan et al., 2016; Maaz et al., in press), facultative wheat (Bewick et al., 2008), and fallow replacement with no-till spring wheat (Thorne et al., 2003). Maaz et al. (in press) concluded, however, given the economic competitiveness of wheat in the iPNW, that (1) economic approaches should be broadened to allow crop rotational rather than single commodity assessments; (2) crop insurance policies should consider more support of whole farm risk management options; and (3) additional multi-commodity groups with an interest in market-driven crop diversification should be established.

CONCLUSIONS

Bioclimatic variables were useful for discriminating among iPNW AECs using Random Forest models. In particular, potential evapotranspiration based indices proved to be more relevant predictors of present iPNW AECs than annual precipitation which is commonly used to describe agricultural zones. Super-imposing future climate scenarios onto current agricultural production systems resulted in significant geospatial shifts in AECs. Dynamic and fallow-based AECs increased in area while stable AECs and annual cropping AECs decreased. Increasing annual fallow is counter to cropping system objectives of increasing intensification, diversification, and productivity. Furthermore, more annual fallow would aggravate soil degradation processes by increasing vulnerability to soil erosion and adversely impacting soil organic matter and biological activity. Our model results do not integrate important future influences including technological and scientific advances, changing agricultural markets, and economies and rising atmospheric CO_2 levels. Integrative, transdisciplinary research that includes genetic, environmental, management, and social-economic dimensions will be required if sustainable agricultural systems are to be developed to address future uncertainties including climate change.

AUTHOR CONTRIBUTIONS

DH, RR, JA, CS, and JR have served on HK's Ph.D. research committee and aided the development of research objectives, methods, and discussion. HK: Worked with the climate and AEC data in ArcGIS and R, developed methods with the help of all committee members to run the empirical analysis. DH: Corresponding author and PI of the project, has made substantial contribution to this study, provided his time in discussion, advising, guiding, and funding to conduct the study and as well as provided immense help in organizing, writing and editing the manuscript. RR has made significant contribution in providing guidance on all the ArcGIS methods applied in this study, provided his time in discussion and answering queries related to ArcGIS. JA has made good amount of contribution by helping answering queries related to accessing climate data during the course of study and provided helpful edits on the manuscript. CS: Provided suggestions during the course of the study which were helpful in improving the study and as well as suggestions on the manuscript. JR: Provided suggestions during the course of the study which were helpful in improving the study and as well as suggestions and edits on the manuscript.

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Impact of Climate Change Adaptation Strategies on Winter Wheat and Cropping System Performance across Precipitation Gradients in the Inland Pacific Northwest, USA

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Ecological instability and low resource use efficiencies are concerns for the long-term productivity of conventional cereal monoculture systems, particularly those threatened by projected climate change. Crop intensification, diversification, reduced tillage, and variable N management are among strategies proposed to mitigate and adapt to climate shifts in the inland Pacific Northwest (iPNW). Our objectives were to assess these strategies across iPNW agroecological zones and time for their impacts on (1) winter wheat (WW) (*Triticum aestivum* L.) productivity, (2) crop sequence productivity, and (3) N fertilizer use efficiency. Region-wide analysis indicated that WW yields increased with increasing annual precipitation, prior to maximizing at 520 mm yr^{-1} and subsequently declining when annual precipitation was not adjusted for available soil water holding capacity. While fallow periods were effective at mitigating low nitrogen (N) fertilization efficiencies under low precipitation, efficiencies declined as annual precipitation exceeded 500 mm yr^{-1}. Variability in the response of WW yields to annual precipitation and N fertilization among locations and within sites supports precision N management implementation across the region. In years receiving <350 mm precipitation yr^{-1}, WW yields declined when preceded by crops rather than summer fallow. Nevertheless, WW yields were greater when preceded by pulses and oilseeds rather than wheat across a range of yield potentials, and when under conservation tillage practices at low yield potentials. Despite the yield penalty associated with eliminating fallow prior to WW, cropping system level productivity was not affected by intensification, diversification, or conservation tillage. However, increased fertilizer N inputs, lower fertilizer N use efficiencies, and more yield variance may offset and limit the economic feasibility of intensified and diversified cropping systems.

Keywords: intensification, diversification, fallow, precipitation, iPNW USA, cropping systems, conservation tillage

INTRODUCTION

Ecological instability, high demand for inputs, and low resource use efficiencies are concerns for the long-term productivity of conventional cereal monoculture systems (Matson et al., 1997; Tilman, 1999). Crop intensification, diversification, reduced tillage, and variable N management are among the strategies proposed to mitigate and adapt monocultures to projected climate shifts (Burney et al., 2010; Smith and Olesen, 2010; Tilman et al., 2011; Powlson et al., 2014; Ponisio et al., 2015). Diversifying crop options may increase the resiliency of agroecosystems (Lin, 2011) and stabilize cropping systems vulnerable to a changing climate (Altieri et al., 2015) through agronomic (Johnston et al., 2005; Kirkegaard et al., 2008; Hansen et al., 2012; Seymour et al., 2012; Cutforth et al., 2013; Angus et al., 2015), economic (Entz et al., 2002; Zentner et al., 2002b, 2004), and environmental (Zentner et al., 2004; Gan et al., 2011; Davis et al., 2012) benefits. In the summer-dominate precipitation region of the North American Great Plains, soil conservation practices have enabled crop intensification through fallow replacement (Lafond et al., 1992; Anderson et al., 2003), which has increased opportunities to diversify crops (Halvorson et al., 1999; Zentner et al., 2002b; Tanaka et al., 2005; Roberts and Johnston, 2007), enhance N and water use efficiencies (Pikul et al., 2012). In addition to conserving soil water, the reduction or elimination of tillage is a strategy to combat water and wind erosion (Singh et al., 2012; Williams et al., 2014) in combination with continuous annual cropping (Thorne et al., 2003; Feng et al., 2011). Heterogeneous topography also challenges nutrient management due to significant variability in plant-soil-nutrient interactions and crop performance (Fiez et al., 1994, 1995) with opportunities for site specific N fertilizer management to mitigate differences in water and N use efficiencies across the landscape (Miao et al., 2011). A combination of these alternative cropping system strategies may increase productivity and economic returns (Tanaka et al., 2002; Alam et al., 2015; Babu et al., 2016), and multiple strategies may be needed (Kirkegaard and Hunt, 2010; Snapp et al., 2010).

The wheat producing region of the iPNW includes a steep precipitation gradient, making it an ideal area to study the influence of climate and management practices on wheat production. The iPNW is a highly productive wheat growing region that encompasses over 3 million ha in Washington, Idaho, and Oregon. The area is characterized by a Mediterranean-like climate, and 80% cropland largely relies on stored soil water to support dryland grain production (Pan et al., 2016b). A steep annual precipitation and temperature gradient, combined with complex topography, contributes to large-scale heterogenetic edaphic, and climatic conditions that delineate the region into three distinct classes of agroecological systems. Continuous, annual cropping systems predominate in cooler, wetter conditions in areas receiving 450–600 mm of annual precipitation, whereas a 2-year grain-fallow rotation dominates under drier, warmer conditions with <330 mm (Pan et al., 2016b). The frequency of fallow decreases as dry and warm conditions become wetter and cooler, and growers may fallow once every 3 years in the fallow-transition systems in areas receiving between 300 and 450 mm (Schillinger and Papendick, 2008; Pan et al., 2016b). In the driest region, grain production requires irrigation. Wheat predominates in these dryland systems, which makes up 98% of crops grown in the grain-fallow systems, 89% in fallow transition, and 70% in the annual systems (Maaz et al., in press).

Over the last decade, average annual temperature in the Pacific Northwest has increased by 0.7°C (Mote et al., 2014), while the coldest winter night has risen by almost 2°C (Abatzoglou et al., 2015). Snowfall has also declined during this time period, with a decreasing proportion of total precipitation as snow (Kunkel et al., 2009). Assuming no changes in greenhouse gas emissions, climate models forecast a 5–15% increase in regional annual precipitation (Mote et al., 2014) with an increasing proportion occurring in winter and spring months and drier summers (Mote et al., 2014). Annual temperatures are also predicted to increase by 3–6°C by mid to late twenty-first century (Walden, 2014) with a greater degree of warming in the summer months (Abatzoglou et al., 2015). Warmer and drier summer conditions may have negative impacts on wheat productivity depending upon the extent of nutrient, heat, and water stress during critical growth stages (Rosenzweig et al., 2014; Asseng et al., 2015), although CO_2 fertilization may counteract such stresses with some uncertainty (Erda et al., 2005; Guo et al., 2010; McGrath and Lobell, 2013). Given the potential impact of climate change, coordinated efforts are required to understand patterns in productivity and the potential for improving yields and resource use efficiency within these systems to ensure long-term resiliency.

The first objective of our study was to characterize WW productivity across the different cropping system zones of the iPNW. The second objective was to provide an initial assessment of the potential to improve WW and cropping system productivity and efficiencies across the iPNW upon (1) fallow reduction, (2) increasing crop diversity, and (3) adopting soil conservation practices, with a particular focus on responses in low-precipitation conditions. Our first hypothesis was that yields would increase with increasing annual precipitation before reaching a maximum prior and then declining. Our second hypothesis was that intensification through the reduction of fallow in the drier zones will reduce WW productivity and rotational yields, as well as increase variability. We anticipated that crop diversification would enhance productivity as WW yield potential increases, and we expected soil conservation practices, such as direct seeding and chemical (i.e., no-till) fallow, would improve crop productivity, particularly under low-precipitation conditions. Because of the reductions in WW yields in intensified rotations, we expected cropping system level productivity to offset any gains due to continuous cropping in intensified and diversified systems utilizing soil conservation practices.

Abbreviations: CV, coefficient of variation; iPNW, inland Pacific Northwest; SD, standard deviation; SW, spring wheat; WW, winter wheat.

MATERIALS AND METHODS

Data from 11 sites and 8 independent studies conducted across the iPNW (**Table 1**) were utilized to determine trends in WW yields and the potential impacts of intensification, diversification, improved use efficiencies, and soil conservation. All soils were classified as silt loams; however, the available water holding capacity was lowest at the location with the highest precipitation due to the presence of dense, subsurface clay layers.

Ralston, WA

The Ralston study is located at the long-term research plots located southwest of Ritzville, WA, which was utilized to assess effects of soil conservation and fertilizer efficiencies. The long-term annual precipitation for the study site is 280 mm yr^{-1}. Information about previous crop rotations and site characterization were published by Young et al. (2015). In 2012 and 2013, the study contained four cropping systems, each replicated four times in a randomized complete block design. There were two complete sets of plots with fallow and crops present in any given year. Individual plots were 7.9 × 152 m. Cropping systems included standard-height (i.e., tall) WW (cv. Farnum) following conservation tillage fallow harvested with a cutter bar header, tall WW following no-till chemical fallow harvested with a stripper header, winter triticale (*Triticosecale hexaploid* L. cv. Trimark 099) following no-till chemical fallow harvested with a cutter bar, and winter triticale following no-till chemical fallow harvested with a stripper header.

Moro, OR

A long-term experiment was initiated in 2003 at the Oregon State University Sherman Station near Moro, OR, to evaluate traditional winter wheat-summer fallow cropping system under conservation tillage, intensified, and diversified cropping systems using no-till practices (Machado et al., 2015). Average annual precipitation at the site is 289 mm. The experimental area consisted of 42 plots, each 15 by 105 m, with 14 treatments of eight crop rotations in a randomized complete block design with three replications. In addition to WW-summer fallow, WW-no-till chemical fallow, WW-spring barley (*Hordeum vulgare* L.)-chemical fallow, WW-winter pea, and continuous WW were evaluated. All phases of the rotations were present every year. Details on management are reported by Machado et al. (2015).

Ritzville, WA

A long term experiment was initiated in 1997 on the Ronald Jirava farm near Ritzville, WA, to evaluate diverse cropping systems using no-till and conservation-till management (Schillinger et al., 2007; Schillinger and Paulitz, 2014). Average annual precipitation at the site is 292 mm. The experiment consisted of 56 plots of 9 by 150 m, six crop rotation treatments with all phases of all rotations present each year in a randomized complete block design with four replications. The traditional rotation was WW-summer fallow. Alternative rotations were WW-spring wheat (SW)-summer fallow, WW-safflower (*Carthamus tinctorius* L.)-summer fallow, winter triticale -SW-chemical fallow, continuous no-till SW, and no-till SW-spring barley. Further details on treatments and management of the experiment are reported by Schillinger and Paulitz (2014).

Davenport, WA

Three- and four-year rotational field experiments were initiated at Davenport, WA, in 2011 to evaluate intensive cropping systems under no-till practices diversified with oilseeds and pulses. Average annual precipitation for the site is 353 mm yr^{-1}. Field plots, measuring 3.7 × 15 m, were established in a randomized complete block designed with four replications with each phase of the rotation present each year, with 96 plots and 5 treatments. Data were collected following the initiation of the rotations in 2011.

Pullman, WA and Davenport, WA

Three-year field experiments were initiated at Pullman, WA and Davenport, WA, following wheat in 2011 and 2012 (Pan et al., 2016a) to determine the rotational effect of pulses on WW. The long-term average annual precipitation at Pullman is 517 mm yr^{-1}. Field plots, measuring 2 by 15 m, were established in a randomized complete block designed with four replications and seeded to spring canola (*Brassica napus* L.). In the following spring after canola, plots were split longitudinally (1 by 15 m) and were randomly seeded with inoculated dry field pea (*Pisum sativum* L.) or SW. In the third year, WW was direct-seeded across the existing split-plot design following spring pea or SW harvest.

In 2013, a subsequent 2-year field experiment was initiated at Pullman, WA and Davenport, WA, to determine the effect of oilseed vs. pulses vs. SW on following WW yields. Field plots, measuring 2 by 15 m, were established in a randomized complete block designed with four replications and seeded to spring canola, spring pea, and spring wheat. In the following year, WW (cv. Madsen at Pullman and Otto at Davenport) was direct-seeded across the existing plot design following spring crops.

Kambitsch Farm, ID

A long-term experiment at the University of Idaho Kambitsch farm, north of Genesee, ID, was established in 2000 to study the impact of conservation tillage on WW (Johnson-Maynard et al., 2007). The average annual precipitation at the farm is 695 mm yr^{-1}. Prior to 2000 the land was managed using conventional methods. Tillage treatments (chisel plow and no-till, each with plots 20 × 80 m) were replicated four times across a hillslope running east to west (across the slope). Each tillage treatment was split into three crop zones planted to either pea/chickpea (*Ciser arietinum* L.), spring barley/wheat, or winter wheat. Tillage plots were 18 × 80 m. Crop subplots are 6 × 80 m (1.2 m alley between tillage strips).

Colfax, WA, Genesee, ID, Troy, ID, and Leland, ID

A site-specific, precision agriculture study was initiated in 2011 southwest of Colfax, WA, southeast of Troy, ID, southeast of Genesee, ID and in Leland, ID. The project focused using

TABLE 1 | Descriptions of sites included in the study and associated data analyses.

Location	Latitude, Longitude	30 year average precipitation	Soil description	Soil water holding capacity	Rotations	Data analysis
Ralston, WA	46°54′52.8″N, 118°23′40.4″W	280	Ritzville silt loam (Coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls)	0.20	Traditional: Winter wheat-reduced till fallow Conservation: Winter wheat-chemical fallow Alternative: Winter triticale-chemical fallow	**Figures 1**, **2**, **3**, **4**, **8**
Moro, OR	45° 29′5.7″N and 120° 43′5.4" W	289	Walla Walla silt loam (coarse, silty, mixed, superactive, mesic Typic Haploxeroll)	0.19	Traditional: Winter wheat-summer fallow Conservation: Winter wheat-chemical fallow Alternatives: Winter wheat-spring barley-chemical fallow Winter wheat-winter pea Continuous winter wheat	**Figures 1–8**
Ritzville, WA	46°54′48.3″N, 118°23′49.4″W	292	Ritzville silt loam	0.20	Traditional: Winter wheat-summer fallow Alternatives: Winter wheat-spring wheat-summer fallow Winter wheat-safflower-summer fallow Triticale-spring wheat-chemical fallow Continuous spring wheat Spring wheat-spring barley	**Figures 1–8**
Davenport, WA	47°39′10.0″N, 118°7′19.6″W	353	Broadax silt loam (Fine-silty, mixed, superactive, mesic Calcic Argixerolls)	0.19	Traditional/Conservation: No till fallow-winter wheat-spring wheat Alternatives: No till fallow-winter wheat-spring canola Spring wheat-winter wheat-spring wheat Winter wheat-spring wheat-spring canola Winter wheat-spring wheat-spring camelina Winter wheat-spring canola-spring pea Winter wheat-spring canola-spring wheat	**Figures 1**, **2**, **3**, **5**, **6**, **7**, **8**
Colfax, WA	46°47′22.8″N, 117°26′23.6″W	484	Palouse silt loam (Fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls)	0.19	Winter wheat-spring wheat-spring wheat	**Figures 1**, **2**, **3**, **8**
Pullman, WA	46°45′36.5″N, 117°11′58.1″W	517	Palouse silt loam	0.20	Winter wheat-spring canola-spring pea Winter wheat-spring canola-spring wheat	**Figures 1**, **2**, **3**, **5**, **8**
Genesee, ID	46°30′43.2″N, 116°49′43.4″W	602	Naff silt loam (Fine-silty, mixed, superactive, mesic Typic Argixerolls) -Palouse complex	0.18	Spring barley-spring canola-winter wheat	**Figures 1**, **2**, **3**, **8**
Troy, ID	46°40′33.6″N, 116°46′29.3″W	675	Southwick silt loam (Fine-silty, mixed, superactive, mesic Oxyaquic Argixerolls) and Larkin silt loam (Fine-silty, mixed, superactive, mesic Ultic Argixerolls)	0.18	Winter wheat-spring garbanzos-winter wheat	**Figures 1**, **2**, **3**
Kambitsch Farm, ID	46°35′1.1″N, 116°56′50.8″W	695	Palouse silt loam	0.20	Winter wheat-spring wheat/barley-spring pea/garbanzos	**Figures 1**, **2**, **3**, **4**, **8**
Leland, ID	46°34′43.8″N, 116°35′45.0″W	721	Naff-Palouse complex	0.13	Winter wheat-spring wheat-spring garbanzo	**Figures 1**, **2**, **3**, **8**
Prosser, WA	46°15′8.6″N, 119°44′16.6″W	227	Warden silt loam (Coarse-silty, mixed, superactive, mesic Xeric Haplocambids)	0.19	Corn-potato-winter wheat	**Figures 1**, **2**, **3**, **4**

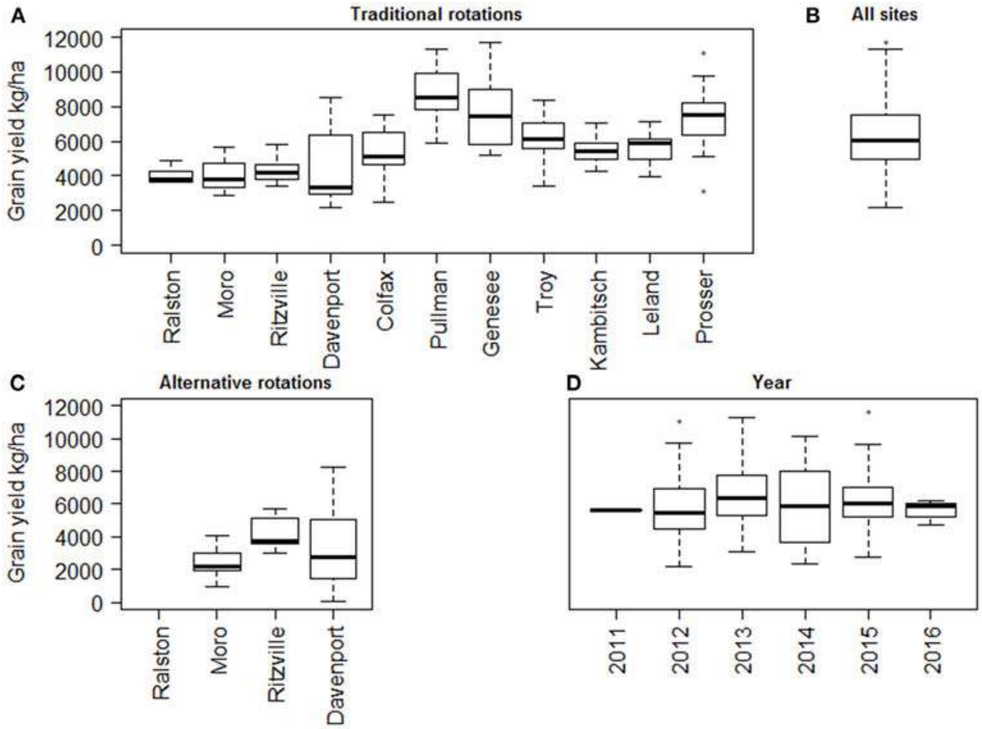

FIGURE 1 | Variance in winter wheat yields in (A) traditional rotations among the sites (ordered by increasing in long term mean annual precipitation of crop season), **(B)** across all site locations and year, **(C)** alternative rotations among the sites receiving <350 mm annual precipitation yr^{-1}, and **(D)** by year. The Prosser location received irrigation.

remote and proximal sensing to characterize and manage field-scale variability in soil water, N, and crop response across the landscape rather than plot-based research. Average annual precipitation is 484 mm yr^{-1} at Colfax; 602 mm yr^{-1}, Genesee; 675 mm yr^{-1}, Troy; and 721 mm yr^{-1}, Leland. Within each farm, two catchments were selected such that the entire drainage area was captured within a single field. At each farm, one of these catchments were selected for intensive automated and manual monitoring. Each site was equipped with 12 spatially representative subsites which serve as the primary sampling locations within the watershed. A second catchment was reserved for validation purposes and was only monitored over the last 2 years of the project.

Prosser, WA

A 3-year field study was initiated in Prosser, WA, following wheat 2011 to assess conservation tillage and cover cropping effects on irrigated WW. Average annual precipitation at Prosser is 227 mm yr^{-1}. The cropping sequence was corn (*Zea mays*)-potatoes (*Solanum tuberosum*)-winter wheat. Winter wheat was irrigated with 458 mm in the spring and summer. Field plots measuring 4.9 by 15 m, were established in a randomized complete block design with four replicates. The treatments were reduced tillage, reduced tillage winter cover crop, conventional tillage, and conventional tillage winter cover crop. Winter cover following sweet corn was triticale (× *Triticolescale*) and following potatoes was mustard (*Brassica hirta*). The conventional tillage treatments were chisel disked prior to planting and post harvesting of every crop. The reduced tillage sequence was only chisel disked prior to planting potatoes and following potato harvest.

Soil and Plant Sample Processing

At Ritzville and Davenport, WA, composite soil samples from three replicates were taken every 30 cm down to 120 cm (or to an impermeable layer) with a giddings probe after harvest. At Moro, WA, soil samples were collected to a depth of 30 cm and composited. Ammonium and nitrate N were analyzed following KCl extraction and measured colorimetrically with a Quickchem 8000 Series FIA+ system and AutoSampler (Lachat Instruments, Hach Company, Loveland, CO). Total C and N of composted soil samples collected in the first year of each study were measured by combustion in a CN analyzer.

At Prosser, Moro, Ritzville, Ralston, Davenport, Pullman, and Kambitsch, grain was harvested using commercial plot combines. Total above ground biomass was sampled from 1 m^2 area at maturity and prior to determining harvest index to calculate residue biomass and N yields. Biomass samples were dried at 45–60°C for 48 h, weighed, and threshed with a Vogel Stationary Grain Thresher, from which seeds, chaff, and stems were collected. Seeds were weighed to determine the harvest index. Seeds were ground with a Cyclone Sample Mill (Thomas Scientific, Swedesboro, NJ) for C and N analysis with a C/N

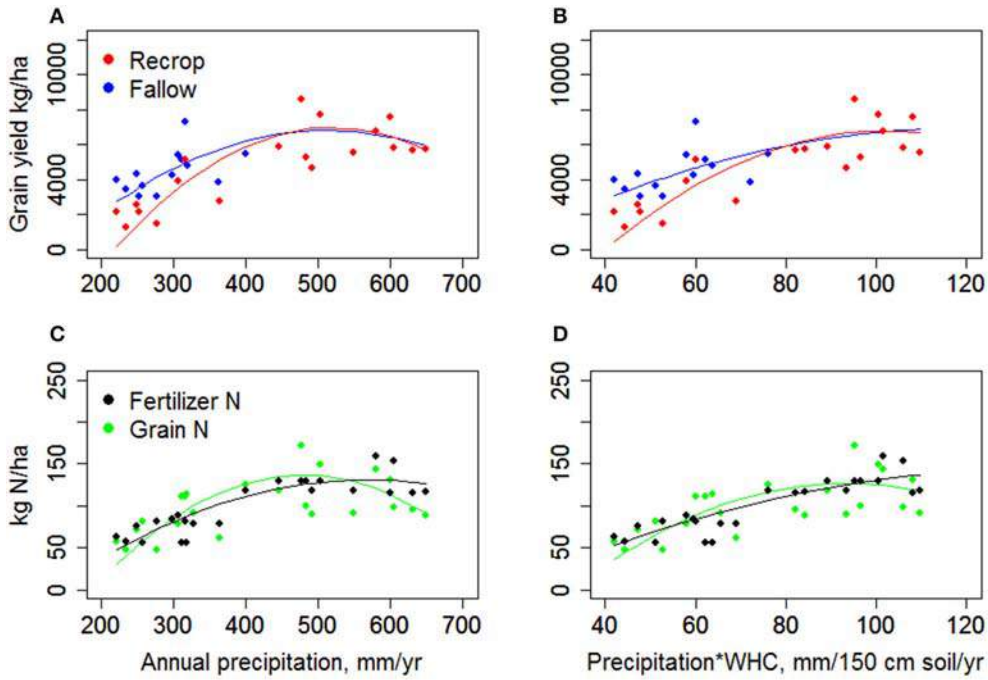

FIGURE 2 | Influence of annual precipitation on (A) winter wheat yields following crops or with fallow when annual precipitation <350 mm, **(B)** winter wheat yields following crops or fallow after adjusting annual precipitation for available soil water holding capacity, **(C)** winter wheat grain N accumulation and fertilizer N applications with increasing annual precipitation, and **(D)** winter wheat grain N accumulation and fertilizer N applications with adjusted annual precipitation based on the available water holding capacity.

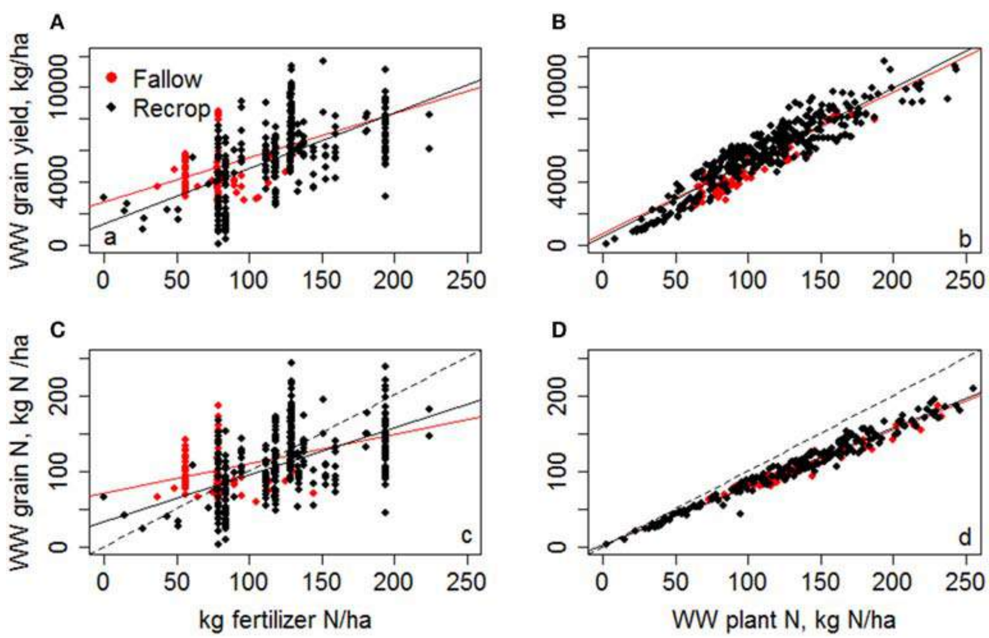

FIGURE 3 | Fertilizer use and N utilization efficiency of winter wheat in cropping systems research conducted in the inland PNW from 2011 to 2016, including (A) the response of winter wheat grain yields to fertilizer N, **(B)** the utilization efficiency of grain N to produce grain, **(C)** ratio of grain N export to fertilizer N additions, and **(D)** winter wheat N harvest index. Wheat was differentiated by cropping sequence, and was grown after fallow or crops (recrop). Broken line represents the 1:1 relationship.

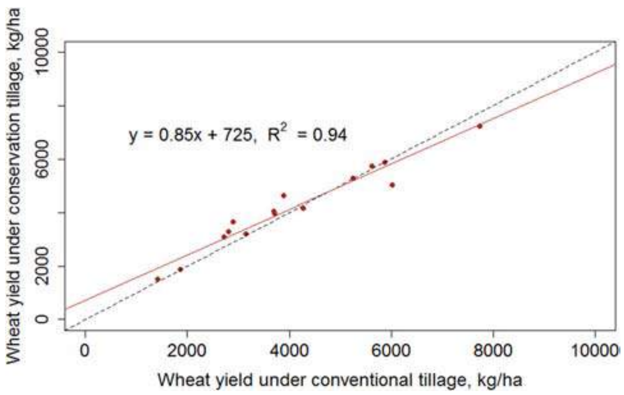

FIGURE 4 | Relative winter wheat yields in the inland PNW under conventional tillage (x-axis) and conservation tillage (y-axis).

autoanalyzer (LECO Corp, St. Joseph, MI) at all sites except for Moro, in which grain protein was measured using the Inframatic 9200 (Perten Instruments, Hägersten, Sweden). Residue yields were calculated from the combined seed yields by applying the harvest index. Residue samples were ground with a Thomas Wiley mill (Thomas Scientific, Swedesboro, NJ) prior to C and N analysis (for all sites except Moro) by combustion using a Truspec Carbon and Nitrogen Analyzer (LECO Corporation, St. Joseph, MI). At Colfax, Genesee, Troy, and Leland locations, total above-ground biomass was determined at each of the 12 locations at harvest by hand-harvesting four 1 m^2 plots at each site, and total grain yield within each 1 m^2 locations was determined by threshing. All grain samples were analyzed for protein using Infratec 1241 Grain Analyzer (Foss, Hillerod, Denmark). Total nitrogen in the above ground residue was determined using a Truspec machine (LECO Corporation, St. Joseph, MI).

Calculations and Statistical Analyses

The mean, standard deviation (SD), and coefficient of variation (CV) were assessed for WW yields within and across all site locations. An analysis was conducted to assess variation in yields from traditional rotations (**Table 1**), in which fallow periods preceding WW when annual precipitation was <350 mm yr^{-1}, under both conventional and conservation tillage. Annual precipitation was calculated on a crop-year basis from September to August. In a separate analysis, variance was assessed for WW in alternative rotations when annual precipitation was <350 mm yr^{-1} in which the fallow frequency was reduced to once every 3 years or WW (i.e., no fallow) followed crops. An analysis of variance was conducted with location as the fixed effect and annual precipitation, cropping sequence, and replicates as the random effects using the lme package in R (R Core Team, 2016).

To determine the effect of fallowing prior to WW, the response of WW yields to increasing annual precipitation were best fitted with a quadratic function, and two yield response curves were derived, including WW following crops vs. fallow when annual precipitation was <350 mm yr^{-1}. To determine the efficiency of fertilization across the region in all systems, the relationship between annual precipitation and N fertilization rate, as well as grain N accumulation, was also best fitted with quadratic equations. These relationships were reassessed after annual precipitation was adjusted for the available water holding capacity of the soil, using data obtained from USDA NRCS Web Soil Survey (Soil Survey Staff, Natural Resources Conservation Service and United States Department of Agriculture, 2016). The regression-based predicted yields following fallow vs. recrop, as well as grain N accumulation vs. N fertilizer rate, were assessed by differencing the definite integrals (to calculate the areas underneath the curve) for precipitation ranges of 200–350, 350–500, and 500–650 mm yr^{-1}.

The comparative effects of cropping sequence on WW yields (WW after fallow vs. cereals/pulses/oilseeds), and WW following wheat vs. other cereals/pulses/oilseeds) were assessed using data collected in the iPNW described above relative to data obtained from a literature survey (Appendix 1). The literature survey included, but were not limited to, references provided by Angus et al. (2015) with a particular focus on wheat-fallow. The effect of tillage on wheat yields was also assessed for the iPNW. Winter wheat yields following break crops (i.e., non-wheat cereals, pulses, or oilseeds) were regressed against WW yields after fallow or SW/WW. Break crops included other cereal crops (barley and triticale), oilseeds [including canola, rapeseed, and camelina (*Camelina sativa* L. Crantz)], and pulse crops [including field pea, lentil (*Len culinaris* L.), garbanzo beans (*Cicer arietinum* L.), and lupin (*Lupinus* L.)]. In addition to the data collected in the present study, WW yields following break crops vs. wheat were compiled from iPNW data presented (Guy, 2013). For tillage comparisons, WW yields under conservation tillage were regressed against WW yields under conventional tillage for selected sites.

Linear regressions were used to assess the relationships among yields, fertilizer N, plant N, and grain N for WW after fallow (only when annual precipitation was <350 mm yr^{-1}) vs. recropped WW for all sites. An analysis of covariance was conducted to determine interaction of cropping sequence with N responses, specifically the relationships between yield vs. fertilizer, grain N vs. fertilizer N, yield vs. grain N, and grain N vs. plant N using the stats package in R (R Core Team, 2016).

For cropping system level comparisons, energy outputs, total fertilizer inputs, and total grain N exports were summed over 3–4 years of observations. Annualized values were calculated to account for differences in the years of observations. Energy was calculated by multiplying grain yields by a conversion factor: legumes and cereals, by 15 MJ kg^{-1}, and oilseed, by 25 MJ kg^{-1} (Zentner et al., 2004; Farine et al., 2010; Unakitan et al., 2010; Mousavi-Avval et al., 2011; Keshavarz-Afshar and Chen, 2015). The variance of annualized energy outputs, fertilization, and grain N export was compared across increasingly intensified cropping systems at Moro, OR, Ritzville, WA, and Davenport, WA, all of which received <350 mm yr^{-1} within the study period. Finally, an analysis of covariance was conducted to determine interaction of cropping sequence with rotational N responses, specifically the relationships between total energy output vs. total fertilizer input, total grain N export vs. total fertilizer input, total energy output

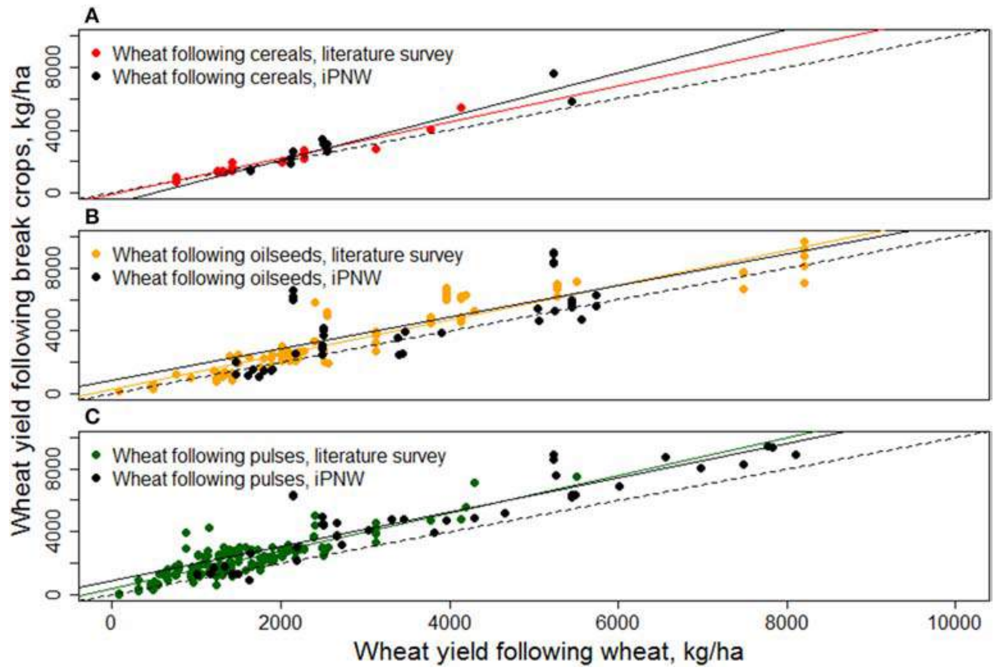

FIGURE 5 | Increase in winter wheat yields in a literature survey of predominately fallow systems and in the inland PNW following other cereals (A) , oilseeds **(B)**, and pulses **(C)** (y-axis) vs. wheat following wheat (x-axis).

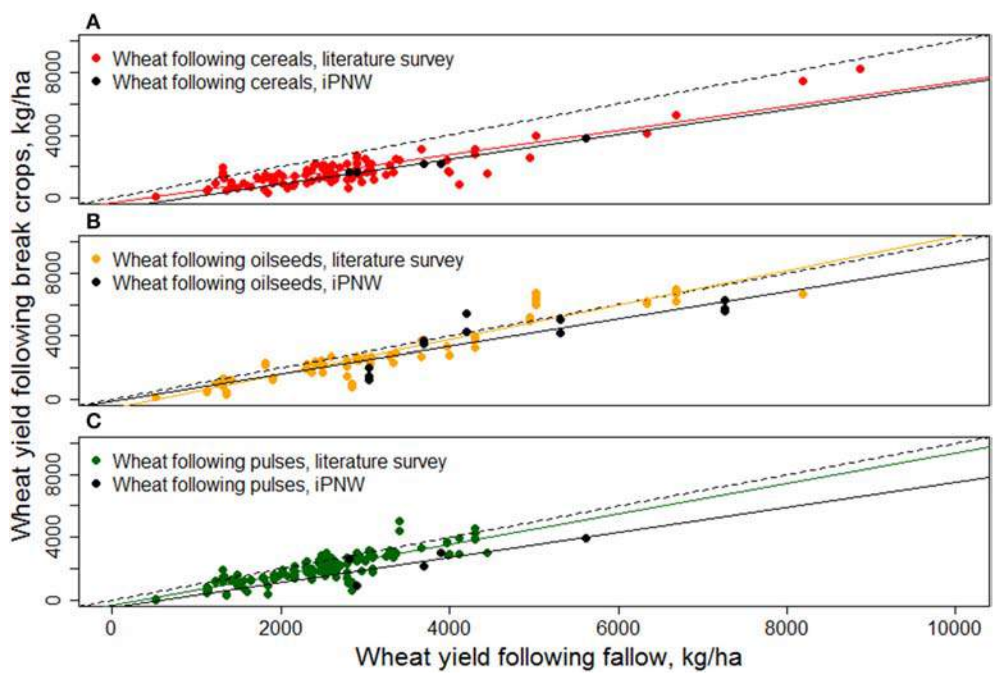

FIGURE 6 | Literature survey of wheat yields following fallow (y-axis) vs. alternative crops, including cereals (A) , oilseeds **(B)**, and pulses **(C)** (y-axis). Fallow replacement by oilseeds, pulses, and other cereals was also assessed in inland PNW.

vs. total grain N, and total grain N export vs. total plant N uptake using the stats package in R (R Core Team, 2016).

At Moro, Ritzville and Davenport, multi-year cropping system N budgets were constructed. Inputs included pre-plant inorganic N summed in the 120-cm soil profile (or 30-cm at Moro),

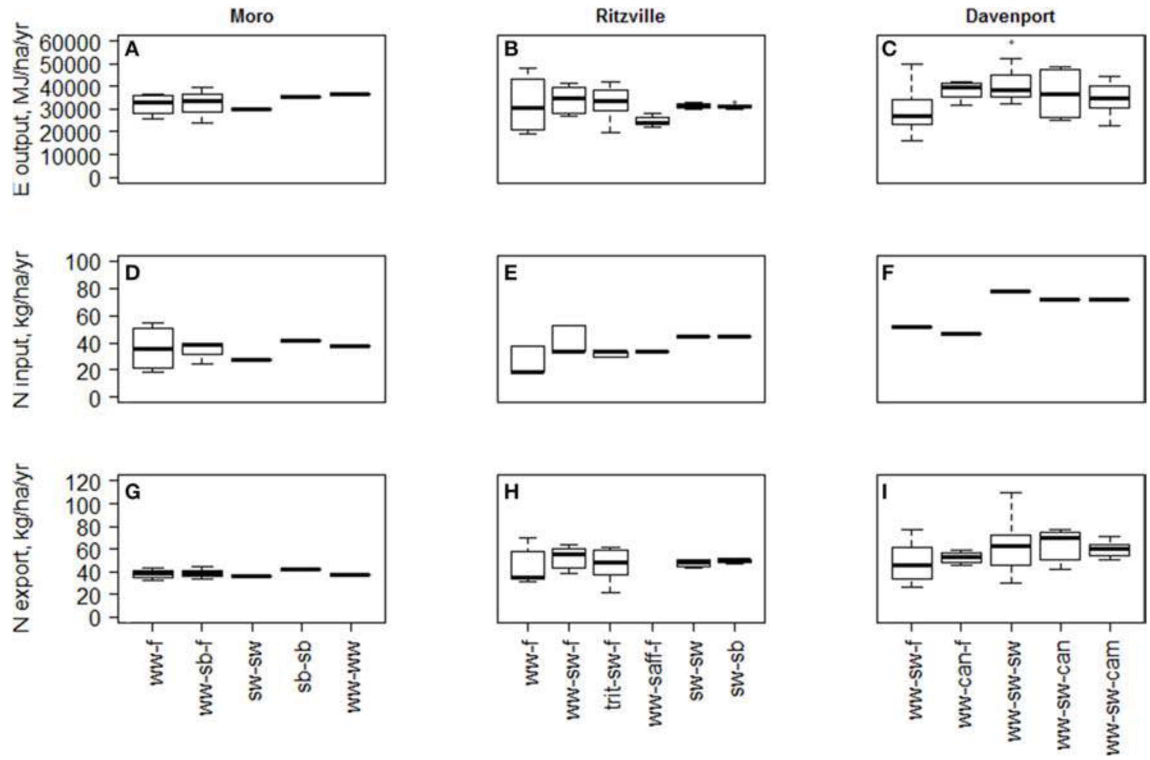

FIGURE 7 | Rotational fertilizer N inputs, energy outputs, and total grain N removal at Moro (A,D,G), Ritzville **(B,E,H)**, and Davenport **(C,F,I)**, respectively, in intensified and diversified conservation cropping systems research. Rotations are more intensified moving left to right of each graph. Inputs and outputs were summed over 3 years of observations, and annualized by dividing sums by years of observation. f, fallow; ww, winter wheat; sw, spring wheat; can, spring canola; cam, spring camelina; trit, winter triticale; saff, spring safflower.

total N fertilizer applied, and estimated N mineralized based on soil organic matter (described by Pan et al., 2016a). Outputs included total crop N uptake and post-harvest inorganic N in the 120-cm soil profile. Nitrogen balance was determined by subtracting N outputs from N inputs. The fertilizer N balance was calculated by subtracting rotational grain N from total fertilizer N inputs.

RESULTS AND DISCUSSION

Winter Wheat Productivity along a Precipitation Gradient

In the iPNW, water is the most limiting resource in crop production due the region's semi-arid Mediterranean-like climate and steep rainfall gradient within the rain shadow of the Cascade Mountains (Schillinger and Papendick, 2008). As a result, yield potential of WW varies along the regional gradient in annual precipitation (Cook, 1986). Schillinger et al. (2008) determined that modern wheat cultivars can reproduce (e.g., yield grain) with 61 mm of available water in the iPNW, and WW yields improved by almost 20 kg ha^{-1} for every millimeter gain in available water as available soil water increased from 60 to 350 mm. However, a regional assessment of WW grain yield along the full extent of the annual precipitation gradient in the iPNW is lacking.

We found that WW yields varied considerably across and within the 11 locations (**Figure 1A**) with annual precipitation ranging from 220 to 650 mm yr^{-1}, with an overall mean of WW in traditional rotations of ~6,000 kg ha^{-1} and a CV of 31% (**Figure 1B**, **Table 2**). The regional variability in WW yields was consistent from 2012 to 2015 (**Figure 1D**). Annual precipitation and field position (plot or replicate) contributed similarly to the variability in WW within sites (**Table 2**). Winter wheat yield means were similar to or higher in the traditional fallow rotations than intensified, alternative rotations (**Figure 1C**), and the stability of WW yields declined, as indicated by the increase in CV, in intensified rotations (**Table 2**).

Winter wheat yields responded significantly to annual precipitation (**Figure 2A**). Summer fallowing prior to WW reduced the yield response to annual precipitation in comparison with intensified WW production following cereal, oilseeds, and pulse crops substituting summer fallow. As a result, annual precipitation explained more of the variation in the WW yields when following crops (R^2 = 0.53) than fallow (R^2 = 0.31). While the fallow frequency (every other year vs. once every 3 years) did not affect the yield response, foregoing fallow prior to WW resulted in an integrated loss of 263 Mt of WW yield ha^{-1} when annual precipitation ranged from 200 to 350 mm yr^{-1}. Ultimately, WW production in the fallow cropping system is restricted by stored soil water plus April, May, and June

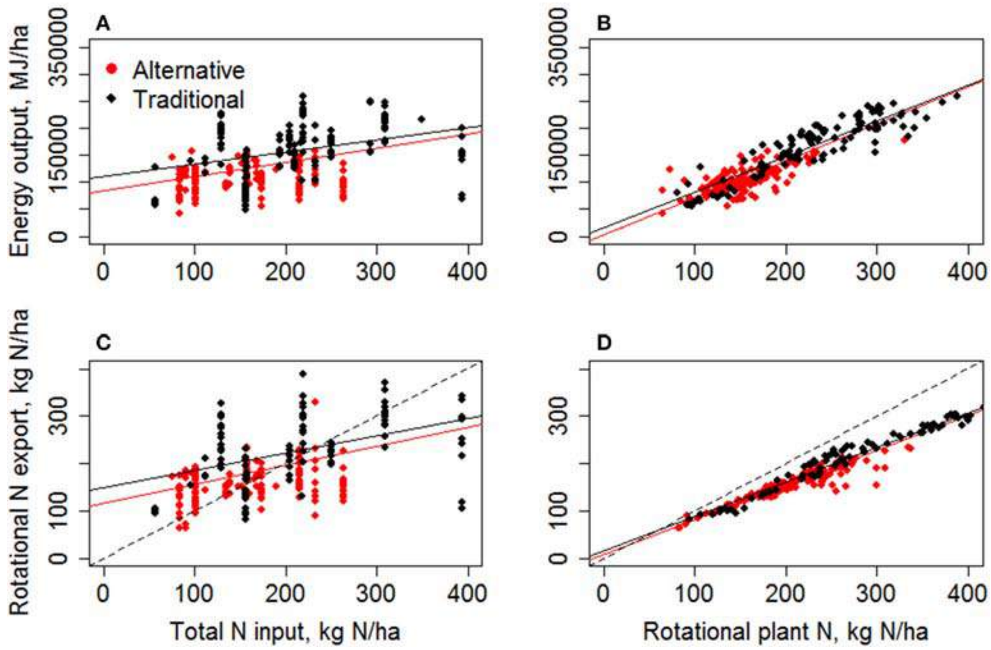

FIGURE 8 | Rotational nitrogen use efficiency of cropping systems in the inland PNW from 2011 to 2016, including (A) the response of rotational energy outputs to total fertilizer N additions, **(B)** the rotational utilization efficiency of grain N to produce energy, **(C)** ratio of rotational grain N export to total fertilizer N additions, and **(D)** rotational N harvest index. Traditional rotations include WW-summer fallow and WW-CF rotations at Ralston, Moro, and Ritzville, and WW-SW-CF at Davenport and all rotations listed in **Table 2**. Alternative rotations replaced WW-F through a reduction or elimination of fallow when precipitation was <350 mm yr^{-1}. Broken line represents the 1:1 relationship.

rainfall; overwinter stored soil water dependent upon soil depth. Furthermore, previous studies have shown that the precipitation storage efficiency of fallowing in the iPNW is generally around 30% (Wuest and Schillinger, 2011).

As annual precipitation increases, the topography becomes increasingly sloping, and soil biology changes. Earthworms may be observed above 330–370 mm of mean annual precipitation (Walsh and Johnson-Maynard, 2016), and soil organic matter increases in the topsoil (Morrow et al., 2017). We determined that WW yields reached a maximum of 6,800 kg ha^{-1} at 520 mm yr^{-1}, within the annual cropping region where precipitation is adequate to economically support crops every year (**Figure 2A**). The decline in WW yields after reaching the maximum may be due to various factors that contribute to an increase in the actual yield gap under more favorable conditions, such as increasing incidences of pests, disease, crop lodging, and nutrient deficiencies (Cook, 1986). Furthermore, topographic complexity varies across the region leading to differences in soil properties (Horner et al., 1957). As precipitation increases, the presence of finer-textured silty-clay and clay-loam soils with dense (∼1.65 Mg m^{-3}) argillic and fragipan horizons at depths from 0.2 to 1.2 m below the soil surface can restrict vertical drainage and root penetration leading to the development of seasonal perched water tables (McDaniel et al., 2001; Brooks et al., 2012). These argillic and fragipan soils are generally found where mean annual precipitation exceeds 600 mm and have a limited soil water holding capacity due to the presence of dense subsurface clays (Brooks et al., 2012). In the Paradise Creek Watershed of North Idaho, which receives 650 mm annual precipitation yr^{-1}, precipitation use efficiency is reduced by both restrictive layers, as well as winter runoff when soils saturate and frozen soils reduce infiltration (Brooks et al., 2010). Timely May and June precipitation is particularly critical in wheat production across the iPNW (Schillinger et al., 2008). Therefore, the soil constraints in the highest precipitation zone add additional risk to annual cropping as these shallow argillic and fragipan soils dry out faster and experience more water stress without adequate precipitation in May and June. The constraint of available soil water in the highest precipitation zones is evident when annual precipitation is adjusted for available water holding capacity (**Figure 2B**), and yields attain a plateau with the range of observed data rather than declining.

Winter Wheat Response to Fertilizer along a Precipitation Gradient

The interaction between WW yields and N fertilizer use efficiency has also never been examined across the extent of the iPNW's precipitation gradient. However, the regional soil and climatic properties have also served as the basis for the hypothesized interaction between N use efficiency and annual precipitation outlined by Pan et al. (2007). As precipitation increases in the region, root growth and yields become less limited by drought conditions, and N use efficiency increases as plants recover increasing amounts of fertilizer N from the topsoil. Therefore,

TABLE 2 | Mean and variance of winter wheat produced at 11 site locations in the inland Pacific Northwest region.

Location	Years of observation	Avg. precipitation	Winter wheat yields in traditional rotations				Winter wheat yields in alternative rotations			
			Mean (kg/ha)	SD (kg/ha)	CV%	*n*	Mean (kg/ha)	SD (kg/ha)	CV%	*n*
Ralston, WA	2012–2013	288	3,991	487	12	8				
Ritzville, WA	2012–2014	294	4,298	669	16	12	4,471	972	22	12
Moro, OR	2011–2015	305	4,030	1,017	25	10	2,944	1,096	37	16
Davenport, WA	2012-2014	334	4,449	2,248	50	20	3,364	2,162	64	89
Colfax, WA	2012, 2015	478	5,213	1,376	26	36				
Pullman, WA	2013–2014	526	8,780	1,405	16	24				
Genesee, ID	2015	575	7,537	1,773	24	24				
Troy, ID	2013, 2015	598	6,124	1,334	22	36				
Kambitsch Farm, ID	2012–2014	591	5,553	706	13	30				
Leland, ID	2013, 2016	658	5,707	1,089	19	32				
Prosser, WA	2013	152+ 458 irrigated	7,333	1,450	16	48				
		Total	6,120	1,909	31	280	3,394	1,980	58	116
	2012	591	5,726	1,893	33	48	2,636	993	38	10
	2013	530	6,545	1,824	28	79	5,181	1,419	27	49
	2014	508	5,941	2,329	39	56	1,837	1,034	56	51
	2015	598	6,173	1,794	29	75	2,399	680	28	3

ANALYSIS OF VARIANCE

	Traditional rotations	Alternative rotations
Fixed effect	***p*-value**	
Site	**	NS
Random effects	SD	
Annual precipitation	969 kg ha^{-1}	1402 kg ha^{-1}
Sequence	0.30 kg ha^{-1}	710 kg ha^{-1}
Field/Plot/Replicate	1195 kg ha^{-1}	720 kg ha^{-1}
Residual	45 kg ha^{-1}	366 kg ha^{-1}

*Rotations are listed in **Table 1**. When annual precipitation was <350 mm yr^{-1}, rotations were differentiated as traditional WW-F at Ritzville and Moro and WW-SW-F at Davenport. Alternative rotations were characterized by a reduction or elimination of fallow at these particular sites.*

fallow periods are practiced to mitigate inefficiencies. A decline in N use efficiency was predicted by Pan et al. (2007) under increasingly high precipitation due to expected N losses in runoff, leaching, and denitrification pathways, in addition to limitations in rooting depth due to the presence of restrictive subsoil clay layers.

Our findings support these hypothesized interactions. First, annual precipitation explained most of the variance in fertilizer N rates ($R^2 = 0.67$), and 39% of the variance in the accumulation of grain N (**Figure 2C**). Grain N increased with annual precipitation, prior to reaching a maximum at 480 mm yr^{-1} before declining. Similar to yield trends, the decline in grain yield at high levels of precipitation was moderated by adjusting for available soil water holding capacity (**Figure 2D**). The regression analyses predicted similar amounts of N were applied as fertilizer and exported in grain when annual precipitation ranged from 200 to 350 mm, corresponding with grain N to fertilizer ratios were >1. These high fertilization efficiencies were the result of residual N carryover and the recycling of mineralized N, particularly for WW after fallow. As a result, fallow periods were not only instrumental in maintaining high yields through soil water storage, but also to reducing N deficiencies, as discussed by Pan et al. (2016a). High efficiencies of fertilization were also observed between 350 and 500 mm yr^{-1}, in which the integrated grain N export exceeded fertilizer N by 2,000 kg N ha^{-1}. However, fertilization inefficiencies declined when annual precipitation exceeded 480 mm. The regressions predicted greater amounts of fertilizer were applied than removed in grain, with an integrated fertilizer N deficit of 2,650 kg N ha^{-1} from 500 to 650 mm yr^{-1}. As fertilization increased beyond this maximum (120–150 kg N ha^{-1}), the grain N to fertilizer ratios were <1. Fall and spring applications of fertilizer are recommended under high precipitation, but current extension guides suggest splitting a predetermined N fertilization rate rather than fine-tuning fertilizer management through tactical in-season applications or variable rates based on crop performance indicators (Mahler, 2007). Furthermore, these findings highlight the opportunity to investigate the utilization of nitrification inhibitors in soils of the inland Pacific Northwest with high risks of nitrate leaching or denitrification (Abalos et al., 2014).

Opportunities for Site–Specific N Management

In addition to regional variability, we observed a considerable amount of within-site variability in WW productivity (**Table 2**), even at a field or plot scale. While a portion of this variability was teased out by differences in year-to-year precipitation, other environmental, genetic, and management factors contribute to within-site variability, such as landscape elevation, slope, aspect (Mulla et al., 1992; Fiez et al., 1994; Yang et al., 1998), subsoil constraints (Robertson et al., 2016), spring rainfall (Schillinger et al., 2008), crop rotation (Hammel, 1995), nutrient availability (Fiez et al., 1995), onset of drought and temperature stress (Gizaw et al., 2016), and crop genetics (Schillinger et al., 2008). Despite the heterogeneity of the landscape, iPNW growers still commonly apply single rates of fertilizer, particularly in the higher precipitation areas (Mahler et al., 2014). The need for site-specific N management across the entire region is warranted, as evidenced by N fertilizer rate explaining only 35% of WW yield (**Figure 3A**) and 28% of grain N variability (**Figure 3C**) when WW followed crops, and 21% of the variation in yield and 11% of grain N accumulation when WW followed fallow when precipitation was $<$350 mm yr^{-1}.

In contrast, our analysis indicated that crop N was a consistent and reliable indicator of yield and grain protein, and may be a useful evaluation tool for site-specific N management in the iPNW. Across all data, grain N accumulation was closely correlated with the synthesis grain biomass (**Figure 3B**) and total above-ground plant N (**Figure 3D**) across all data, regardless of location, years, fertilizer rate, and previous crop, with R^2 values ranging from 0.80 to 0.98. Magney et al. (2016a) demonstrated that in-season canopy monitoring using daily Normalized Difference Vegetation Index (NDVI) data could be used to explain 83% of yield variance and 80% of grain N accumulation. Total N in the biomass and grain has also been shown to be highly correlated to vegetation indices, particularly using red-edge bands, acquired from high resolution (5 × 5 m) satellite imagery (Magney et al., 2016b). Therefore, precision agriculture based on plant-based sensing opportunities may be used in combination with tactical nutrient management to optimize wheat performance. Ultimately, these data can be utilized by decision support tools emerging for the region which allow growers to systematically evaluate their site specific N management practices based on performance criteria, and to diagnose conditions that contribute to suboptimal performance (Brown et al., 2015).

Winter Wheat Productivity under Alternative Practices

The traditional WW-summer fallow system was developed as an economically feasible strategy to accumulate water and N, manage weeds, and mitigate risk associated in low precipitation areas of the iPNW (Leggett et al., 1974; Bolton and Glenn, 1983). Crop diversity is largely lacking in the iPNW and fallow periods remain common in the low and intermediate precipitation cropping systems, and a decrease in species richness has also been reported along the diminishing mean annual precipitation gradient in other Mediterranean-like, semi-arid regions (Koocheki et al., 2008). The lack of crop diversity may be contrasted with other major wheat belts, such as the dryland systems of Canada and Australia (Cook et al., 2002; Zentner et al., 2002b; Conley et al., 2004; Kirkegaard et al., 2008). For instance, in the semi-arid region of Canada, the prevalence of fallow has decreased from 50 to 15% since the 1970s, coinciding with the development of chemical weed management and the adoption of direct seeding practices (Zentner et al., 2002a). The intensification of crop rotations enabled the expansion of pulse crops in semi-arid Canada (McVicar et al., 2000), which performed well in water-stressed environments of the Canadian prairies dominated by summer rainfall (Angadi et al., 2008; Cutforth et al., 2009; Bueckert and Clarke, 2013). Furthermore, the shallower rooting depth of pulse crops compared to cereals left behind deep residual water to support subsequent cereal and oilseed crops (Gan et al., 2009). By the late 1990s, research on pulse crops highlighted the rotational benefits of pulses to cereals (Miller et al., 2003) as a means to economically intensify crop rotations in Canada's semi-arid zone. These developments provide the rationale for assessing the effects of reduced tillage, crop diversity, and intensified of wheat-based systems in the iPNW.

Conservation Tillage

The adoption of conservation tillage practices was instrumental in intensifying and diversifying cropping systems in the Northern Great Plains (Zentner et al., 2002a). Across five locations in the iPNW, the adoption of conservation tillage practices was tightly correlated with WW productivity under conventional tillage practices (**Figure 4**). We found that conservation tillage increased WW yields at lower yield potentials, which diminished as yield potential increased (y-intercept of 725 ± 257 kg ha^{-1} with a regression slope of 0.85). However, conservation tillage practices were not effective at mediated the WW yield loss associated with fallow elimination. Similarly, Williams and Robertson (2016) at an 430 mm annual precipitation site reported that WW yields, as well as precipitation use efficiency, were not affected by tillage practice in long-term plots, whereas WW following crops had significantly lower yields and precipitation use efficiency.

Crop Diversity

In a review of the literature, Angus et al. (2015) reported that fallow periods were instrumental in increasing wheat yields at low yield potentials, whereas break crops were more effective at enhancing wheat yields at higher yield potentials ($>$1,700 kg ha^{-1}) relative to wheat following wheat. In our survey of the literature (Appendix 1), wheat yields were enhanced to a greater extent following oilseed (**Figure 5B**) and pulse (**Figure 5C**) break crops than cereals (**Figure 5A**) even at low yield potentials, which increased with greater yields (y-intercept $>$ 0 and slope $>$ 1) (**Table 3**). In comparison, the advantage of wheat following other cereal break crops rather than wheat was only observed at high yield potentials. In the iPNW, the effect of break crops were within the range reported in the literature (**Figure 5**), and the response of WW following pulses was greater than oilseeds and cereal crops, particularly due to influential observations pulse and oilseed crops at high and low yield potentials.

Crop Intensification

There were two means of intensifying crop rotations in this study. The first strategy was to eliminate fallow altogether, and continuous cropping practiced instead, whereas the second was to reduce the frequency of fallow from every other year to once every 3 years. In this scenario, WW is grown after fallow, while a spring crop follows WW. The effect of fallow elimination prior to WW reduced yields in the iPNW, which is within the range reported in the literature (**Figure 6**). However, within our dataset, differences in trends between the iPNW and the literature were observed. The substitution of summer fallow in the iPNW led to reductions in WW yield potential regardless of break crop (cereal vs. oilseed vs. pulse), as indicated by the negative y-intercepts and regression slopes of <1.0 (**Table 4**). In contrast, the intensification with cereals led to the greatest reduction in wheat yields reported in the literature (**Figure 6A**), particularly at higher yield potentials with a regression slope of 0.76 (**Table 4**). Yet, when wheat followed oilseeds (**Figure 6B**) and pulses (**Figure 6C**) rather than fallow, wheat yields reported in the literature were reduced to a lesser extent across a range of yield potentials—approximately 600 kg ha^{-1} following oilseeds in place of fallow, and 325 kg ha^{-1} following pulses (as indicated by the negative y-intercepts and regression slopes of 0.97–1.10, **Table 4**).

These trends illustrate that break crops could not replace fallow without penalizing WW yields in the iPNW, unlike effects reported elsewhere. These results may be attributed to systematic differences between the iPNW and other regions, such as the Northern Great Plains. Despite similarities in soils and water holding capacity, the Great Plains is characterized by summer-dominated rainfall (Pan et al., 2016b). Spring crops dominate in the Northern Great Plains, whereas WW is predominant in the iPNW due to its winter-dominant precipitation patterns, moderate winter temperatures, and drought and heat stress frequently encountered during the flowering and grain-fill period with spring crops. In the iPNW, WW yields greatly exceed those for SW, due to their more efficient utilization of winter precipitation and earlier grain filling (Schillinger et al., 2008). Together, these conditions make WW production more economic but also highly reliant on stored precipitation for both crop establishment and in-season growth. While our study indicated that conservation tillage practices have benefits compared to traditional tillage on WW yields at lower yield potentials, chemical fallow may not provide advantages observed in the Northern Great Plains. In particular, chemical fallow does not provide gains in soil water storage efficiency (Schillinger and Bolton, 1993) over conservation-tillage fallow. Nevertheless, chemical fallow has been reported to be, overall, just as efficient as tilled fallow in retaining soil moisture throughout the 13 month fallow period in areas receiving more than 290 mm annual precipitation (Schillinger, unpublished; Machado et al., 2015). Previous research in the region has also demonstrated that conservation practices can be more profitable if weeds are properly managed, and conservation production systems may incorporate multi-faceted approaches to manage weeds in the low precipitation zone (Young, 2004).

Importantly, we found that the timing and frequency of fallow was an important consideration for the region. In particular, a reduction of fallow frequency could be practiced under low-precipitation conditions without penalizing WW yields as long as fallow preceded WW. Our results also support previous results at individual sites in Moro, OR (Machado et al., 2015) and Lind, WA (Schillinger, 2016), who determined that intensified rotations were agronomically competitive to a traditional WW-fallow rotation which practiced fallow every 3 years but prior to WW.

TABLE 3 | Regression parameters for the linear relationship between winter wheat yield following other cereals, oilseeds, or pulses and wheat following wheat.

	R^2	Slope	Intercept	*n*
LITERATURE SURVEY				
Wheat-cereal	0.94	1.15 ± 0.08***	−85 ± 158 NS	18
Wheat-oilseed	0.87	1.10 ± 0.04***	303 ± 147*	105
Wheat-pulse	0.75	1.20 ± 0.06***	362 ± 98**	162
PNW				
Wheat-cereal	0.92	1.39 ± 0.12***	−692 ± 349 NS	14
Wheat-oilseed	0.49	1.01 ± 0.17***	849 ± 624 NS	39
Wheat-pulse	0.80	1.09 ± 0.09***	927 ± 380*	40

, **, *, indicates significance at a $p < 0.05$, 0.01, and 0.001 level. NS, Not significant.*

TABLE 4 | Regression parameters for the linear relationship between winter wheat yield following other cereals, oilseeds, or pulses and wheat following fallow.

	R^2	Slope	Intercept	*n*
LITERATURE SURVEY				
Wheat-cereal	0.76	0.77 ± 0.04***	−332 ± 131**	99
Wheat-oilseed	0.89	1.10 ± 0.05***	−593 ± 174**	69
Wheat-pulse	0.75	0.97 ± 0.05***	−325 ± 126 NS	138
PNW				
Wheat-cereal	0.98	0.79 ± 0.06***	−695 ± 247 NS	12
Wheat-oilseed	0.73	0.87 ± 0.17***	−109 ± 840 NS	5
Wheat-pulse	0.66	0.80 ± 0.33 NS	−475 ± 1,302 NS	5

***, ***, indicates significance at a $p < 0.01$, 0.001 level. NS, Not significant.*

Cropping System Productivity in Continuous Cropping

Despite the yield penalty on WW in continuous cropping systems under low precipitation conditions, continuous cropping may be agronomically feasible on an annualized basis of whole rotations. From 2012 to 2014/2015, intensification of cropping systems through the reduction of fallow frequency or elimination of fallow periods did not affect annualized energy outputs or grain N export (**Figure 7**), though more intensified systems received more fertilizer inputs at Moro,

TABLE 5 | Rotational fertilizer and total N balance for Moro, Ritzville, and Davenport from 2012 to 2014.

	1. Initial soil inorganic N	2. Total N mineralization	3. Total fertilizer N inputs	4. Total grain N	5. Final soil inorganic N	Total inputs	Total outputs	Fertilizer N balance	Rotational N balance
			kg N ha^{-1}			1+2+3	4+5	3−4	(1+2+3)−(4+5)
MORO, OR									
ww-sf	66	59	95	154	92	220	246	−59	−26
ww-cf	58	78	75	173	96	211	269	−98	−58
ww-sb-cf	76	62	129	157	84	266	241	−29	25
sw-sw	53	59	111	144	80	223	224	−33	−1
sb-sb	45	55	166	167	116	266	283	−1	−17
ww-ww	9	73	148	151	53	230	204	−3	26
RITZVILLE, WA									
ww-tf	156	65	98	166	54	319	220	−68	100
ww-sw-tf	20	73	129	148	30	221	178	−19	43
trit-sw-cf	16	73	101	137	60	190	197	−36	−7
sw-sw	18	79	135	143	57	231	199	−8	32
sw-sb	18	83	135	149	42	236	191	−14	45
DAVENPORT, WA									
cf-ww-sw	85	110	155	146	139	350	284	10	66
cf-ww-can	85	110	139	158	74	333	232	−19	101
sw-ww-sw	85	110	232	184	86	427	270	48	157
can-ww-sw	85	110	215	194	138	410	332	21	78
cam-ww-sw	85	110	215	179	151	410	330	37	80

Fertilizer N balance represented the deficit between fertilizer added and grain N exported. Rotational N balance was calculated as the difference between estimated total N supply and grain N export and final residual soil N. Crop residue N was omitted from the N balance. ww, winter wheat; sf, summer fallow; sb, spring barley; cf, no-till chemical fallow; sw, spring wheat; trit, winter tricticale; can, spring canola; cam, spring camelina.

OR, Ritzville, WA, and Davenport, WA. Alternative cropping systems also did not differ significantly in rotational fertilizer use efficiency patterns from traditional rotations. In particularly, the relationship between fertilizer N and annualized energy production (**Figure 8A**) and grain N accumulation (**Figure 8C**) did not differ whether wheat followed fallow or crops when annual precipitation was <350 mm yr^{-1}. Nitrogen fertilization increased energy yields and grain N accumulation, but explained only 13% of the variation in energy outputs (**Figure 8A**) and 21% of grain N accumulation (**Figure 8C**) in traditional systems. In comparison, 17% of energy outputs and 25% of grain N variability were explained by N fertilization rates in alternative rotations with the reduction or elimination of fallow. Like WW, plant N was tightly regulated to produce grain (**Figure 8B**) and synthesis grain protein (**Figure 8D**) across all data, explaining 82–97%. Importantly, no differences among relationships were observed due to reduction or elimination of fallow when annual precipitation was <350 mm yr^{-1}.

Researchers in other Mediterranean climates have also reported agronomically viable intensified rotations, despite lower wheat yields upon the elimination of fallow (Christiansen et al., 2015). Cropping systems research in Canada have indicated that intensified rotations were agronomically feasible (Zentner et al., 2003), and fallow timing (e.g., wheat following fallow or recrop) predominately influenced annual wheat productivity in intensified rotations even though annualized grain yields increased with cropping intensity (Campbell et al., 2004). Continuous cropping of wheat rotated with legumes reduced the fertilizer requirements of a wheat-fallow rotation, and economics were dependent on commodity prices (Zentner et al., 2001). However, despite greater economic returns, financial risk increased with continuous wheat (Zentner et al., 2006).

In the iPNW, research has indicated that continuous spring cropping may be agronomically feasible (Schillinger et al., 2007; Bewick et al., 2008), even with less precipitation than we observed in our study (Machado et al., 2015). However, in six cropping seasons previously conducted at Ralston, the wheat-fallow system yielded 25% more than continuous spring wheat (Young et al., 2015). Furthermore, observations taken from a only few years, such as in the present study, may not be consistent over decades (Nielsen and Vigil, 2014). Previous research has also found that the profitability diminishes relative to WW-fallow rotations in the low precipitation zone due to high year-to-year yield variability and associated economic risk (Juergens et al., 2004; Schillinger and Young, 2004; Schillinger et al., 2007; Bewick et al., 2008). This finding may be due to differential pricing of alternative spring crops, increased costs associated with N fertilizers, changes in weed pressure (Sullivan et al., 2013), and grain yields in continuous cropping systems that average only 50–60% of WW following fallow.

Lastly, we developed N budgets at Moro, Ritzville, and Davenport to determine the effect of crop intensification in fertilizer N balances and unaccounted for N over multiple years (**Table 5**). At all locations, the fertilizer N balance was greater (fertilizer N exceeded grain N) for all continuous cropping systems with spring wheat, barley, camelina, or canola implementing conservation practices than the traditional fallow rotations. However, the total N balance had no discernible trends according to intensification. Earlier examination of N fertilizer balances at the Ralston site also revealed that the WW-summer fallow conventional system, when fertilized during the fallow period, had the highest fertilizer N efficiency (grain N/fertilizer $N = 76.8\%$) compared to spring wheat-chemical fallow (64%), due to deeper rooting and efficient soil N extraction by winter wheat down to 150 cm (Pan et al., 2001). Similar to the latter rotation, continuous no-till spring cereal cropping also had a lower fertilizer N efficiency (grain N/fertilizer $N = 61.7\%$) and water extraction, as evidenced by nitrate movement below 90 cm. It is notable that although conventional WW is fertilized during fallow nearly a year before the accelerated N uptake phase of winter wheat, the grain N to fertilizer index is surprisingly high in this low rainfall zone. While mineralized N accumulates during the fallow period in addition to the fertilizer application, soil tests indicate minimal overwinter nitrate leaching beyond the 150 cm root profile. The pre-plant N application during fallow allows growers to spread their workloads, and for the ammonia to nitrify and move into the middle of the winter wheat root zone, at 60–90 cm soil depths. Similarly, high N fertilizer efficiencies of WW-summer fallow grown in the northern iPNW near Okanogan, WA, has been observed, with 79% of fallow-applied ammonia over 20 years accounted for in harvested grain, and the remainder was accountable in an increase in soil organic N over that period (Pan et al., in review). This fertilizer N recovery was higher than the biosolids N recovery (24–37%) WW-summer fallow, when biosolids were applied once every 4 years at 3 different rates. However, biosolids significantly made greater contributions to the build-up of soil organic N, leading to the conclusion that while the synthetic fertilizer mainly fed the wheat grain, the biosolids fed both the wheat grain and the soil organic matter build-up. Nevertheless, the biosolids applications resulted in more net unaccounted for N than the ammonia.

CONCLUSION

Our region-wide assessment examined the performance of WW across the regional precipitation gradient. We observed that WW yields increased with increasing annual precipitation before maximizing at 520 mm yr^{-1} and subsequently declining. While fallow periods were effective at mitigating low N fertilization efficiencies under low precipitation, fertilization efficiencies decreased as annual precipitation exceeded 500 mm yr^{-1}. Reduction in WW yields in the highest precipitation zones were partially explained by decline in the overall soil water holding capacity in the argillic and fragipan soils in this region. We also observed considerable between-site and within-site variability in WW yields in response to annual precipitation and N fertilization. These results indicate that other soil, climatic, and management factors other than annual precipitation and fertilizer N rate have a large influence on WW yields. These results provide a rationale that precision N management is needed across the region and not limited to regions with risks of leaching or denitrification losses or areas with high topographic complexity.

Although, WW yields seem to increase following pulses and oilseeds rather than spring wheat across a range of yield potentials and when under conservation tillage practices at low yield potential sites, WW yields declined when following crops rather than fallow when annual precipitation was <350 mm yr^{-1}. The variance in WW yields also increased in alternative rotations. Nevertheless, WW yields were not affected when the frequency of fallow was reduced to once every 3 years, as long as fallow preceded the WW. Despite the yield penalty associated with eliminating fallow prior to WW, cropping system level productivity under the low annual precipitation (<350 mm yr^{-1}) was not affected by intensification, diversification, or conservation tillage. Nevertheless, multi-year N balances did not reveal any consistent benefit of intensified and diversified cropping in reducing unaccounted for N, whereas fertilizer N balance (fertilizer N > grain N) increased with intensification. Therefore, increased fertilizer N inputs and lower fertilizer efficiencies may offset and limit the economic feasibility of intensified and diversified cropping systems.

AUTHOR CONTRIBUTIONS

WP conceptualized, initiated, and organized the study; TM drafted the manuscript and performed data analyses; WS, SM, EB, FY, and JJ provided data, proposed analytical analyses, conceptualized individual site research, revised the manuscript; LY, IL, AG, IM collected, managed, and provided data and site information; AE, HC helped organize the study and managed individual site research.

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APPENDIX 1

Location	Comparisons	Angus et al., 2015	Citation
AUSTRALIA			
Formartin, Eastern Australia	Wheat, barley, canola, chickpea, fababean, fallow	Yes	Owen et al., 2010
Tamworth, Eastern Australia	Wheat, chickpea, fallow	Yes	Holford et al., 1997
N NSW, Eastern Australia	Wheat, barley, canola, mustard, chickpea	Yes	Kirkegaard et al., 2004
N NSW, Eastern Australia	Wheat, chickpea	Yes	Felton et al., 1998
Walpeup, Southeastern Australia	Wheat, barley, oats, canola, pea, lupin, fallow	Yes	Kollmorgen et al., 1983
NSW and Vic. Southeastern Australia	Wheat, canola, mustard, flax, pea, fallow	Yes	Ryan et al., 2002
S. NSW, Southeastern Australia	Wheat, canola, mustard, fallow	Yes	Gardner et al., 1998
S. NSW, Southeastern Australia	Wheat, canola, flax, pea, fallow	Yes	Kirkegaard et al., 2000
Kantannig, Western Australia	Wheat, barley, oats, canola, pea, lupin, fallow	No	Malik et al., 2015
Beverley, Western Australia	Wheat, barley, canola, mustard, flax, fababean, lupin, fallow	Yes	Gregory and Gregory, 1997
NORTHERN GREAT PLAINS, NORTH AMERICA			
Swift Current, SK, Canada	Wheat, flax, fallow	Yes	Zentner and Campbell, 1988
Swift Current, SK, Canada	"Cereal," pea, lentil, fallow	No	Gan et al., 2015
Stewart Valley and Swift Current, SK, Canada	Wheat, pea, lentil, chickpea, fallow	Yes	Miller et al., 2003
Indian Head, SK, Canada	Wheat, "legume," fallow	No	Campbell et al., 2011
Scott, SK, Canada	Wheat, canola, fallow	Yes	Brandt and Zentner, 1995
Indian Head, SK, Canada	Wheat, flax, pea, fallow	Yes	Lafond et al., 1992
Bow Island, AB, Canada	Wheat, flax/mustard, pea, fallow	No	Bremer et al., 2011
Beaverlodge, AB, Canada	Wheat, oilseed rape, pea	No	Soon and Arshad, 2004
Havre, MT, USA	Mustard, pea, lentil, chickpea, fallow	No	Lenssen et al., 2007
Moccasin, MT, USA	Wheat, pea, lentil, fallow	No	Chen et al., 2012
Amsterdam, Bozeman, Denton, Dutton, and Havre, MT, USA	Wheat, flax, pea, chickpea, fallow	Yes	Miller and Holmes, 2005
WEST ASIA			
Khamishly, Syria	Wheat, lentil, fallow	No	Christiansen et al., 2015
Tel Hayda, Syria	Wheat, pea, lentil, fallow	Yes	Ryan et al., 2008
Tel Hayda, Syria	Wheat, chickpea, fallow	No	Pilbeam et al., 1998
WESTERN EUROPE			
Cordoba, Spain	Wheat, sunflower, chickpea, faba bean, fallow	No	López-Bellido et al., 2000
Cordoba, Spain	Wheat, sunflower, chickpea, faba bean, fallow	No	Garrido and López-Bellido, 2001

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Winter Pea: Promising New Crop for Washington's Dryland Wheat-Fallow Region

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A 2-year tillage-based winter wheat (*Triticum aestivum* L.)-summer fallow (WW-SF) rotation has been practiced by the vast majority of farmers in the low-precipitation (<300 mm annual) rainfed cropping region of east-central Washington and north-central Oregon for 140 years. Until recently, alternative crops (i.e., those other than WW) so far tested have not been as economically viable or stable as WW-SF. A 6-year field study was conducted near Ritzville, WA (292 mm avg. annual precipitation) to determine the yield and rotation benefits of winter pea (*Pisum sativum* L.) (WP). Two 3-year rotations were evaluated: WP-spring wheat (SW)-SF vs. WW-SW-SF. Winter pea yields averaged 2,443 vs. 4,878 kg/ha for WW. No fertilizer was applied to WP whereas 56 kg N and 11 kg S/ha were applied to WW. Winter pea used significantly less soil water than WW. Over the winter months, a lesser percentage of precipitation was stored in the soil following WP compared to WW because: (i) very little WP residue remained on the soil surface after harvest compared to WW, and (ii) the drier the soil, the more precipitation is stored in the soil over winter. However, soil water content in the spring was still greater following WP vs. WW. Soil residual N in the spring (7 months after the harvest of WP and WW) was greater in WP plots despite not applying fertilizer to produce WP. Spring wheat grown after both WP and WW received the identical quantity of N, P, and S fertilizer each year. Average yield of SW was 2,298 and 2,011 kg/ha following WP and WW, respectively ($P < 0.01$). Adjusted gross economic returns for these two rotation systems were similar. Based partially on the results of this study, numerous farmers in the dry WW-SF region have shown keen interest in WP and acreage planted WP in east-central Washington has grown exponentially since 2013. This paper provides the first report of the potential for WP in the typical WW-SF region of the inland Pacific Northwest (PNW).

Keywords: winter pea, Inland Pacific Northwest USA, dryland cropping systems, winter wheat-summer fallow, crop diversification

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INTRODUCTION

A monoculture WW-SF rotation is the dominant cropping system practiced by farmers on 1.5 million cropland hectares in east-central Washington and north-central Oregon. Researchers and farmers have experimented with numerous crops and rotations over many decades, but none have been found to be as stable, reliable, and profitable as WW-SF (Juergens et al., 2004). Grassy weeds, mostly downy brome (*Bromus tectorum* L.) and jointed goatgrass (*Aegilops cylindrica* Host.), are a huge problem with monoculture WW-SF. Many farmers have resorted to the "Clearfield"^{TM} system for WW production that depends on use of the long soil-residual imazamax herbicide to control grassy weeds. A viable, stable, and profitable broadleaf crop is much needed for crop diversity and grassy weed control without the use of soil-residual herbicides.

Pulse crops are cool-season annual grain legumes mostly grown in the northern tier states of North Dakota and Montana, the high-precipitation (>450 mm average annual) Palouse region of Washington and Idaho (NASS, 2017), and the Canadian provinces of Alberta, Saskatchewan, and Manitoba (Statistics Canada, 2017). During the past 20 years, pulse crops have become an integral component of diversified and profitable dryland cropping systems in the Canadian and US northern Great Plains (Miller et al., 2003, 2015; Chen et al., 2006; Long et al., 2014).

In the PNW Palouse region, dry edible spring pea is commonly grown in rotation with wheat, with 48,000 ha of this crop harvested in 2016 (NASS, 2017). However, very little spring pea is produced in PNW areas that receive <450 mm annual precipitation. Experience in east-central Washington has demonstrated that water and heat stresses during flowering and pod fill limits yield potential of spring pea whereas WP better avoids such abiotic stresses by reaching physiological maturity before the onset of high air temperatures (Nelson, 2017).

Chen et al. (2006) reported that fall-planted WP in the high-precipitation Palouse of the PNW yielded as much as 1,830 kg/ha more than spring-planted pea cultivars. This (Chen et al., 2006) is the only published paper of such nature on WP in the PNW. Such observations of higher yield potential with WP compared to spring pea are not in general agreement with the much more comprehensive data sets from the Canadian and US northern Great Plains where winter temperatures are considerably colder than in the PNW. Chen et al. (2006) found that WP cultivars did not have a yield advantage over spring pea in central and south-central Montana. Similarly Strydhorst et al. (2015) recommended that farmers consider WP over spring pea only in the southernmost locations in Alberta. Although edible dry pea was harvested on 206,000 ha in Montana in 2016 (NASS, 2017) only about one percent of this was WP (P.R. Miller, personal communication).

Essentially no edible WP was produced anywhere in the PNW, (including the typical WW-SF region that receives <300 mm average annual precipitation, prior to 2012. Field research (this study) conducted since 2010 near Ritzville, WA (292 mm annual average precipitation) has demonstrated that WP is well-suited for the low-precipitation drylands. Winter pea plantings in the WW-SF region have gone from basically zero to 2,730 hectares from 2013 to 2017 (Howard Nelson, personal communication). Although the land area planted to WP currently is still small, the annual increase in planted hectares has been exponential during this 5-year period. The objective of the 6-year study reported here was to determine the yield potential and yield stability of WP and associated rotation benefits to the subsequent crop compared to WW in the low-precipitation WW-SF region of east-central Washington.

Abbreviations: PNW, inland Pacific Northwest; SF, summer fallow; SW, spring wheat; WP, winter pea; WW, winter wheat.

MATERIALS AND METHODS

A long-term WP cropping systems experiment was initiated at the Ronald Jirava farm near Ritzville, WA (47.16394,-118.473225) in August 2010. The WP cultivar "Windham" (McPhee et al., 2007) was selected for inclusion in the experiment based on the experience and recommendation of Howard Nelson of Central Washington Grain Growers. Windham is a yellow pea with mottled seed coat; with an average 100-seed weight of 13.8 g. Windham can withstand ambient air temperatures as low as −18°C without undue damage to plant stands (Nelson, 2017). This cultivar has an average mature plant height of 44 cm with upright growth habit that allows for direct combining at harvest with a conventional header (i.e., swathing and/or a pick-up header not required).

Precipitation was measured on site during all years of the study by the Washington State University (WSU) AgWeatherNet (http://weather.wsu.edu/) with a Campbell Scientific CR-1000 logger and associated hardware. The soil at the site is a Ritzville silt loam (coarse-silty, mixed, superactive, mesic, Calcidic Haploxerolls; Soil Survey Staff, 2010). The soil is more than 2 meters deep to underlying basalt bedrock with uniform texture throughout the profile and with no rocks or restrictive layers. Slope is <1%. Long-term (100-year) annual precipitation at/near the site averages 292 mm. Annual crop-year (Sept. 1–Aug. 31) precipitation during the study period ranged from 207 to 370 mm and averaged 277 mm.

Treatments and Field Operations

Throughout the 6-year experiment, glyphosate herbicide was applied at a rate of 0.48 kg acid equivalent (ae)/ha in March to control weeds in the undisturbed residue of the WP, WW, and SW plots that had been harvested the previous July or August. The two 3-year crop rotations in the experiment were (i) WP-SW-SF vs. (ii) WW-SW-SF. Experimental design was a randomized complete block with four replicates. All phases of both rotations were present every year for a total of 24 individual plots. Size of individual plots was 5 × 30 m.

During the fallow year, conservation primary spring tillage was conducted with a Haybuster™ undercutter implement in mid-to-late May at a depth of 10 cm. For the WW-SW-SF treatment, 56 kg/ha aqua NH_3-N + 11 kg/ha thiosol S fertilizer was injected with the undercutter implement during primary spring tillage. No fertilizer was applied to the WP-SW-SF treatment with the undercutter during primary spring tillage. Summer fallow in both treatments was rodweeded once in July at a depth of 8 cm to control broadleaf weeds.

Winter pea (cv. Windham) and WW (cv. Xerpha) were planted at the same time and depth each year in either the last week of August or first week of September with a deep-furrow drill with 43 cm spacing between rows. Seed was inoculated with powdered rhizobium bacteria at time of planting to facilitate root nodulation and fixation of atmospheric nitrogen. Seeding rate for WP was 100 kg/ha (70 seeds/m^2) and for WW 56 kg/ha (160 seeds/m^2). An average of 10 cm of soil covered the seeds. Excellent stands of both WP and WW were achieved every year.

Spring wheat (cv. Louise) was planted and fertilized in late March in one-pass directly into the undisturbed soil and residue left from the previous WP or WW crop. A no-till hoe-opener drill was used to place seed in paired rows 10-cm apart with 30 cm spacing between openers. Fertilizer was placed in a band between and 3 cm below the paired rows. Seeding rate for SW was 78 kg/ha (225 seeds/m^2) and soil covering the seed averaged 2 cm. Prior to SW planting and fertilization, soil samples were obtained from 2,014 to 2,106 in 30-cm increments from the middle of each plot to a depth of 120 cm in all four replicates, then combined to make one sample for each treatment per depth increment, where the previous crop was WP or WW. Soil samples were then analyzed for N, P, K, S, and other nutrients at a commercial soil-testing laboratory (Soil Test Farm Consultants, Inc., Moses Lake, WA). Fertilizer rate for SW was based on soil test residual soil fertility, available soil water, and perceived grain yield potential. Potassium fertilizer was not required as soils contain naturally adequate quantities of this nutrient. Although soil fertility values following WP vs. WW differed somewhat (**Table 1**), SW after either WP or WW always received the same fertilizer application rate each year. Solution 32 (NH_4NO_3 + urea) provided the liquid fertilizer base to supply an average of 38 kg N, 7 kg P (aqueous solution of $NH_4H_2PO_4$), and 10 kg S [aqueous solution of $(NH_4)_2S_2O_3$]/ha. Excellent stands of SW were achieved every year.

Crop yields were determined in early-to-mid July (WP) and early August (WW and SW) by harvesting a 1.5-m swath through the center of each 30-m-long plot with a Hege™ 140 plot combine. After grain harvest with the plot combine, the remaining standing crops in the experiment were harvested with a commercial-size combine.

In-Crop and Post-Harvest Weed Control with Herbicides

When WP reached the three-leaf (or four-node) stage of growth in April, 1.1 kg active ingredient (ai)/ha sodium salt of bentazon broadleaf-weed herbicide was tank mixed with 0.1 kg ai/ha quizalofop P-ethyl grass-weed herbicide and applied. Bentazon and MCPA Amine are currently the only non-soil-residual broadleaf-weed herbicides labeled for use in WP. The major grass weeds of concern in the region are downy brome and jointed goatgrass. Both these grass weeds are winter annuals with growth cycles similar to WW and are particularly problematic in the 2-year WW-SF rotation (Young and Thorne, 2004).

Herbicides used to control broadleaf weeds in WW were either 2,4-D ester at a rate of 0.84 kg acid equivalent (ae)/ha or 0.56 kg ai/ha bromoxynil applied in April after WW had four tillers but before the "jointing" stage of WW growth development. In-crop broadleaf herbicides used for SW were 0.56 kg ai/ha bromoxynil or 0.45 kg ai/ha bromoxynil + 0.02 L ai/ha thifensulfuron applied in May.

Glyphosate was applied at a rate of 0.90 kg ae/ha following the harvest of SW in August of 2014 and 2015 (the two driest crop years) to control Russian thistle (*Salsola tragus* L.). Post-harvest herbicide application was not required for WP or WW in any year.

TABLE 1 | Soil nitrate-N, Olsen-P, sulfate-S, and soil organic matter (SOM) in late March during 3 years after either winter pea or winter wheat and prior to planting spring wheat.

	Nitrate (mg/kg/120 cm)	Phosphorus (mg/kg/30 cm)	Sulfate (mg/kg/90 cm)	SOM (30 cm, %)
2013				
Winter wheat	24	53	39	1.7
Winter pea	30	52	45	1.5
2014				
Winter wheat	16	35	17	1.8
Winter pea	22	38	17	1.6
2016				
Winter wheat	17	45	16	1.4
Winter pea	24	43	13	1.6

Soil Water

Soil water was measured to a depth of 180 cm three times each year: (i) in early August immediately after WP, WW, and SW grain harvest (16 plots); (ii) at the end of fallow in late August for the SF plots (8 plots); and (iii) in mid-March (all 24 plots). Volumetric soil water content in the 0–30-cm depth was determined from two 15-cm core samples with gravimetric procedures (Topp and Ferre, 2002) using known soil bulk density values for these depths. Soil volumetric water content in the 30–180-cm depth was measured in 15-cm increments by neutron thermalization (Hignett and Evett, 2002).

Market Price, Gross Returns, and Adjusted Gross Returns

Gross returns for WP and WW per hectare were calculated based on the yield results for each year of the study. Edible WP grown by farmers in eastern Washington was sold through a "market pool" operated by Central Washington Grain Growers in Wilbur, WA. Market streams for WP through the years included seed for cover crops, US government food aid, export for food to Asia, and for pet food. Winter pea marketing pool prices ranged from 160 to 339 US$/metric ton (MT).

Soft white wheat market price used was the price offered during the first week of September for each year of the study at Ritzville Warehouse, Ritzville, WA. Ritzville Warehouse accepts WW and WP for storage and is the closest commercial elevator delivery site for the study. Gross returns per hectare for both WP and WW were calculated by multiplying yields obtained from the study by the market prices for each year. Adjusted gross returns were then calculated for both rotations by tabulating for each year the cost of N and S used for WW (but not for WP) and any differences in SW yields.

Statistical Analysis

Statistical analyses using a randomized complete block design analysis of variance (ANOVA) were conducted for: (i) water use of WP vs. WW as well as overwinter storage of precipitation in the soil following these two crops averaged over 5 years, and; (ii) within-year and 5-year average differences in SW grain yield following either WP or WW. A split-plot in time ANOVA was used for the 5-year average soil water data and the 5-year average SW yield data with treatment as the fixed effect factor and year as the random effect factor. The least significant difference test was used to detect statistical differences in treatment means. All ANOVA tests were done at the 5% level of significance.

RESULTS

Soil Water

Averaged over the years, WP used an average of 30 mm less soil water than WW ($P < 0.001$, **Table 2**). The majority of this water savings with WP occurred at soils depths below 100 cm (**Figure 1**) as WP roots do not reach this depth. These data on soil water use by WP agree closely with those reported by Miller and Holmes (2012) in Montana and Merrill et al. (2004) in North Dakota. However, by late March, WP plots had only 13 mm more soil water than WW plots (**Table 2**) because: (i) the greater the surface residue cover, the more water will be stored in the soil (e.g., WP produces little residue compared to WW); and (ii) the drier the soil, the more overwinter precipitation will be stored in the soil (Kok et al., 2009).

The overwinter precipitation storage efficiency (PSE) in the soil averaged 55 and 69% for WP and WW plots, respectively (**Table 2**). Similar overwinter PSE-values were reported following spring lentil (*Lens culinaris* L.) vs. following SW in a 21-year study in Saskatchewan (Campbell et al., 2007). This increase in overwinter PSE for WW over WP plots occurred within the first 100 cm of the soil profile whereas the relative difference in spatial water distribution at the 100–180-cm depths remained about the same for WP and WW plots (**Figure 1**). The end result, however, was that when SW was planted in late March, average overwinter soil water content was 290 and 277 mm following WP and WW, respectively (**Table 1**).

Soil Nitrate-N

When measured in late March, soil nitrate-N-values trended higher after a crop of WP compared to WW, despite the fact that zero N was applied for WP and 56 kg of N/ha was applied for WW (**Table 1**). This can be explained by the fact that WP is a legume that fixes atmospheric nitrogen. Although statistical analysis was not possible (soil samples were pooled from the four replicates), nitrate-N-values were 25–41% greater following WP vs. WW.

Grain Yield

Yield of WP ranged from 1,696 to 3,158 kg/ha and averaged 2,443 kg/ha over 5 years (**Table 3**). Winter pea was killed by −21°C air temperatures with no snow cover in 2014 and was replaced by spring pea (cv. Banner) which yielded 870 kg/ha. Winter wheat grain yield ranged from 3,372 to 5,841 kg/ha for an average of 4,878 kg/ha over 6 years (**Table 3**).

Spring wheat grain yield was significantly greater following WP vs. following WW in 2013 and 2015. The 5-year average SW grain yield of 2,298 kg/ha following WP was significantly different from 2,122 kg/ha following WW (**Table 3**).

TABLE 2 | (i) Soil water content to a depth of 180 cm measured after harvest of winter pea and winter wheat and again in late March following these two crops; (ii) overwinter gain in soil water, and; (iii) overwinter precipitation storage efficiency in the soil (PSE).

	Beginning (late Aug.)	Spring (late Mar.)	Overwinter gain	PSE (%)
Soil water content (mm)				
Winter pea	180	290	110	55
Winter wheat	150	277	127	69
P-value	<0.001	ns	0.001	

Data are averaged over 5 years. Average overwinter precipitation was 164 mm.

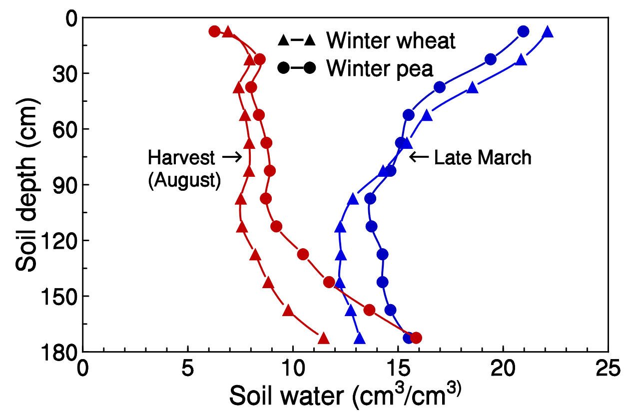

FIGURE 1 | Soil volumetric water content to a depth of 180 cm in early August after harvest of winter pea and winter wheat (red lines on left) and overwinter soil water recharge following these two crops measured in late March (blue lines on right). Data are averaged over 5 years.

Market Price, Gross Returns, and Adjusted Gross Returns

Gross returns for WW exceeded that for WP in most years (**Table 4**). However, cost of 56 kg/ha aqua NH_3-N + 11 kg/ha thiosol S fertilizer for WW (where none was used for WP) ranged from \$66 to \$97/ha and averaged \$86/ha over the 6 years (actual costs paid for the fertilizer each year). Also, SW yield after WP vs. WW from 2012 to 2016 ranged from −143 to +589 kg/ha and averaged +176 kg/ha (**Table 3**). Using the commodity market prices shown in **Table 4**, SW after WP generated from −\$35 to +S85/ha and averaged +\$39/ha more return than SW after WW. Thus, the fertilizer savings plus the greater SW grain yield revenue provided in the WP rotation should be considered rather than just the gross returns shown in **Table 4**.

DISCUSSION

Winter wheat-summer fallow has been the dominant cropping system practiced throughout the low-precipitation dryland cropping region of east-central Washington and north-central Oregon for well-over 100 years. Despite long-term and ongoing

TABLE 3 | Yield of winter pea (WP) and winter wheat (WW) as well as the subsequent yield of spring wheat (SW) following both WP and WW over a 6-year period at Ritzville, WA.

	Grain yield (kg/ha)						
	2011	2012	2013	2014	2015	2016	Avg.
WINTER CROP							
Winter pea	2,193	3,158	2,336	- - - -*	1,696	2,833	2,443**
Winter wheat	5,180	5,729	5,841	3,372	4,211	4,932	4,878
SPRING CROP* **							
SW after WP		2,010	2,992 a	1,043	2,293 a	3,151	2,298 a
SW after WW		2,153	2,700 b	965	1,704 b	3,086	2,122 b
Crop-year precipitation (mm)							
	330	294	254	207	208	370	277

Values at the bottom show crop-year (Sept. 1–Aug. 31) precipitation at the site.
**WP was winterkilled in 2014 and replanted to Banner edible spring pea, which yielded 870 kg/ha.*
***Winter pea average yield is for 5 years (i.e., 2014 not included).*
****ANOVA is for SW only. Within-column means followed by a different letter are significantly different at $P < 0.05$.*

TABLE 4 | Ritzville soft white wheat market prices during the first week of September and winter pea market pool price as well as gross return for these crops based on the yield results of the experiment from 2011 to 2016.

	Commodity market price (US$/MT)*		Gross returns (US$/hectare)**	
	Soft white wheat	Winter pea	Soft white wheat	Winter pea
2011	198	291	1,245	776
2012	242	289	1,680	1,112
2013	202	339	1,433	963
2014	172	No pool, winterkill	701	- - - -
2015	145	377	746	778
2016	123	160	731	674

**Soft white wheat price data from Ritzville Warehouse, Ritzville, WA. Winter pea market pool price data from Howard Nelson, Central Washington Grain Growers, Wilbur, WA.*
***Gross return values shown here to not account for cost of N and S used for WW (but not used for WP) or the additional revenue from greater SW yield after WP vs. WW (see Results section).*

efforts, farmers and scientists have not yet identified any spring-planted crop, including SW spring barley (*Hordeum vulgare* L.), and numerous others, that can provide the yield stability and economic viability of WW-SF.

A big benefit of growing WP in wheat-based cropping systems is the opportunity for in-crop control of winter-annual grass weeds such as downy brome and jointed goatgrass. These two grass weeds have growth cycles similar to WW and infestations are frequently heavy and troublesome (Appleby and Morrow, 1990), especially in the 2-year WW-SF rotation.

Another benefit of WP is its large seed size and strong "push" by the elongating hypocotyl which enables it to emerge from deep planting depths. For optimum grain yield potential, farmers in east-central Washington seed WW into SF as deep as 20 cm below the soil surface with deep-furrow drills to reach adequate soil moisture in late August-early September, and WW seedlings need to emerge through as much as 15 cm of dry soil cover. Data from planting-date experiments in east-central Washington suggest that late August-early September is also the best planting time for optimum yield potential of WP (Rebecca McGee, personal communication). Experience of farmers and scientists strongly demonstrates that WP seedlings can emerge from even deeper planting depths than WW. In addition, WP seedlings easily emerge through surface soil that has been crusted by rain showers whereas WW seedlings cannot do so.

A new yellow WP cultivar "Blaze" (ProGene Plant Research, Othello, WA) is presently under seed multiplication and will be available to farmers in 2018. Compared to Windham in regional trials, Blaze has (i) 13% higher yield, (ii) 18 cm taller plant height at maturity, 22% larger seed, and (iii) better cold tolerance (Nelson, 2017). For example, during a cold event of −18°C with no snow cover in 2014, Windham was winterkilled at regional locations whereas, at these same locations, Blaze survived (Nelson, 2017). It is estimated that Blaze has similar cold tolerance as regionally-adopted WW cultivars. Additionally, three advanced WP numbered lines in the USDA-Agricultural Research Service legume breeding program in Pullman, WA show excellent potential and are expected to be released soon. These numbered WP lines have better cold tolerance than Windham in addition to smooth seed coat, clear hilum, and large seed size that are deemed highly desirable for food markets (Rebecca McGee, personal communication).

A soil management concern about growing WP is the fact that they produce very little durable residue. Wind erosion and dust emission from agricultural soils is a major environmental and air quality concern in east-central Washington (Sharratt and Vaddella, 2012). Wind tunnel studies during the fallow year after the oilseed crops camelina (*Camelina sativa* L. Crantz) and safflower (*Carthamus tinctorius* L.) showed up to 250% greater blowing dust emissions even using best management practices for tillage-based SF compared to after WW (Sharratt and Schillinger, 2014). Personal observation suggests that WP residue decomposes at about the same rate as residue of camelina and safflower. In a practical sense, this means that farmers must be especially judicious in protecting the soil after WP by either (i) recropping to the spring crop (as done in this study), or (ii) conducting no tillage during the 13-month SF cycle.

There are currently few effective in-crop broadleaf herbicide options for WP. Bentazon herbicide (used every year in WP in the study) provides little control for tumble mustard (*Sisymbrium altissimum* L.) or tansy mustard (*Descurainia pinnata* L.). Although considered minor weeds that are easily controlled with herbicides in WW, both were present in minor to moderate levels in WP. The soil residual imazamox herbicide can be used in WP and is used by many farmers who practice the Clearfield™ method for WW production. However, many farmers are reluctant to use soil-residual herbicides due to limitations imposed on rotation to other crops or to WW cultivars that are not tolerant of this herbicide. Russian thistle, by far the most troublesome broadleaf weed in the region, was not a problem in WP in any year, presumably due to the ability of WP to provide canopy closure relatively early in the spring before this weed can establish.

The potential impact of increased pulse crop production on greenhouse gas emissions deserves some discussion. Lemke et al. (2007) and Cutforth et al. (2007) wrote review articles about the impact of pulse crop production on climate change in the Canadian and US northern Great Plains and the contribution of pulse crops to the balance of greenhouse gases. Authors of these papers agreed that rotations which include pulse crops will likely have lower nitrous oxide emissions compared to rotations that do not contain a pulse because legumes fix atmospheric N compared to rotations that rely solely on fertilizer N. Lemke et al. (2007) and Cutforth et al. (2007) further agreed that replacing a cereal with a pulse crop will likely result in the same or slightly smaller carbon dioxide emissions in direct relation to reduction in fertilizer N usage.

CONCLUSION

This study showed that WP has excellent production potential in the typical WW-SF region of east-central Washington. Although gross returns for WW were greater than for WP during most years, adjusted gross returns for the two rotations were equivalent. Winter pea has unsurpassed seedling emergence from deep planting depths, even when surface soils have been crusted by rain showers before emergence. Excellent WP plant stands were consistently achieved that effectively competed against Russian thistle. New WP cultivars will be available to farmers in 2018 that have cold tolerance similar to that of WW, greater yield potential than cv. Windham, and better quality traits that will fetch higher prices in regional, national, and international markets.

Land area planted of WP in the PNW drylands is still minor, but farmers and scientists are excited about this crop and planted acreage has increased exponentially every year since 2013. This paper provides the first report in the literature on WP production in the typical WW-SF region of the PNW.

AUTHOR CONTRIBUTIONS

Contributions to this article were made by WS and he is accountable for the content of the work.

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Comparison of Greenhouse Gas Offset Quantification Protocols for Nitrogen Management in Dryland Wheat Cropping Systems of the Pacific Northwest

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In the carbon market, greenhouse gas (GHG) offset protocols need to ensure that emission reductions are of high quality, quantifiable, and real. Lack of consistency across protocols for quantifying emission reductions compromise the credibility of offsets generated. Thus, protocol quantification methodologies need to be periodically reviewed to ensure emission offsets are credited accurately and updated to support practical climate policy solutions. Current GHG emission offset credits generated by agricultural nitrogen (N) management activities are based on reducing the annual N fertilizer application rate for a given crop without reducing yield. We performed a "road test" of agricultural N management protocols to evaluate differences among protocol components and quantify nitrous oxide (N_2O) emission reductions under sample projects relevant to N management in dryland, wheat-based cropping systems of the inland Pacific Northwest (iPNW). We evaluated five agricultural N management offset protocols applicable to North America: two methodologies of American Carbon Registry (ACR1 and ACR2), Verified Carbon Standard (VCS), Climate Action Reserve (CAR), and Alberta Offset Credit System (Alberta). We found that only two protocols, ACR2 and VCS, were suitable for this study, in which four sample projects were developed representing feasible N fertilizer rate reduction activities. The ACR2 and VCS protocols had identical baseline and project emission quantification methodologies resulting in identical emission reduction values. Reducing N fertilizer application rate by switching to variable rate N (sample projects 1–3) or split N application (sample project 4) management resulted in a N_2O emission reduction ranging from 0.07 to 0.16, and 0.26 Mg CO_2e ha^{-1}, respectively. Across the range of C prices considered ($5, $10, and $50 per metric ton of CO_2 equivalent), we concluded that the N_2O emission offset payment alone ($0.35–$13.0 ha^{-1}) was unlikely to encourage a change in fertilizer N management; however, the fertilizer cost savings from adopting variable or split N management would incentivize adopting these practices. Therefore, the monetary incentive of adopting agricultural N management BMPs for reducing N_2O emission should be tied to other co-benefits and existing conservation programs to encourage N rate reductions that do not limit yield, crop quality, or economic stability.

Keywords: agriculture, wheat, nitrous oxide, greenhouse gas, nitrogen, offset

INTRODUCTION

There is growing concern over rising atmospheric concentrations of nitrous oxide (N_2O), a greenhouse gas (GHG) 310 times more potent than carbon dioxide (CO_2) (Robertson and Vitousek, 2009; United States Environmental Protection Agency, 2013). GHG concerns are coupled with negative environmental consequences associated with accelerated rates of reactive N entering and cycling through ecosystems (Vitousek et al., 1997; Robertson and Vitousek, 2009). The agricultural sector is the largest contributor to rising N_2O emissions in the US with 69% of N_2O emissions from agricultural soil management (United States Environmental Protection Agency, 2013) (**Figure 1**). Increased N_2O emissions from agricultural soil management result from application of synthetic N fertilizer, manure additions, and drainage and cultivation of organic soils (United States Environmental Protection Agency, 2013). Therefore, reducing N rate has been targeted as an opportunity to reduce GHG emissions and achieve other co-benefits, such as reducing N in runoff. However, under GHG offset programs, N fertilizer rate reductions must not result in substantial yield reductions (American Carbon Registry, 2010, 2012; Climate Action Reserve, 2012; Verified Carbon Standard, 2013) as an increasing world population will demand greater agricultural productivity from cropping systems that are currently reliant on synthetic N fertilizers to achieve high yields. This has placed considerable pressure on agriculture to reduce hydrologic or gaseous losses of N without compromising yield which supports increased N use efficiency that may or may not result in N rate reductions (Robertson and Vitousek, 2009).

One policy tool to incentivize N fertilizer rate reductions is carbon offsets. Carbon offsets, also known as GHG offsets, are emission reductions achieved at sources outside of a capped sector that result in offset credits. Offset programs provide a mechanism where covered entities can offset their emissions by purchasing emission reduction credits. Offset protocol methodologies have been developed to ensure that GHG emission reductions are actually achieved (i.e., real and verifiable) and beyond what would have occurred without the incentive of the offset program payment (i.e., additional to business as usual) (Broekhoff and Zyla, 2008). The protocol methodology for quantifying emission reductions are the standard for accurate accounting of emission reductions and offset credits generated by project activities. Offset quantification protocols are therefore critical for establishing credibility in emission reductions and offset markets (Kollmuss et al., 2010; Lazarus et al., 2010).

Fertilizer N rate reductions have been targeted in offset programs because the addition of N increases the amount of available soil N for processes that produce N_2O emissions from agricultural soils (mainly nitrification and denitrification)

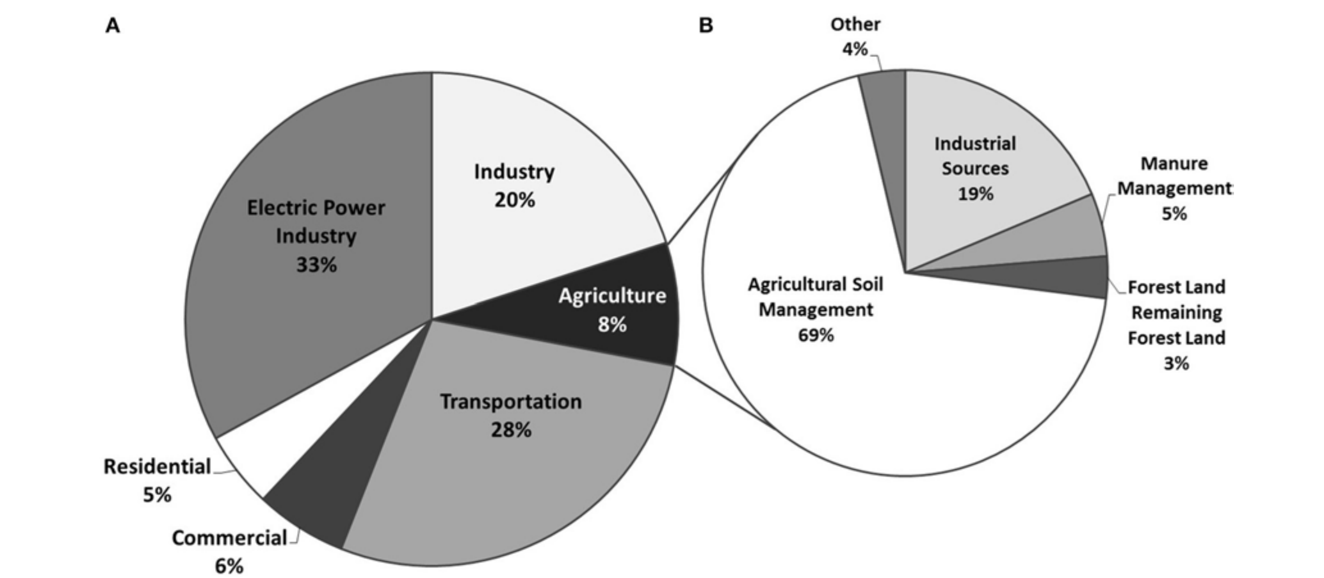

FIGURE 1 | Emission estimates from EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks from 1990 to 2011 by: **(A)** major U.S. economic sector; and **(B)** N_2O emission sources (United States Environmental Protection Agency, 2013).

(Smith et al., 2008) and are relatively easy to monitor and verify (Intergovernmental Panel on Climate Change, 2006). Furthermore, fertilizer N rate can be used as an integrator of several management practices that can be adopted alone or simultaneously to reduce N_2O emissions. This might include adopting crop rotations with an N capturing component, improving prediction of N requirement, and employing the principles of precision N management of right place, right time, right source, and right rate (Smith et al., 2008; Robertson and Vitousek, 2009). Offset protocols for agricultural N management encourage practices that better predict crop N demand and increase N-use efficiency (Robertson and Vitousek, 2009; Millar et al., 2012) and can allow for reduced N fertilization rates while also meeting crop N demand. Precision N management practices that reduce N fertilizer application rates without reducing crop yield therefore offer one potential management strategy to reduce agricultural N_2O emissions, generate GHG offsets, and decrease the amount of reactive N entering the environment.

Currently, N fertilizer rate recommendations for wheat are based on an expected yield goal and the unit N requirement (UNR). The UNR is the amount of nitrogen needed to produce one unit of grain (e.g., a bushel or kilogram). In the iPNW, where wheat is the dominant and most profitable crop for farmers, the UNR is generally determined by wheat class across a given region and reported in regional fertilizer guides (e.g., Koenig, 2005; Mahler and Guy, 2007). Yield goal and UNR are often assumed to be uniform across a given field and are used to calculate a uniform N application rate for a given field. However, variability in wheat yield and N requirement has been observed across agricultural fields within the Palouse region of the iPNW (Mulla et al., 1992; Fiez et al., 1994a,b; Huggins, 2010). For example, Fiez et al. (1994a) reported soft white winter wheat grain yield to vary by up to 63% and the UNR to vary by up to 70% in the Palouse. Sowers et al. (1994) observed split N applications in winter wheat to produce similar grain yield with 25–40% less N. This indicates that variable rate and/or split N fertilizer application have the potential to reduce overall N rate without decreasing yield.

Our focus was to improve understanding of methodologies for quantifying GHG offset credits generated under current offset programs with agricultural N management protocols. Quantification of offset credits was applied to sample projects developed from a literature review of precision N management for dryland wheat cropping systems of the iPNW. Offset quantification under sample project scenarios was used to evaluate the relevance of existing offset programs and quantification protocol methodologies for iPNW agroecosystems. A road test of agricultural N management protocols was performed following the approach of Lee et al. (2013) and Lazarus et al. (2010) to provide a framework for comparing N-based GHG offset programs for iPNW dryland wheat agriculture. The objectives of this project were to (i) review and assess the current components of agricultural N management protocols for relevance to the iPNW; (ii) road-test quantification approaches for N_2O emission reductions under applicable protocols using sample projects; (iii) investigate the impact of quantification approaches on the magnitude of offsets generated; and (iv) assess the role of agricultural N management offset credits as incentive for changing N management strategies for PNW wheat-based cropping systems.

METHODS

Offset Quantification Methodologies for iPNW Agricultural N Management

Eligibility Requirements

We identified four voluntary GHG reduction programs applicable to North America with agricultural N management protocols: the American Carbon Registry (ACR), Verified Carbon Standard (VCS), Climate Action Reserve (CAR), and Alberta Offset Credit System (Alberta) (**Table 1**). The ACR and VCS offset programs have international applicability. The CAR program is applicable to project locations within the US and the Alberta program is applicable in the Canadian province of Alberta. All programs are associated with an offset registry system where verified emission reductions from approved project activities are transparently serialized and tracked. Within the four GHG reduction programs, five agricultural N management

TABLE 1 | Greenhouse gas offset programs and agricultural nitrogen management protocols for North America.

Offset program/Protocol component	Alberta offset system (Alberta)	American Carbon Registry (ACR)	Climate Action Reserve (CAR)	Verified Carbon Standard (VCS)
Regional scope of protocol	Canadian province of Alberta	International	U.S.	International
Start of program	2007	1996	Unknown	2005
Relative market share of offset credits†	118,355,719	81,401,214	87,327,828	200,676,374
Protocol version and date‡	October 2010. Version 1.0.	ACR1-November 2010; and ACR2-July 2012. Version 1.	January 2013. Version 1.1.	March 2013. Version 1.0.

†Total offset credits issued in metric ton of carbon dioxide equivalents (note 1 Mg is ≈1 metric ton). Data from online registries accessed online on 1/31/2017 for: ACR, http://americancarbonregistry.org/carbon-registry; CAR, http://www.climateactionreserve.org; VCS, http://www.v-c-s.org; and Alberta, http://carbonoffsetsolutions.climatechangecentral.com/offset-registry.

*‡Protocol titles are: **Alberta**, Quantification Protocol for Agricultural Nitrous Oxide Emissions Reductions; **ACR1**, The American Carbon Registry Methodology for N_2O Emission Reductions through Changes in Fertilizer Management; **ACR2**, Methodology for Quantifying Nitrous Oxide (N_2O) Emissions Reductions through Reduced Use of Nitrogen Fertilizer on Agricultural Crops; **CAR**, Nitrogen Management Project Protocol.; and **VCS**, Quantifying N_2O Emissions Reductions in Agricultural Crops through Nitrogen Fertilizer Rate Reduction.*

protocols with approved methodologies for quantifying N_2O emission reductions from adoption of approved N management practice were identified (**Table 1**).

Programs and protocols whose eligible project locations included the iPNW (i.e., Washington, Idaho, Oregon) were considered currently applicable to iPNW wheat-based cropping systems. Based on the regional scope of each program, only three of the five quantification protocols for agricultural N_2O emission offsets could be used to quantify voluntary offsets for the iPNW (**Table 1**). Projects are accepted on land worldwide under the ACR1 (American Carbon Registry, 2010) and ACR2 (American Carbon Registry, 2012) protocols. The VCS protocol is applicable for offset projects occurring within the US (Verified Carbon Standard, 2013). Sites throughout the US were eligible under the CAR program but the only agricultural N management protocol currently approved by CAR was specific to corn crops grown in the North Central Region of the US (Climate Action Reserve, 2012). Therefore, the ACR and VCS protocols are currently the only three protocols applicable to the iPNW based on eligible project location. Though not applicable to the iPNW, the Alberta and CAR protocols were reviewed as their general features and quantification approaches could inform the future development of an agricultural N management GHG offset protocol for iPNW wheat-based agricultural systems.

In addition to eligible project locations, quantification protocols also include general eligibility conditions such as project start date, eligible crops, additionality, and regulatory surplus requirements that once satisfied did not appear to factor into the quantification of offsets generated (**Table 2**). The project start date indicated the earliest date that project activities could be credited for offsets generated. All fertilized agricultural crops requiring external N inputs to achieve high production of food, fiber, or fodder were accepted under the protocols except for CAR in which only corn crops can be credited. Regulatory surplus is an additionality test, generally requiring project activities to be in addition to the requirement of current laws and regulations.

Eligible N Sources and Management Activities

Sources of N inputs into a cropping system during any given crop year might include manure, synthetic N fertilizer, crop residue N, soil organic matter N mineralization, and biological N fixation (**Table 2**). The ACR1 protocol accepts a broad range of fertilizer management activities to reduce N rate (i.e., change in fertilizer rate, type, placement, timing, use of time-release fertilizers, and use of nitrification inhibitors). The ACR2 and VCS protocols require adherence to regionally adapted N fertilizer best management practices (BMPs), which include N fertilizer source, timing of N application, and method of N fertilizer application. Under ACR2 and VCS, project developers are referred to state specific resources for detailed N fertilizer BMPs (e.g., USDA-NRCS). The Alberta quantification protocol, distinct from the other protocols, requires project participants to adopt an increased level of N management within the "Consistent 4R Nitrogen Stewardship Plan," which is an integrated set of management practices (Alberta Environment, 2010). The CAR protocol does not specify eligible practices but requires that project N application rates must decrease below baseline.

Baseline and Project Emission Calculation

Greenhouse gas (GHG) emissions are expressed as carbon dioxide equivalents (CO_2e) and reported in megagram (metric ton) increments (Mg CO_2e). Carbon dioxide equivalents are a global warming potential weighting that is based on radiative forcing over a 100-year time scale and resulting from the release of 1 kg of a substance as compared to 1 kg of CO_2 (Intergovernmental Panel on Climate Change, 2006). Under all of the protocols reviewed, a global warming potential of 310 was used for N_2O-N emission conversions to CO_2e. Baseline N_2O emissions represent the emissions that would have occurred absent the offset market incentive. Project N_2O emissions represent the emissions that occur under the project scenario. The general equation for calculating N_2O emission reduction from project activities was based on the difference between the baseline and project emissions as follows:

$$\text{ERMtCO2e per yr} = \text{BMtCO2e per yr} - \text{PMtCO2e per yr.} \quad (1)$$

Where ERMtCO_2e yr^{-1} are emissions reductions from the project; BMtCO_2e yr^{-1} are baseline emissions; and PMtCO_2e yr^{-1} are project emissions.

Sources and Sinks Included in Emission Quantification

The assessment boundary specifies the GHG sources and sinks to be included in the quantification of baseline and project emissions. The assessment boundary does not necessarily represent a physical boundary, but instead represent the quantification boundary for including/excluding GHG sources and sinks. The emission sources and sinks included or excluded varies by protocol. The direct and indirect emissions associated with baseline and project N management for each protocol are shown in **Table 3**. Direct emissions are included in the emissions of N_2O from N fertilizer addition to the project lands for enhancing crop productivity. The indirect emissions are included in the N_2O emissions that occur beyond the project site but are the result of N fertilizer applied at the project field site. Indirect N_2O emissions result from the re-deposition of volatilized ammonia, leaching of N from the soil, and N runoff to surface waters (Intergovernmental Panel on Climate Change, 2006). Depending on the protocol, the boundary may also include combustion emission sources and sinks from fertilizer manufacture, fertilizer distribution, or N application to the field.

Additionality

Additionality for these protocols was based on a performance standard of reducing the N fertilizer application rate on project lands, and subsequently N_2O emissions, below that of the baseline. It is important that protocol quantification methodologies assure offsets generated by a project are real, not a result of inaccurate quantification, and exceed common practice. The ACR2 and VCS baseline N_2O emission calculation used the same number of historical crop years and depend on

TABLE 2 | Eligible conditions and practices for agricultural nitrogen management offset protocols.

Protocol component	ACR1	ACR2	VCS	Alberta	CAR
Eligible project locations	Global	Global	U.S.	Canadian province of Alberta	North Central Region of U.S.†
Eligible project start date	On or after 11/1/1997. Case-by-case prior.	On or after 01/1/2002.	On or after 03/1/2008. Possibly as early as 01/01/2002.	On or after 01/1/2002.	Within 6 months of the 1st day of new cultivation cycle‡.
Eligible crop(s)	Fertilized agricultural crops.	Fertilized agricultural crops.	Fertilized agricultural crops.	Fertilized agricultural crops.	Corn
N INPUT SOURCES CREDITED					
Inorganic N fertilizers	Y	Y	Y	Y	Y
Organic N fertilizers	Y	Y	Y	Y	N
Crop residue N	?	N	N	Y	N
Approved practices	May include changes in fertilizer rate, type, placement, timing, use of timed-release fertilizers, and use of nitrification inhibitors.	Adherence to regionally adapted fertilizer N best management practices (BMPs).	Adherence to BMPs related to application of synthetic and organic N fertilizers (right source-rate-time-place).	Integrated set of N best management practices-Consistent 4R Nitrogen Stewardship Plan.	Must decrease synthetic and/or organic N applied. Only synthetic N credited for emission reductions.
Regulatory surplus	Must exceed existing laws, regulations, statutes, legal rulings, or other regulatory frameworks that directly or indirectly affect GHG emissions associated with project action.		No mandatory law requiring reduced N input rate below BAU.	Emissions must not be required by law.	Must exceed federal, state, or local regulations or other legal mandates.
Other specifications pertinent to quantification	If project activity area non-homogeneous, must stratify.	Eligible crops must have been cultivated from at least 5 years prior to start date.	Encourages adoption of economically optimum N fertilizer rate.	All fields must be under project activities (4R). Accounts for all forms of N.	Encourages use of variable rate technology and other adaptive management strategies.

† The North central region includes the following states: IL, IN, IA, KS, MI, MN, MS, NE, ND, OH, SD, and WI.
‡ Also accept projects beginning on or after June 27, 2010 until Jan 2014.

TABLE 3 | Emission sources and sinks included in quantification of baseline and project N_2O emissions by protocol.

	Physical boundary and emissions sources or sinks included	Gas	ACR1	ACR2	VCS	Alberta	CAR
Baseline activity	Direct emissions from fertilizer application	CO_2	N	N	N	N	N
		CH_4	N	N	N	N	N
		N_2O	Y	Y	Y	Y	Y
	Indirect emissions from fertilizer application (Re-deposition of volatilized ammonia, N leaching, and N runoff)	CO_2	N	N	N	N	N
		CH_4	N	N	N	N	N
		N_2O	Y[†]	Y	Y	Y	Y
	Emissions from fossil fuel combustion on-site as a result of N management	CO_2	Y	N	N	Y	Y
		CH_4	Y	N	N	N	N
		N_2O	Y	N	N	Y	N
	Emissions from fertilizer production and distribution	CO_2	Y[‡]	N	N	N	N
	Soil crop dynamics[§]	CO_2	N	N	N	Y	N
		N_2O	N	N	N	Y	N
Project activity	Direct emissions from fertilizer application	CO_2	N	N	N	N	N
		CH_4	N	N	N	N	N
		N_2O	Y	Y	Y	Y	Y
	Indirect emissions from fertilizer application (Re-deposition of volatilized ammonia, N leaching, and N runoff)	CO_2	N	N	N	N	N
		CH_4	N	N	N	N	N
		N_2O	Y[†]	Y	Y	Y	Y
	Emissions from fossil fuel combustion on-site as a result of N management	CO_2	Y	N	N	Y	Y
		CH_4	Y	N	N	N	N
		N_2O	Y	N	N	Y	N
	Emissions from fertilizer production and distribution	CO_2	Y[†]	N	N	N	N
	Soil crop dynamics[§]	CO_2	N	N	N	Y	N
		N_2O	N	N	N	Y	N

[†] *The ACR1 protocol does not include N_2O emissions from runoff for quantification of indirect N_2O emissions.*
[‡] *In ACR1, emissions from fertilizer production included in quantification but emissions from fertilizer distribution are not included.*
[§] *Soil Crop Dynamics includes the emissions of CO_2 and N_2O from the cycling of soil and plant N. This includes N deposition in plant tissue (residue), decomposition of crop residues, and stabilization in organic matter.*

the crop rotation (**Table 4**). The number of crop years ranges from 2 to 5 years. The ACR1 protocol specifies five and Alberta three previous crop years. Under CAR, at least three and up to five previous crop years can be used to calculate the baseline N fertilizer rate and N_2O emissions.

Description of Sample Projects

Annual N fertilizer additions are a function of the current crop N demand, N credits from soil-residue N cycling, and inorganic N content in the soil before planting (Koenig, 2005). For this road test, existing N management literature values as well as field specific crop and N management data from the Cook Agronomy Farm Long-Term Agroecosystem Research site (CAF-LTAR), near Pullman, WA were used to develop four sample projects and quantify N_2O emission reductions under existing agricultural N management protocols. The CAF-LTAR is under annual cropping and has been direct-seeded since 1998. The soil, agronomic, and field conditions are representative of a "typical" eastern Washington Palouse landscape. The CAF-LTAR receives an average of 550-mm of precipitation and has been under various 3-year dryland cereal crop rotations. The winter wheat—spring wheat—spring legume crop rotation was used for the sample projects, and represents a typical rotation for the eastern WA region of the iPNW (Papendick, 1996; Rasmussen et al., 1998).

Emission reductions were quantified on a crop event basis and offset credits were only generated for each year the credited crop was grown and managed under project conditions. Hard red winter wheat (HRWW) and hard red spring wheat (HRSW) classes were grown in the rotation during the first 10 years of crop production at the CAF-LTAR (2001–2009) followed by soft white winter wheat (SWWW) and soft white spring wheat (2010–2017). For the field specific hard red wheat data, average yield and N fertilizer rates were calculated from the 9 years of data at CAF-LTAR. Field specific SWWW data from a 2010–2012 study at CAF-LTAR was used for SWWW calculations (Brown, 2015). The sample projects were designed to represent feasible agricultural N practices for achieving both high grain yield and optimum protein concentration under dryland conditions in southeastern Washington. It is recognized that these sample project activities represent science-based and commercially viable N fertilizer rate reduction strategies but may not represent the entire range of project circumstances that might arise in practice. To improve the general applicability of this

TABLE 4 | Quantification approaches for baseline and project emissions.

Protocol parameter	ACR1	ACR2	VCS	Alberta	CAR
BASELINE EMISSIONS					
Baseline N_2O emission calculation	Baseline emissions calculated using pre-project fertilizer management with DNDC† model	Business as usual N management. Determined from: 1. Site-specific records or 2. Derived from county-level yield data and N fertilizer guides	Business as usual N management. Determined from: 1. Site-specific records or 2. Derived from county-level yield data and N fertilizer guides	Site-specific average N Rate prior to starting project activities	Annual N rate from field records for eligible crop years
Crop Years used in baseline N rate Determination	Previous 5 years of specified crop	Monoculture: 5 years 2 year Rotation: 3 cycles (6 years) 3 Year Rotation: 2 cycles (6 years)	Monoculture: 5 years 2 year Rotation: 3 cycles (6 years) 3 Year Rotation: 2 cycles (6 years)	Previous 3 years of each crop	At least 3 and up to 5 years
Baseline data source	Unclear	Field-specific or state/county data	Field-specific or state/county data	Field specific	Field specific
PROJECT EMISSIONS					
Project N_2O emissions	Project emissions calculated using DNDC model	Reduction in N rate from business as usual on same crop as baseline	Reduction in N rate from business as usual on same crop as baseline	Emission reduction under basic, intermediate or advanced level of 4R Consistent Plan. Crop by Crop basis	Reduce N rate, emissions based on MSU-EPRI methodology
Leakage‡	Considered zero as long as: Yield does not decline more than 5% on project lands; No increase in N fertilizer use on lands outside project boundary	Leakage considered negligible for project activities§	Leakage considered negligible for project activities§	Must account for increased emissions from project activities that increase trips across field (e.g., split N)	If yields significantly reduced on project land, must account for N_2O, CO_2, and CH_4 emission increases from shifted production on non-project lands

† *DNDC is the Decomposition and Denitrification biogeochemical process model (Li, 2000).*
‡ *Leakage is when a project action results in an increase in GHG emission or decrease in sequestration outside of the project boundary but as a result of project activities.*
§ *No reduction in crop productivity is expected to result from project activities. Thus, negative leakage from increased N fertilizer applied to non-project lands is not anticipated leading to a protocol specified assumption of negligible leakage potential.*

project, the N_2O emission results were reported on a land area basis (i.e., per hectare basis).

Sample Projects 1 through 3: Switch from Uniform to Variable Rate N Application

For SWWW under sample project 1, we assumed that site specific N management could, on average, result in a 25 kg N ha^{-1} decrease in N fertilizer rate compared to uniform N management without decreasing yield (Mulla et al., 1992; Fiez et al., 1994a; Huggins, 2010; Taylor, 2016). For HRWW and HRSW under sample projects 2 and 3, we assumed that site specific N management could, on average, result in a 10 and 20 kg N ha^{-1} decrease in N fertilizer rate compared to uniform N management without decreasing yield or grain protein concentration, respectively (Huggins, 2010). The mean N rate reduction under all wheat classes in sample project 1 were considered a realistic N rate decrease that could be achieved by variable rate (VR) N management and also likely acceptable to farmers. However, these N rate decreases were likely to be most appropriate and less risky only in low-yield management zones only rather than the entire field (Huggins, 2010; Taylor, 2016). Increased N rates in high-yielding zones were not expected to negate N rate reductions in low-yielding zones as greater N mineralization under favorable conditions would likely supply greater N to meet a higher crop N demand under this circumstance. Low-yielding areas were assumed to cover ∼30% of a field to allow for scaling GHG offsets to the field-scale (i.e., 30% of the 37 ha CAF-LTAR). This number could be adjusted to match field-specific knowledge or historical yield data.

Sample Project 4: N Rate Reductions from Split N Application

Under sample project 2, we assumed that split N application in SWWW could reduce overall N rates by 40 kg N ha^{-1} compared to all fall N application without decreasing yield (Sowers et al., 1994; Huggins, 2010). To date, no consistent N rate reductions have been observed under split N application for HRSW, though in 1 year an N savings of 19 kg N ha^{-1} was observed by Huggins (2010). There was concern that the mean N rate reduction under sample project 4 may be greater than what would be acceptable to farmers but the N rate decrease from split N application was considered applicable across the entire field rather than just the low-yielding areas as in sample projects 1 through 3.

Summary of Sample Projects

Sample Project 1 (SWWW-VR):

Wheat Class—soft white winter wheat.
N Management Activity—switch from uniform N to variable rate N fertilizer application.
Project N Fertilizer Rate Reduction Compared to Baseline—25 kg N ha^{-1}

Sample Project 2 (HRWW-VR):

Wheat Class—hard red winter wheat
N Management Activity—switch from uniform N to variable rate N fertilizer application.
Project N Fertilizer Rate Reduction Compared to Baseline—10 kg N ha^{-1}

Sample Project 3 (HRSW-VR):

Wheat Class—hard red spring wheat.
N Management Activity—switch from uniform N to variable rate N fertilizer application.
Project N Fertilizer Rate Reduction Compared to Baseline—20 kg N ha^{-1}

Sample Project 4 (SWWW-Split N):

Wheat Class—soft white winter wheat.
N Management Activity—switch from an all fall N fertilizer application to split applying N fertilizer between the fall and spring.
Project N Fertilizer Rate Reduction Compared to Baseline—40 kg N ha^{-1}

Evaluating Quantification Approaches

Impact of Data Source for Baseline Emissions

Offset quantification methodologies also specify approved data sources for calculating baseline emissions. Field specific data is required under the Alberta and CAR quantification methodologies. The ACR2 and VCS protocols provide the option of using field specific data or county level data to determine the baseline N rate contributing to baseline N_2O emissions. Baseline fertilizer N rates calculated from county level data required a yield goal estimate calculated from county level yield records available from the USDA-National Agricultural Statistics Service (USDA-NASS, 2007–2010) and yield-goal based N recommendations obtained from regional fertilizer guides (e.g., Koenig, 2005). Two years of county level yield data for winter wheat were obtained from 2007 to 2010 and for spring wheat from 2008 to 2011 yield data (Brown, 2015). The winter and spring wheat years for county level data were chosen to reflect the two most recent years that those crops were grown in the rotation used at CAF-LTAR for sample project scenarios as specified in ACR (American Carbon Registry, 2012). We compare the implications of each data source on the overall emission reduction estimate.

Impact of Emission Factor for Direct N_2O Emissions

The default direct and indirect emission factors for calculating N_2O emissions from fertilizer N application to a project field are specified in each offset protocol (**Table 5**). Generally, direct emission factors are determined by geographic location, crop, and the level of existing peer-reviewed literature available. Where regional peer-reviewed data is lacking for a crop or cropping system, Intergovernmental Panel on Climate Change (IPCC) methodology is the default for estimating N_2O emissions (Tier I). The IPCC default emission factor is that 1% of N fertilizer applied is lost as direct N_2O emissions from the field. The IPCC default indirect N_2O emission factors for volatilization and leaching are 0.1 and 0.75%, respectively (**Table 5**). Limited regional data

TABLE 5 | Comparison of approaches for calculating direct† and indirect N_2O emissions.

Emission source/sink	ACR1	ACR2‡	VCS§
DIRECT N_2O FROM FERTILIZER			
Method 1	DNDC	1- MSU-EPRI eqn.	1- 0.01 IPCC Tier I
Method 2		2- 0.01 IPCC Tier I	2- MSU-EPRI eqn.
Method 3		3- IPCC Tier II	
Indirect N_2O Emissions		2006 IPCC guidelines	
VOLATILIZATION WITH SUBSEQUENT RE-DEPOSITION			
Fraction of synthetic N fertilizer volatilized		0.10	
Emission factor for N_2O emission from atmospheric deposition of volatilized N on soil and water surfaces		0.01	
LEACHING AND RUNOFF			
Fraction of synthetic N fertilizer leached		0.30	
Emission factor for N_2O emission from N leaching and runoff		0.0075	

†*Direct N_2O emission factors are used to quantify the amount of N_2O emitted as a result of the amount of N fertilizer applied to a project field. Methods differ by protocol but IPCC Tier II considered a generally accepted and Tier II an empirically derived emission factor.*

‡*For ACR2 (2010), The ACR2 has three project categories for specifying the direct N_2O emission factor to be used. Method one uses a Tier II direct emission factor equation (MSU-EPRI equation, Millar et al., 2010) that is specific to the corn crop portion of a row crop system located in the 12 North Central Region states of the USA (Category 1). Method two uses a Tier I direct emission factor applied to fertilized agricultural crops worldwide and must be demonstrated as conservative (Category 2). Method three applies to all non-corn fertilized crops worldwide and uses project-specific Tier II direct emission factors from peer-reviewed sources that must be conservative and approved by ACR experts (Category 3).*

§*For Verified Carbon Standard (2013), Direct emission factor depends on US state where project activity occurs and other cropping system requirements. Method 1 uses a Tier I emission factor for all fertilized crops within the US. Method 2 applies to corn in row crop systems within the 12 North Central Region states.*

DNDC, Denitrification and Decomposition model (DNDC) derived emissions (Li, 2000).

showed that the direct emission factor for PNW cropping systems may be much lower than the 1% emission factor used under IPCC Tier I methodology. A Tier II approach was evaluated using a direct emission factor of 0.2% for the PNW (Cochran et al., 1981; Yorgey and Kruger, 2015) and compared to the Tier I factor of 1% across the four sample projects to highlight how regional values would impact the magnitude of mitigation potential for the iPNW.

RESULTS

PNW Relevant Protocols for Agricultural N Management Offset Credits

Based on the regional scope of each program, only three of the five quantification protocols for agricultural N_2O emission offsets could be used to quantify voluntary offsets for the PNW (**Table 1**). Those were ACR1, ACR2, and VCS. However, the ACR1 specified use of the Denitrification and Decomposition (DNDC) model for quantification of baseline and project emissions and was not used as the expertise needed to complete the model N_2O emission quantification was found to be outside the scope of this project (Li, 2000). Emission reductions were quantified for the sample projects using only the ACR2 and VCS protocols as they were found to be the most applicable and appropriate for PNW wheat-based agriculture. No GHG offset projects for agricultural N management had been registered under ACR, CAR, or VCS at the time this research was completed (**Table 1**). However, VCS had the largest number of other GHG projects registered (1,409 projects; ∼200 million metric tons CO_2e offsets issued) followed by CAR (479 projects; ∼87 million metric tons CO_2e offsets issued), Alberta (229 projects, ∼118 million metric tons CO_2e offsets issued), and ACR (216 projects; ∼81 million metric tons CO_2e offsets issued) (**Table 1**).

Sources and Sinks Included in Emission Quantification

There were differences among the protocols as to the N fertilizer sources credited under the offset quantification methodology (**Table 2**). The ACR, VCS, and Alberta protocols issue emission offset credits for N rate reductions from both inorganic and organic N sources. Under CAR, the N rate reduction included both synthetic and organic N sources but only synthetic N fertilizer source reductions could be credited for N_2O emission reductions. The Alberta protocol was unique in that quantification of N inputs from crop residue decomposition were included (**Table 2**). Approved N management practices in the N_2O offset protocols reviewed differed among protocols but generally appeared to encourage adoption of precision agriculture principles and use of N fertilizer stabilizer technology (e.g., nitrification inhibitors) (**Table 2**). Differences in eligible project start dates may have implications for driving innovation and adoption of GHG reduction techniques or technologies but did not appear to impact offset quantification. There were also some differences in regulatory surplus requirements among protocols. However, our projects were not designed to focus on these parameters.

The emission sources included in calculating N_2O emission reductions from project activities differed among protocols (**Table 3**). On-site fossil fuel emissions were included in the ACR1, Alberta, and CAR protocols. The ACR2 and

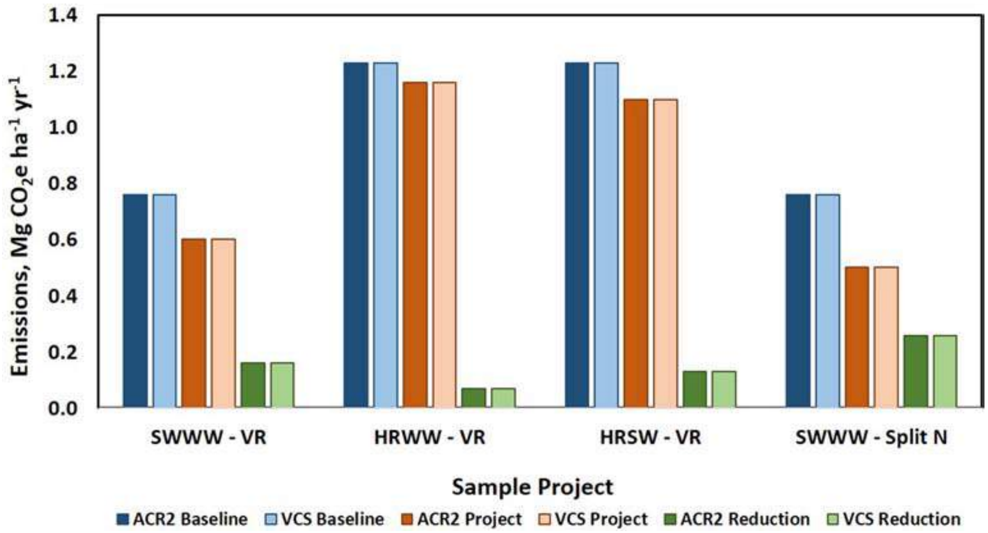

FIGURE 2 | Baseline, Project, and Offset (Reduction) Emissions by American Carbon Registry (ACR2) and Verified Carbon Standard (VCS) Protocols. For quantification used field scale data from Cook Agronomy Long-term Agroecosystem Research Farm, IPCC Tier I direct emission factors, and IPCC default indirect emission factors to determine N_2O emission reductions from management changes for: SWWW-VR, soft white winter wheat uniform to variable rate N (Sample Project 1); HRWW-VR, hard red winter wheat uniform to variable rate N (Sample Project 2); HRSW-VR, hard red spring wheat uniform to variable rate N (Sample Project 3); and SWWW-Split N from all fall to split N application between fall and spring (Sample Project 4).

VCS quantification methodologies did not include any fossil fuel combustion emissions from N management, fertilizer production and distribution, or soil crop dynamics. The ACR1 protocol included CO_2, CH_4, and N_2O from on-site fossil fuel combustion. The Alberta protocol included CO_2 and N_2O from on-site fossil fuel combustion during N management as well as the inclusion of CO_2 and N_2O emissions from soil crop dynamics. The CAR protocol included only CO_2 from fossil fuel combustion. The ACR1 protocol was the only methodology to include CO_2 emissions from N fertilizer production though it did not include N fertilizer distribution emissions. Another difference among protocol quantification methodologies was the exclusion of indirect N_2O emissions from runoff in the ACR1 protocol. The other four protocols included indirect N_2O from N runoff as well as N_2O emissions from re-deposition of volatilized N and N leaching.

Additional to Business as Usual

Overall, the protocols differed slightly in the number of years of historical crop data used to calculate the baseline N fertilizer rate (**Table 4**). In our study, we used three historical crop years for baseline quantification given the 3-year crop rotation at CAF-LTAR, as specified in the ACR2 and VCS protocols (**Table 4**). However, the number of crop years to calculate baseline N fertilizer rate and N_2O emissions ranged among the protocols from 2 to 5 years (**Table 4**). The ACR1 protocol specified 5 and Alberta 3 previous crop years. Under CAR, at least 3 and up to 5 previous crop years could be used to calculate baseline N fertilizer rate and subsequent baseline N_2O emissions.

Differences in the approved data sources for calculating baseline N_2O emissions were also observed (**Table 4**). Field specific data was required under the Alberta and CAR quantification methodologies. For ACR2 and VCS, baseline N fertilizer rate can be calculated using one of two approaches. One approach relied on field specific N application records from the project field for the specified number of crop years prior to the project (**Table 4**). The other approach utilized county level data to estimate N application rates for the specified number of crop years prior to the project. The number of crop year data for calculating the average yield goal for the county level estimate of baseline emissions was the two most recent years since the project scenarios were developed assuming a three-year crop rotation (**Table 4**).

N_2O Emissions by Protocol and Baseline Approach

The ACR2 and VCS protocols had identical baseline and project emission quantification methodologies (e.g., using the same default factors for direct and indirect emissions). This resulted in the same baseline, project, and emission reduction values under the two protocols for all four sample projects (**Figure 2**) with no differences observed between these protocols for the sample projects considered. Reducing N fertilizer application rate by switching to variable rate N (sample projects 1-3) or split N application (sample project 4) management resulted in an estimated N_2O emission reduction of 0.16, 0.07, 0.14, and 0.26 Mg CO_2e ha^{-1} for SWWW-VR, HRWW-VR, HRSW-VR, and SWWW-Split N sample projects, respectively. Variable rate N management for HRWW (sample project 2) resulted in the least amount of emission offsets compared to variable rate N under SWWW or HRSW (**Figure 3**). The highest N_2O emission reduction from N management project activities was observed

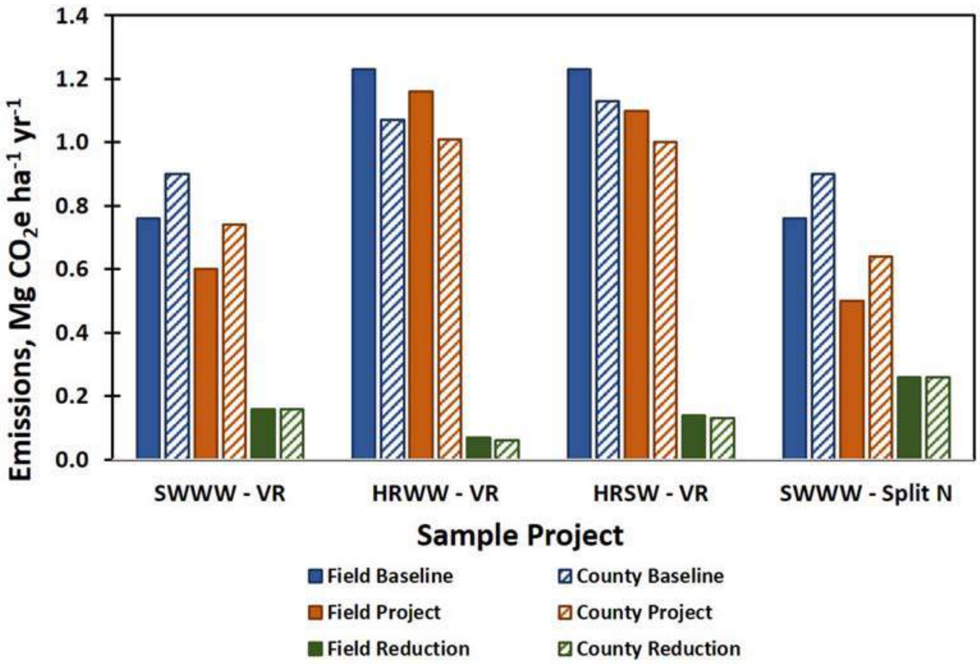

FIGURE 3 | Comparison of Baseline, Project and Offset (Reduction) Emissions Using Field Specific or County Level Data to Determine Baseline Emissions. American Carbon Registry Quantification Methodology, Tier I IPCC direct emission factor and IPCC default indirect emission factors used. Field specific N application records from CAF-LTAR were used to determine N_2O emission reductions from management changes for: SWWW-VR, soft white winter wheat uniform to variable rate N (Sample Project 1); HRWW-VR, hard red winter wheat uniform to variable rate N (Sample Project 2); HRSW-VR, hard red spring wheat uniform to variable rate N (Sample Project 3); and SWWW-Split N from all fall to split N application between fall and spring (Sample Project 4).

under split N application in SWWW. The highest emission reductions occurred where the greatest N rate reductions were estimated from the literature and decreased by sample project accordingly: SWWW-Split N (40 kg N ha^{-1} reduction) > SWWW-VR (25 kg N ha^{-1} reduction) > HRSW-VR (20 kg N ha^{-1} reduction) > HRWW-VR (10 kg N ha^{-1} reduction) (**Table 6**).

Approaches for Quantifying Baseline N_2O Emissions

The approach used in determining baseline N_2O emissions impacted the quantity of baseline emissions and hence relative magnitude of N_2O emission reductions from project activities (**Figure 3**). The difference in baseline N_2O was more pronounced for the sample projects with SWWW compared to the sample projects with HRWW and HRSW. Using county level yield data to estimate the baseline N fertilizer application for SWWW in sample projects SWWW-VR and SWWW-Split N resulted in baseline emissions of 0.90 Mg CO_2e ha^{-1} compared to 0.76 Mg CO_2e ha^{-1} using historical field N application records. The county level estimated N fertilizer rate resulted in HRWW baseline emissions of 1.07 Mg CO_2e ha^{-1} and HRSW of 1.13 Mg CO_2e ha^{-1} compared to 1.23 Mg CO_2e ha^{-1} using historical field N application records (**Figure 3**). This was due to using 2 years of county level data for a yield goal based N fertilizer recommendation rate that resulted in a higher baseline N fertilizer rate for the SWWW in sample projects SWWW-VR and SWWW-Split N (0.139 Mg N ha^{-1}) and a lower baseline N fertilizer rate for sample projects HRWW-VR and HRSW-VR of 0.166 and 0.175 Mg N ha^{-1}, respectively (**Table 6**). This was compared to historic field specific N rates of 0.118, 0.191, 0.191, and 0.118 Mg N ha^{-1} for the different wheat in sample projects SWWW-VR, HRWW-VR, HRSW-VR, and SWWW-Split N, respectively (**Figure 3**).

N_2O Emissions Using Tier I vs. Tier II Direct Emission Factors

All four of the protocols reviewed did not have N_2O emission factors specific to iPNW wheat-based cropping systems. The ACR2 and VCS protocols specify a Tier II emission factor equation to be used for direct N_2O emissions from N fertilizer additions to corn crops in row crop agriculture within the 12 North Central Region states (Millar et al., 2010), with remaining agricultural crops defaulting to the IPCC Tier I emission factor (**Table 5**). This means that IPCC Tier I default factors must be used to calculate emission reductions from sample project activities (i.e., 1% of nitrogen fertilizer rate lost as N_2O) since no other Tier II equations have been accepted for other crops. However, limited regional data showed that the direct emission factor for iPNW cropping systems may

TABLE 6 | Direct and indirect emissions for baseline and project conditions under different baseline and direct N_2O emissions quantification methodologies.

Quantification	Sample project†							
	SWWW-VR	HRWW-VR	HRSW-VR	SWWW-Split	SWWW-VR	HRWW-VR	HRSW-VR	SWWW-Split
	NITROGEN FERTILIZER RATE, Mg N ha^{-1} yr^{-1}							
	Field specific N rate data				County level yield goal based N rate			
Baseline N rate	0.118	0.191	0.191	0.118	0.139	0.166	0.175	0.139
Project N rate	0.093	0.180	0.170	0.077	0.114	0.156	0.155	0.099
N rate reduction	0.025	0.010	0.020	0.040	0.025	0.010	0.020	0.040
	EMISSIONS REDUCTION RATE‡, Mg CO_2e $ha^{-1}yr^{-1}$							
	Tier I emission factor				Tier II emission factor			
BASELINE EMISSIONS								
Direct	0.57	0.93	0.93	0.57	0.11	0.19	0.19	0.11
Indirect	0.19	0.30	0.30	0.19	0.19	0.30	0.30	0.19
Baseline total	0.76	1.23	1.23	0.76	0.30	0.19	0.19	0.30
PROJECT EMISSIONS								
Direct	0.45	0.88	0.83	0.38	0.09	0.18	0.17	0.08
Indirect	0.15	0.28	0.27	0.12	0.15	0.28	0.27	0.12
Project total	0.60	1.16	1.10	0.50	0.24	0.46	0.43	0.20
N_2O emissions reduction	0.16	0.07	0.14	0.26	0.06	0.03	0.05	0.10

†Sample Projects represent emission reductions using field specific N application data for SWWW-VR: soft white winter wheat uniform to variable rate N (Sample Project 1); HRWW-VR: hard red winter wheat uniform to variable rate N (Sample Project 2); HRSW-VR: hard red spring wheat uniform to variable rate N (Sample Project 3); and SWWW-Split N from all fall to split N application between fall and spring (Sample Project 4).
‡A megagram (Mg) is equivalent to a metric ton (t).

be much lower than the IPCC Tier I methodology default (Cochran et al., 1981; Yorgey and Kruger, 2015). Using a Tier II approach and assuming a direct emission factor of 0.2% of the N fertilization rate for wheat resulted in the generation of offset credits that were 2.3–2.8 times lower compared to the Tier I emission factor (**Figure 4**). Emission reductions using the Tier I direct emission factor of 1% resulted in a 0.16, 0.07, 0.14, and 0.26 $MgCO_2e$ ha^{-1} yr^{-1} emission reductions for SWWW-VR, HRWW-VR, HRSW-VR, and SWWW-Split N sample projects, respectively. In comparison, Tier II emission reductions using a direct emission factor of 0.2% resulted in a 0.06, 0.03, 0.05, and 0.10 Mg CO_2e ha^{-1} yr^{-1} reduction in N_2O emissions for sample projects SWWW-VR, HRWW-VR, HRSW-VR, and SWWW-Split N, respectively. Interestingly, for this analysis only the direct emissions changed and the default indirect emissions remained the same for each sample project (**Table 6**).

Market Size for Washington State

Field-scale emission reductions in this study, using the CAF-LTAR, were 1.18, 0.71, 1.42, and 9.55 Mg CO_2e yr^{-1} under Tier I as compared to 0.70, 0.31, 0.59, and 3.88 Mg CO_2e yr^{-1} under Tier II for sample projects SWWW-VR, HRWW-VR, HRSW-VR, and SWWW-Split N, respectively (**Table 7**). The potential revenue that could be generated per hectare from reducing N_2O emissions through agricultural N management offset projects in the higher precipitation zone of the dryland PNW are shown in **Table 7**. Sample project four, SWWW-Split N, had the highest per hectare payment incentive followed by sample projects SWWW-VR, HRSW-VR, and HRWW-VR (**Table 7**). At a carbon price of \$10 per $MgCO_2e$, offset credits generated would be worth \$1.60, \$0.70. \$1.30, and \$2.60 ha^{-1} yr^{-1} for sample projects SWWW-VR, HRWW-VR, HRSW-VR, and SWWW-Split N, respectively.

The monetary incentive was substantially increased when the cost savings on N fertilizer was included with the offset payment incentive (**Table 8**). At average anhydrous ammonia prices for 2006–2011, the N fertilizer cost savings that could be added to the GHG offset credit incentive was \$21, \$9, \$18, and \$35 ha^{-1} yr^{-1} for sample projects SWWW-VR, HRWW-VR, HRSW-VR, and SWWW-Split N, respectively (**Table 8**). This creates a payment incentive that ranges from \$9 to \$48 ha^{-1} yr^{-1} under Tier I and \$9 to \$40 ha^{-1} under Tier II methodologies across all carbon prices. Though still relatively small, the direct N_2O emission factor had a considerable effect on the overall monetary incentive from N_2O emission reduction offset credits.

In 2011, there were ~630,000 hectares of SWWW, 86,000 hectares of HRWW, and 124,000 hectares of HRSW grown in WA State (United States Department of Agriculture, National Agricultural Statistics Service (USDA-NASS), 2011). This would result in an estimated potential annual carbon offset market size of 10.1, 0.6, 1.6, and 16.4 Gg CO_2e yr^{-1} for SWWW-VR, HRWW-VR, HRSW-VR, and SWWW-Split N sample projects,

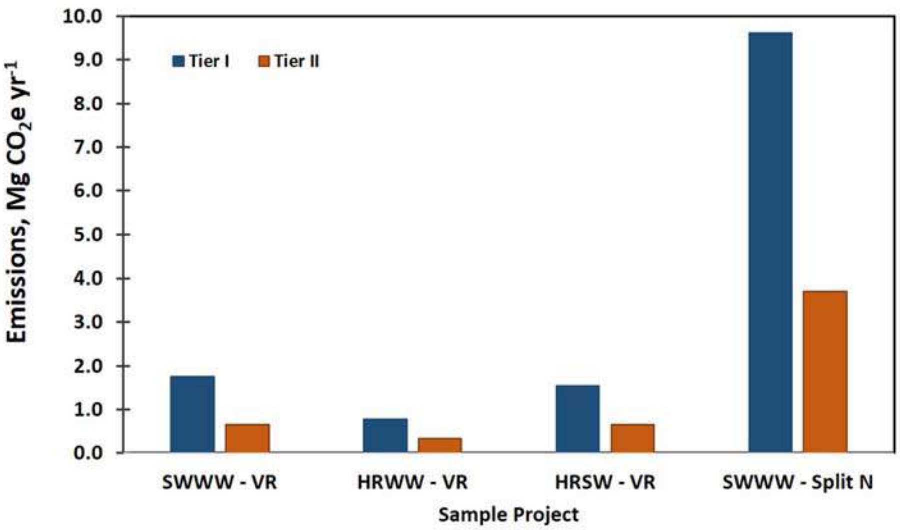

FIGURE 4 | Offset Credits for Project Activities under Tier I and Tier II Direct N_2O Emission Factors. The IPCC Tier I default of 1% (blue) and potential Tier II emission factor of 0.2% (orange) of N fertilizer applied. The IPCC default indirect emission factors were used. Data represent field specific N application data from CAF-LTAR for sample projects. The American Carbon Registry Quantification Methodology was used to determine N_2O emission reductions from management changes for: SWWW-VR, soft white winter wheat uniform to variable rate N (Sample Project 1); HRWW-VR, hard red winter wheat uniform to variable rate N (Sample Project 2); HRSW-VR, hard red spring wheat uniform to variable rate N (Sample Project 3); and SWWW-Split N from all fall to split N application between fall and spring (Sample Project 4).

TABLE 7 | Nitrous oxide emission reduction potential and offset credit incentive for the agricultural N management sample projects[†].

Sample project scenario by direct emission factor	N_2O emission reduction rate[†]	Total area[‡]	Total potential emissions reduction	Per area monetary incentive for N_2O emission reductions by offset price		
	$Mg\ CO_2e\ ha^{-1}\ yr^{-1}$	ha	$Mg\ CO_2e\ yr^{-1}$	$\$\ ha^{-1}\ yr^{-1}$		
				Price per Mg CO_2e		
				$5	$10	$50
TIER I DEFAULT (1%)[§]						
1: SWWW-VR	0.16	11	1.18	0.80	1.60	8.00
2: HRWW-VR	0.07	11	0.71	0.35	0.70	3.50
3: HRSW-VR	0.14	11	1.42	0.65	1.30	6.50
4: SWWW-Split N	0.26	37	9.55	1.30	2.60	13.00
TIER II REGIONAL (0.2%)						
1: SWWW-VR	0.06	11	0.70	0.30	0.60	3.00
2: HRWW-VR	0.03	11	0.31	0.15	0.30	1.50
3: HRSW-VR	0.06	11	0.59	0.30	0.60	3.00
4: SWWW-split N	0.10	37	3.88	0.50	1.00	5.00

[‡] *Emission reductions calculated using field specific N fertilization data and the total area (37 ha) from the Cook Agronomy Farm Long-term Agroecosystem Cropping System Research (LTAR). A megagram (Mg) is equivalent to a metric ton (t).*
[‡] *N rate reductions from variable rate for projects 1 through 3 are only expected in low yielding areas which represent 30% of the total field area (i.e., 30% of 37 ha=11 ha).*
[§] *Tier 1 direct emission factor is 1% and regional emission factor is 0.2% of N fertilizer applied to agricultural soil is lost as N_2O.*

respectively, if 10% of the crop land acreage for the market class was under the sample project N management (**Table 9**). Greater emission reductions could be achieved with greater adoption of sample project N management with as much as 82 Gg $CO_2e\ yr^{-1}$ generated by sample project SWWW-Split N under a fifty percent adoption on soft white winter wheat acreage.

DISCUSSION

Review of Agricultural N Management Protocols: Components and Relevance to iPNW

Consistency across GHG protocols for quantifying voluntary offset credits is needed to provide high quality offset credits

TABLE 8 | Including the fertilizer cost savings for calculating the offset credit incentive for the agricultural N management sample projects that reduce N_2O emissions.

Sample project scenario by direct emission factor	N_2O emission reduction rate[†]	Monetary incentive for N_2O emission reductions			Average expected fertilizer cost saving[‡]	Total Monetary incentive (N_2O offset Credit + N fertilizer cost savings)[§]		
	$Mg CO_2e ha^{-1} yr^{-1}$	$\$ ha^{-1} yr^{-1}$			$\$ ha^{-1}$	$\$ ha^{-1} yr^{-1}$		
		Price per $Mg CO_2e$				Price per $Mg CO_2e$		
		$5	$10	$50		$5	$10	$50
TIER I DEFAULT (1%)[¶]								
1: SWWW-VR	0.16	0.80	1.60	8.00	21	22	23	29
2: HRWW-VR	0.07	0.35	0.70	3.50	9	9	9	12
3: HRSW-VR	0.14	0.65	1.30	6.50	18	18	19	24
4: SWWW-Split N	0.26	1.30	2.60	13.00	35	36	38	48
Tier II REGIONAL (0.2%)								
1: SWWW-VR	0.06	0.30	0.60	3.00	21	22	22	24
2: HRWW-VR	0.03	0.15	0.30	1.50	9	9	9	10
3: HRSW-VR	0.06	0.30	0.60	3.00	18	18	18	21
4: SWWW-Split N	0.1	0.50	1.00	5.00	35	36	36	40

[†] *N rate reductions from variable rate for projects 1 through 3 are only expected in low yielding areas which represent 30% of the total field area (i.e., 30% of 37 ha).*
[‡] *Based on average anhydrous ammonia costs from 2006 to 2011 of \$763 ton^{-1} or \$0.87 ha^{-1} (Brown, 2015).*
[§] *Data from Enterprise budgets developed by Painter for 2009, 2011, and 2012 crop years.*
[¶] *Tier 1 direct emission factor is 1% and regional emission factor is 0.2% of N fertilizer applied to agricultural soil is lost as N_2O.*

TABLE 9 | Total potential annual emission reductions for Washington state under different n management adoption scenarios for each sample project using 2011 Washington Wheat Facts (Washington Wheat Commission, 2011).

Sample project	Emission reduction	Total area in wheat for WA in 2011	Total potential emissions reduction	Emission reduction for WA state under adoption scenarios on total hectares, $Mg CO_2e yr^{-1}$		
	$Mg CO_2e ha^{-1}yr^{-1}$	ha	$Mg CO_2e yr^{-1}$	% of area adopting N management		
				10	25	50
1: SWWW-VR	0.16	630,059	100,809	10,081	25,202	50,405
2: HRWW-VR	0.07	86,346	6,044	604	1,511	3,022
3: HRSW-VR	0.13	123,991	16,119	1,612	4,030	8,059
4: SWWW-Split N	0.26	630,059	163,815	16,382	40,954	81,908

and develop large-scale offset markets that support practical climate policy solutions (Kollmuss et al., 2010; Erikson and Lazarus, 2013; Lee et al., 2013). Methodologies for quantifying N_2O emissions reductions have been developed for agricultural N management, but key elements within available protocols need to be reviewed periodically. Evaluating existing protocols for GHG emission reductions from agricultural N management applicable to iPNW wheat cropping systems illustrated differences in policy and technical approaches to quantifying N_2O emission reductions. Differences in eligible conditions, boundaries for baseline, project and leakage activities, and the data and default values for emission reduction quantification observed across the five agricultural N management protocols in this study have been observed in protocol reviews for other project types (Kollmuss et al., 2010; Lee et al., 2013). Identifying the nature of GHG program or protocol differences will be critical to developing appropriate policy tools and ensuring consistency in the quantity and quality of each offset ton generated by a project and entering the carbon market (Erikson and Lazarus, 2013; Lee et al., 2013).

Overall, the eligible N management practices required to achieve the performance levels in the ACR1, ACR2, VCS, Alberta, and CAR protocols aligned with implementing the principles of precision agriculture including improved prediction of crop N demand and enhanced N use efficiency. Precision N fertilizer management (otherwise known as variable rate) has been considered one of the most practical strategies for improving agricultural N-use efficiency and reducing N loss to unintended portions of the environment (Cassman et al., 2002; Robertson and Vitousek, 2009). Adoption of precision N management has been slow in the US (Cassman et al., 2002) and especially in the iPNW (Pan et al., 2007; Huggins, 2010). Participation in carbon markets could enhance adoption of innovative precision N management that is practical, economically feasible, and capable of feeding a growing world population. One insight from this review was inconsistency in specifying approved N management practices. From a policy standpoint, protocols that refer project developers to state best management practices (i.e., ACR2 and VCS) were less clear on approved N management practices compared to other protocols that specified N fertilizer rate reducing actions. However, there appeared to be sufficient performance outcome specificity (i.e., reduce N rate below baseline) that less defined management practices might be critical in supporting grower driven on-farm innovations in reducing N fertilizer rates.

Another key finding from this research was that the fossil fuel emissions, excluded in the ACR2 and VCS protocols, could be an important, but relatively small source of GHG emissions under currently approved project activities if N fertilizer management changes result in increased fossil fuel consumption (e.g., more trips across the field for split application of N). Exclusion of emissions from fertilizer production and distribution under ACR2 and VCS protocols were also noted and could potentially be a large source of GHG emissions. However, such source or sink exclusions in the ACR2 and VCS methodologies could be justified as increasing the conservativeness of the project. These exclusions would be expected to create differences in the quantity and quality of offsets generated across protocols. Carbon sequestration was not included in any of the protocols reviewed because N fertilizer rate reductions were not expected to impact soil C stocks and would further increase the conservativeness of the N_2O offset quantification (American Carbon Registry, 2012; Millar et al., 2012).

Differences in the approved data sources for calculating baseline N_2O emissions observed could result in different baseline N_2O emissions which impact the magnitude of offsets generated by a project. Differences in the number of pre-project crop years used to quantify baseline N_2O emissions would be expected to result in different emission reductions among the five protocols. Currently relevant protocols (ACR2 and VCS) did not have emission factors specific to iPNW wheat cropping systems. We also observed that using IPCC Tier I default methodology may dramatically over-estimate gross N_2O emissions. The ACR2 and VCS protocols generated identical emission reduction offsets limiting the ability to determine the impact of differences in quantification methodologies. However, the lack of consistency across sources and sinks and in default factors across all five protocols could contribute to inequities in offset credits generated under the different programs. Ensuring each "ton is a ton" across offset programs requires better congruency among quantification approaches in approved protocols (Lee et al., 2013). This could be investigated in future efforts by relaxing location eligibilities and running the road test on all existing agricultural N management protocols (e.g., Alberta protocol).

Quantify N_2O Emission Reductions under Applicable Protocols using Sample Projects

The emission reductions in this road test, ranging from 0.07–0.26 Mg CO_2e ha^{-1} yr^{-1}, were at the lower end reported by Eagle et al. (2012) but similar to those reported by Millar et al. (2010) for Midwest corn using linear direct emission factors. Nitrous oxide emission reductions from agricultural N management have been estimated to potentially provide voluntary GHG offsets on the order of 0.2–0.6 and 0.09–0.15 Mg CO_2e ha^{-1} yr^{-1} in Eagle et al. (2012) and Millar et al. (2010), respectively. In this study, project N rate reductions of 21, 6, 11, and 35% of the baseline for SWWW-VR, HRWW-VR, HRSW-VR, and SWWW-Split N sample projects, respectively, were considered feasible N rate reductions as generated from the literature for variable or split as compared to uniform or all fall N management. Specifically, the N rate reduction at this level seemed appropriate without contributing to a reduction in crop yields (CAST, 2004; Millar et al., 2010; Eagle et al., 2012).

Impact of Quantification Approaches on Offsets Generated

Quantification of sample project emissions in this study, following the work of Lazarus et al. (2010) and Lee et al. (2013), improved understanding of the differences in agricultural N management protocols and subsequent implications in the generation of GHG offsets for the carbon market. The results of this study highlighted the value of regionally applicable protocols for quantifying emissions and emission reductions. Historical and current research show that the direct emission factor for Washington cropping systems may be much lower than 1% of N fertilizer additions used under IPCC Tier I methodology. The IPCC methodology recognizes that the 1% of N fertilizer rate emission factor for direct N_2O emissions may be good for global inventories but not for quantifying regional N_2O emissions (Intergovernmental Panel on Climate Change, 2006). In addition, an earlier study in the iPNW showed that N_2O emissions were not a linear function of N rate as is assumed using IPCC Tier I methodology (Cochran et al., 1981). Under the IPCC methodology, the direct and indirect emissions from application of N fertilizer to agricultural soils are calculated according to a three tier approach (Intergovernmental Panel on Climate Change, 2006). As quantification methods move from a Tier I to Tier III emission factor approach, the uncertainty in the emission quantification is reduced (i.e., improved accuracy). This is a result of better accounting for regional differences in environmental conditions and management practices (Intergovernmental Panel on Climate Change, 2006). However, determination of emission factors under the Tier II and Tier III approaches are more complex and expensive to determine (Bracmort, 2011).

The review and road test of current agricultural N management protocols showed that some improvements could be made to ensure quantification approaches are applicable to more regions, and in particular for the iPNW dryland wheat-based cropping systems. Development of an iPNW focused agricultural N management protocol should utilize an agroecological zone approach (Huggins et al., 2014) in developing regional emission factors and evaluating GHG emission reductions from project activities to better reflect local conditions and management practices. This could be informed by the Ecodistrict approach used in the Alberta protocol (Alberta Environment, 2010). In addition, the Alberta protocol offered three performance levels within the Consistent 4R Nitrogen Stewardship Plan: basic, intermediate, and advanced with a greater amount of field variability addressed and more complex BMPs adopted as a participant moves to the intermediate and advanced levels. New N management protocols can be submitted to these programs to improve applicability to regional or cropping system specific conditions. New protocols must be reviewed and approved before they can be used under a program. Nevertheless, as discussed here, given the relatively small economic incentive offsets are likely to provide iPNW wheat farmers, further protocol revisions may not seem worthwhile. However, for other practice-based incentives these iPNW-specific quantification approaches, as well as some parameters from the offset protocols, could serve as the basis for payments or proactive accounting of ecosystem services provided by agricultural BMPs.

The accuracy of emission reductions for the iPNW could also be improved through development of regional emission factors (Tier II or Tier III) and might be achieved through field measurements or employing existing biophysical models, such as CropSyst (Stockle et al., 2012), and assessment frameworks, such as BioEarth (Adam et al., 2014). However, lower input models (e.g., COMET-Farm) rather than high input process-based models (e.g., CropSyst, DNDC) would likely reduce transaction costs associated with project development and verification (Li, 2000; Stockle et al., 2012). In particular, the relationship between N rate and N_2O emissions should be considered in developing accurate emission factors if quantification methodologies continue to estimate N_2O emissions based on N fertilization rate.

An N_2O emission reduction protocol for the iPNW would be strengthened by including additional performance metrics such as the nitrogen-use efficiency metric used in the CAR (Climate Action Reserve, 2012) protocol [Removed to Applied (RTA) = N removed/N applied]. This may be added as a monitoring requirement only or implemented as a performance standard in addition to N fertilizer rate reduction. The performance could require an improvement in nitrogen-use efficiency over the baseline nitrogen-use efficiency. This would also improve the ability of project developers and climate policy to avoid crop yield reductions in more efficient agroecosystems and thus reduce leakage of emissions from these type of management efforts (Eagle et al., 2012). In addition, decision support to understand the conditions under which precision N management actually reduces N rate without reducing yield is needed. This is especially important for managing the economic risk of underapplying N.

Are Offset Payments Enough to Impact N Management Decisions?

The potential revenue farmers could earn by participating in the carbon market were examined to understand the relative importance of the incentive for encouraging adoption of improved N management. In general, the offset credit incentive payment alone did not appear to be enough to impact N management changes to participate in GHG offset markets at offset prices of \$5, \$10, or even \$50 per $MgCO_2e$. Though the incentive becomes more appealing at \$50 per $MgCO_2e$, the cost to implement variable or split N rate as well as costs for project development and verification are likely to outweigh the incentive payment. Adding the N fertilizer cost savings increased the incentive payment to a point that is more comparable with the potential return from the management changes of the sample projects. The incentive for switching from uniform to variable N management or from all fall N application to splitting the N fertilizer between fall and spring would have to be similar or greater than the cost to adopt these changes or risk to under applying N in order to stimulate adoption.

Precision agriculture techniques make use of fertilizer N rate, timing, placement, and formulation to match N supply with crop demand (Robertson and Vitousek, 2009). An overall N rate decrease can often, but not always, be realized by applying one or more of these principles (Huggins, 2010). In evaluating the potential to generate GHG offset credits from agricultural N management for a particular region, it is important to consider the tradeoffs and what level or type of incentive is needed to influence N management decisions. Adoption of precision agriculture techniques within the iPNW generally lacks sufficient decision support (Pan et al., 1997; Huggins, 2010) and monetary incentives. Furthermore, managing N in cropping systems involves consideration of the total N supply needed for not only supporting crop growth but also achieving grain yield and quality (Huggins and Pan, 2003). Therefore, N fertilizer rate reductions will likely be seen as economically risky and require a monetary incentive that compensates for the risk of under applying N (Robertson and Vitousek, 2009; Huggins, 2010).

Leakage provisions in agricultural N management protocols specify that N rate reductions must not result in a decrease in yield. Though not addressed in current protocols, it should be noted that farm economics would also require any N rate reductions to not come at the expense of yield quality (e.g., protein concentration specifications for the wheat market class). Maintained yield with less N is believed to be possible because typical yield-goal based N fertilizer recommendations tend to overestimate N requirements (Millar et al., 2012). This could be especially true for winter wheat crops in the PNW because it is difficult to accurately estimate yield goal at the time of planting and N fertilizer application. For dryland winter wheat, a majority of N fertilizer is applied in the fall when N demand is the lowest. Yield may also be maintained with less N in situations where N is applied in excess of the N requirement to minimize economic risk if growing conditions are exceptional. Insurance applications of N as a means to manage the economic risk of under applying N should not be dismissed. Especially considering that decision support and other incentives are generally lacking for managing the site-specific N requirement. An additional monetary incentive may be needed to cover insurance N fertilizer applications.

Offsets from agricultural N management do not appear to be the best tool for GHG mitigation and reducing additions of reactive N to the environment. The monetary incentive for agricultural N management for N_2O emission reductions could be tied to existing conservation programs such as the USDA-NRCS Conservation Stewardship Program to improve the return on investing in GHG emissions reduction activities. There may be co-benefits to encouraging a reduction in N application rate beyond generating GHG emission reductions, such as avoided acidification of soils and water bodies, limiting N leaching impacts on ground and surface water quality, avoided ozone destruction, and reducing the cost of production. Furthermore, the offset credits generated from N_2O emission reductions from reducing N fertilizer rate are irreversible. An avoided N_2O emission cannot be reversed as is the case for carbon sequestration projects. This means no future obligation for farmers enrolled in a project making them more attractive to offset purchasers.

CONCLUSIONS

Differences observed across the five agricultural N management protocols in this study highlighted inconsistencies among protocols. The implications are that there could potentially be discrepancies in the quantity and quality of GHG offsets generated across the different programs. This impacts credibility of carbon markets and limits the ability to offer GHG credits in larger-scale national or global carbon markets. In order to support the participation of iPNW farmers in offset credit markets for N_2O reductions, one or more of the existing protocols should be adapted for the region. At least a Tier II direct emission factor will need to be determined or modeled (Tier III) to accurately reflect baseline, project, and overall emissions reductions. However, our assessment found that the financial incentive from the carbon offset credit alone was not likely to encourage any management changes. Nitrogen fertilizer cost savings will be one of the most practical incentives for a farmer to adopt the N management proposed in the sample projects. Therefore, stacking of offset credit revenue, along with other incentive-based approaches, is likely to be required in order to realize N_2O emissions reductions in the region that are economically feasible.

AUTHOR CONTRIBUTIONS

TB performed the offset protocol literature review with guidance from CL, both authors contributed to the writing of this manuscript. TB contributed a majority of the writing. CL provided extensive review of early versions of the analysis and writing for the manuscript. CK provided guidance on policy aspects and manuscript review. DH and JR provided extensive editorial review of the manuscript.

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Soil Organic Carbon Pools as Early Indicators for Soil Organic Matter Stock Changes under Different Tillage Practices in Inland Pacific Northwest

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Soil organic matter (SOM) is essential for sustaining soil health and crop productivity. However, changes in SOM stocks in response to agronomic practices are slow and show years later when it is too late for adjustments in management. Identifying early indicators of SOM dynamics will allow early management decisions and quick remedial action. The objectives of this study were to evaluate long-term effects of tillage intensity and timing on SOM pools and determine the most responsive SOM pools to tillage practice. Soil from a long-term (53 years) winter wheat (*Triticum aestivum* L.)-spring pea (*Pisum sativum* L.) rotation and undisturbed grass pasture (GP) in inland Pacific Northwest (iPNW) was sampled to evaluate the effect of four tillage systems [no-till (NT), disk/chisel (DT/CT), spring plow (SP), and fall plow (FP)] on soil organic carbon (SOC, proxy for SOM), total nitrogen (TN), particulate organic matter carbon (POM-C) and nitrogen (POM-N), permanganate oxidizable carbon (POXC), water extractable organic carbon (WEOC), total dissolved nitrogen (TDN), KCl-extractable nitrogen (KEN), microbial biomass carbon (MBC) and nitrogen (MBN), basal respiration (BR), carbon mineralization (Cmin), and metabolic quotient (qCO_2). GP had higher levels of SOC pools than cultivated treatments. On average, tillage significantly decreased SOC and TN by 28 and 26%, respectively, compared to GP. Among the cultivated soils, tillage had no significant effect on SOC and TN, except for DT/CT that had slightly higher SOC than FP ($P = 0.08$). On the contrary, NT and DT/CT significantly ($P < 0.05$) increased levels of POM-C, POM-N, POXC, WEOC, MBC, BR, Cmin, and qCO_2 over FP or SP. However, tillage did not affect TDN, MBN, and KEN. The C-pools (POM-C, POXC, MBC, WEOC, BR, and Cmin) were more strongly correlated with SOM than the N-pools (TDN, MBN, and KEN), with an exception to POM-N. Under wheat-pea rotation in the iPNW, reduced tillage systems (NT and DT/CT) have a potential to maintain or increase SOM, which can be assessed early through its physical (POM), chemical (POXC, WEOC), and microbiological (MBC, BR, Cmin) indicators. POXC and WEOC were the most sensitive indicators of tillage-induced changes in SOM dynamics.

Keywords: carbon sequestration, dissolved organic matter (DOM), labile carbon pools, microbial biomass, particulate organic matter, permanganate oxidizable carbon, soil organic matter, tillage

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INTRODUCTION

Anthropogenic loading of atmospheric CO_2, a greenhouse gas, could be partially offset or mitigated by sequestering carbon into soil organic matter (SOM) through increasing net primary productivity of cropping systems (Lal, 2004). Accumulation of SOM is also crucial for soil fertility, water retention, and maintaining crop productivity (Machado et al., 2008; Machado, 2011). Over the long-term, the magnitude of SOM storage depends on land-use and management practices (West and Post, 2002). Usually, SOM tends to decline when native ecosystems are converted to cropping systems (Machado et al., 2006), but the effect of different management practices on SOM dynamics in dryland cropping systems varies and is site-specific (Ghimire et al., 2017; Wang et al., 2017).

Winter wheat (*Triticum aestivum* L.)-summer fallow cropping systems (WW-SF) dominate the inland Pacific Northwest (iPNW), an ecoregion receiving relatively low precipitation (<400 mm) and most (70%) of which is received during winter months (Purakayastha et al., 2008; Machado, 2011). To this end, fallowing is widely practiced as a means to store soil water for the next crop. Tillage is used to control weeds and facilitate water storage by breaking surface- and sub-soil pore continuum during fallow (Fuentes et al., 2004). In addition, tillage also facilitates seeding operations by removing surface residues and reducing weed germination by burying weed seeds (Young et al., 2014). Although reliable in terms of grain yield, WW-SF exacerbated soil erosion (Feng et al., 2011; Machado et al., 2015) and has depleted more than 50% of the original SOM in Walla Walla silt loam soil (0–60 cm) near Pendleton, Oregon (Ghimire et al., 2015). In response to high soil erosion rates and depletion of SOM, adoption of reduced tillage systems, including delaying tillage until crop seeding, minimum tillage, and no-till (NT), has increased in recent years (Machado, 2011; Machado et al., 2015). Erosion rates have dramatically decreased under conservation tillage systems but SOM build up has been slow (Williams et al., 2009; Machado, 2011; Ghimire et al., 2017).

Storage of SOM in cropping systems depends on the balance between C-additions primarily from crop residues and C-losses through SOM decomposition (Machado et al., 2006; Awale et al., 2013). Therefore, the degree to which a tillage technique influences SOM turnover is generally determined by the frequency and timing of soil disturbance, depth of soil disturbance, and degree of soil-residue mixing (Cookson et al., 2008; Dou et al., 2008; Machado, 2011). Usually, inversion tillage buries almost all residues and enhances their decomposition by increasing soil-residue contact. Tillage also enhances microbial decay of SOM by regulating soil temperature, introducing oxygen, and disintegrating soil aggregates (Six et al., 2000). Furthermore, tillage induced alterations on soil edaphic properties can significantly influence crop productivity and ultimately the quantity of residue input in soils (Payne et al., 2000). On the contrary, delaying residue incorporation or leaving it on soil surface may provide a steady substrate for microbial community (Balota et al., 2003; Machado et al., 2006).

Nevertheless, changes in SOM stocks in response to tillage management may be difficult to detect due to soil's inherent variability (Cookson et al., 2008). More importantly, due to the slow recovery of SOM stocks, it may take several years to observe significant changes in SOM, often leading to late decision making and delayed remedial actions (West and Post, 2002). It took more than 30 years to measure a significant decrease in SOM in a WW-SF long-term experiment near Pendleton, Oregon (Ghimire et al., 2015). Besides, other studies have also indicated that the magnitude and direction of tillage-induced changes are often site-specific (Purakayastha et al., 2008; Morrow et al., 2016). Recently, microbiological properties and readily decomposable pools of SOM, such as particulate organic matter (POM), permanganate oxidizable C (POXC), water extractable organic matter (WEOM), microbial biomass C (MBC) and N (MBN), and microbial respiration, have received more attention due to their sensitivity to management practices than bulk SOM (Dou et al., 2008; Awale et al., 2013; Culman et al., 2013; Morrow et al., 2016; Wang et al., 2017). These physical, chemical, and microbiological pools constitute relatively small fractions of SOM but have rapid turnover rates of weeks to months or few years compared with more recalcitrant bulk SOM pools (Haynes, 2005). Identifying early indicators of SOM dynamics would allow early interventions before significant SOM loss (Purakayastha et al., 2008).

SOM pools can represent a multitude of interrelated soil processes and functions (Awale et al., 2013). For instance, POM plays major roles in soil aggregation and production of WEOM, and serves as an energy source for soil microbial biomass (Gregorich et al., 2000; Six et al., 2000; Zotarelli et al., 2007). The WEOM includes C-substrates as well as other associated nutrients (such as N, P, and S), and therefore its turnover is crucial in nutrient cycling (Gregorich et al., 2006). Soil microbes are responsible for transforming organic matter and nutrients within soil (Mooshammer et al., 2014). Basal respiration (BR) and C-mineralization are adequate indicators of microbial activity, which is dependent on substrate availability and the soil edaphic environment (Balota et al., 2003). A build-up of POXC in soil indicates long-term SOM stabilization (Culman et al., 2012, 2013; Hurisso et al., 2016). To this end, analyzing SOM pools and characterizing their interrelationships could improve our understanding of management effects on SOM dynamics in the iPNW. The objectives of this study were to (i) evaluate the effects of tillage intensity and timing on SOM pools and (ii) determine the most responsive SOM pools to tillage under winter wheat-spring pea (*Pisum sativum* L.) rotation in the iPNW.

Abbreviations: BR, basal respiration; C, carbon; C:N, carbon-to-nitrogen ratio; CBARC, Columbia Basin Agricultural Research Center; Cmin, carbon mineralization; CO_2, carbon dioxide; DT/CT, disk/chisel tillage; FP, fall plow; GP, grass pasture; KEN, KCl-extractable nitrogen; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; N, nitrogen; NT, no-till; PNW, Pacific Northwest; POM, particulate organic matter; POM-C, particulate organic matter carbon; POM-N, particulate organic matter nitrogen; POXC, permanganate oxidizable carbon; qCO_2, metabolic quotient; SOC, soil organic carbon; SOM, soil organic matter; SP, spring plow; TDN, total dissolved nitrogen; TN, total nitrogen; WEOC, water extractable organic carbon; WEOM, water extractable organic matter; WHC, water holding capacity; WP-LTE, wheat-pea long-term experiment; WW-SF, winter wheat-summer fallow.

MATERIALS AND METHODS

Site Description and Experimental

This study was conducted on an ongoing wheat-pea long-term rotation experiment (WP-LTE) located at the Columbia Basin Agricultural Research Center (CBARC) near Pendleton, Oregon (45°42′N, 118°35′W). The WP-LTE was initiated in 1963 on a nearly-level (0–1% slope) Walla Walla silt loam soil (coarse-silty, mixed, mesic Typic Haploxeroll) (Soil Survey Staff, 2014). The site is characterized by a semiarid climate with cool wet winters and hot dry summers. Long-term (1930–2015) average annual temperature is 8°C, and annual precipitation is 418 mm, 70% of which falls between September and April (CBARC, 2016).

The WP-LTE consisted of a 2-year winter wheat-spring pea rotation, with each phase of the rotation present every year in order to facilitate yearly data collection for both crops. The experimental design was a split-plot arrangement with crop phases (wheat and pea) as whole-plot factors and tillage systems as sub-plot factors and replicated four times. Each sub-plot measured 7.3 m wide by 36.5 m long. Semi-dwarf soft white winter wheat was planted in early October using a double disk drill with 18-cm row spacing and harvested in late July of the following year. Spring pea was sown in late March or early April and harvested in June or July of the same year. After 28 years of growing green peas, dry peas were introduced in 1991. For the last 20 years, all wheat plots received 90 kg N ha^{-1} as urea ammonium nitrate (32-0-0) shanked 12 cm deep before planting, while ammonium sulfate (21-0-0-24) or ammonium phosphate sulfate (16-20-0-14) was broadcast applied at the rate of 22 kg N ha^{-1} in pea. Payne et al. (2000) and Machado et al. (2008) reported further details on crop management prior to 1995. The WP-LTE consisted of four tillage treatments as follows:

(i) Fall plow (FP): The plots were moldboard-plowed (20–25 cm deep) after wheat harvest in fall, followed by one to three times of spring cultivation (15 cm deep) before planting pea. Pea vines were moldboard plowed in summer after pea harvest and cultivated twice (10 cm deep) before planting wheat in the fall.

(ii) Spring plow (SP): This treatment was identical to FP treatment, except that the plots were moldboard-plowed in spring before planting pea.

(iii) Disk/chisel (DT/CT): The plots were disked twice to a depth of 10 cm after wheat harvest in the fall, followed by sweep-cultivation (5 cm) in spring before planting pea. After pea harvest, the plots were chisel-plowed (20 cm) and sweep-cultivated before seeding wheat.

(iv) No-till (NT): No tillage was implemented in 1995 and weeds were controlled by herbicides. In earlier years (1963–1995), minimum tillage had been implemented in these plots, which included skew-treading (2.5 cm deep) once or twice after wheat harvest in fall followed by sweep-cultivation (5 cm deep) before planting pea, and skew-treading two to three times in summer after pea harvest. A skew-treader consists of tined wheels on two angled ganged shafts that break and uniformly distribute residues to improve drill performance during seeding.

An undisturbed grass pasture (GP) served as a reference for comparisons of changes in SOM dynamics in the WP-LTE. The GP plot (45 m wide by 108 m long) is in proximity to the WP-LTE at CBARC and is maintained under native vegetation (since 1931) that is predominantly tall fescue (*Festuca arundinacea* Scheeber) with lesser amounts of bulbous bluegrass (*Poa bulbosa* L.), green foxtail (*Setaria viridis* L.), and yellow foxtail [*S. pumila* (Poiret) Roemer and Schult]. The GP plot was divided into four transverse sections and represented four sub-plots.

Soil Sampling and Analyses

In June 2016, two soil cores (3.8 cm diameter) were collected from 0- to 15-cm surface layer within each sub-plot and composited. Samples were taken between crop rows after clearing surface residues. Soils were air-dried in a greenhouse for 72 h and finely ground in a mechanical grinder to pass through a 2-mm sieve after removing visible pieces of plant materials. To determine bulk density, three separate soil cores (1.84 cm diameter and 0–15 cm deep each) were also taken within 0.5 m radius of initially collected soil cores. These soil cores were oven dried at 105°C for 24 h and bulk density was computed by dividing oven dried soil mass with soil volume (Blake and Hartge, 1986).

Approximately 10 g subsamples of air-dried soils (<2 mm) were finely ground (<0.05 mm) in a Shatter Box 8530 ball mill (Spex Sample Prep., Metuchen, New Jersey, USA) for 3 min, and then analyzed for total C and N concentrations by dry combustion method (Purakayastha et al., 2008) at 950°C using a LECO CN628 analyzer (LECO Corp., St. Joseph, Michigan, USA). Previous investigations have confirmed the absence of inorganic carbon at 0–15 cm layer within the experimental site, and therefore, total C measured for all soils is safely assumed to be soil organic carbon (SOC) (Ghimire et al., 2015). This was confirmed by pH-values measuring below 6.7 in all soils (**Table 1**). Soil bulk density was used to convert SOC concentration (g kg^{-1}) to SOC stock per area (Mg ha^{-1}) to remove confounding effects of compaction when comparing all treatments. Soil pH of extracts from 5 g air-dried soils (<0.05 mm) in 10 mL of 0.01 *M* $CaCl_2$ was measured electrometrically using an Orion Star A215 pH/conductivity bench top meter (Thermo Fisher Scientific Inc., Beverly, MA, USA) (Ghimire et al., 2015). Water holding capacity (WHC) of air-dried soil (<2 mm) was determined as described by Awale and Chatterjee (2015). Briefly, 10 g air-dried soil was saturated with deionized water in a conical funnel with a filter paper (Whatman no. 42) and WHC was determined as the water retained in soil after draining excess water for 1 h.

Particulate organic matter carbon (POM-C) and nitrogen (POM-N) were assessed by following the procedure of Sollins et al. (1999). A 10 g air-dried soil sample (<2 mm) was dispersed in 30 mL of 5 g L^{-1} sodium hexametaphosphate and shook for 18 h on a reciprocal shaker (240 strokes per min). The mixture was then passed through a 53-μm sieve by rinsing several times with deionized water. The material retained on the sieve was dried in an oven at 105°C for 24 h, weighed, finely ground using mortar and pestle, and analyzed for C and N by dry combustion as described above. POM-C or POM-N (g kg^{-1}) was

TABLE 1 | Treatment effects on bulk soil characteristics in 0- to 15-cm Walla-Walla silt loam near Pendleton, Oregon.

Treatments	Soil properties†							
	SOC ($g\ kg^{-1}$)	TN ($g\ kg^{-1}$)	C:N	SOC ($Mg\ ha^{-1}$)	TN ($Mg\ ha^{-1}$)	Bulk density ($g\ cm^{-3}$)	pH	Water content ($g\ kg^{-1}$)
Grass pasture	24.2a‡	1.78a	13.5a	40.1a	2.96a	1.11a	6.35a	193a
No-till	17.9b	1.33b	13.5a	34.7b	2.59b	1.30b	5.02b	95b
Disk/Chisel	18.2b	1.36b	13.3ab	34.3b	2.57b	1.28b	5.29b	100b
Spring plow	17.2b	1.33b	12.9b	33.9b	2.64b	1.32b	5.33b	89b
Fall plow	16.3b	1.26b	12.9b	31.8b	2.45b	1.30b	5.28b	85b
SE§	1.06	0.06	0.3	1.9	0.12	0.03	0.22	11

†*Soil properties are SOC, soil organic carbon; TN, total nitrogen; C:N, SOC/TN ratio.*
‡*Means followed by different lower case letters within a column are significantly different ($P \leq 0.05$).*
§*Standard error (SE) values of least square mean differences provided at $\alpha = 0.05$.*

then computed from the following equation:

$$\text{POM} - \text{C or POM} - \text{N} = \text{Cs or Ns} \times \text{Ws} \times 10$$

where, Cs or Ns is % C or % N of sand fraction, and Ws is dry mass of sand fraction ($g\ g^{-1}$).

Potassium permanganate oxidizable carbon (POXC) was determined as proposed by Weil et al. (2003) with a slight modification as discussed in Culman et al. (2012). A 2.5 g air-dried soil sample (<2 mm) was mixed with 20 mL of 0.02 *M* $KMnO_4$ in a 50-mL polypropylene conical centrifuge tube. The mixture was vigorously shaken for 2 min on a reciprocal shaker (240 strokes per min) and allowed to settle for 10 min. Following settling, 0.5 mL of the supernatant from the upper 1 cm of the suspension was transferred into another 50-mL centrifuge tube and mixed with 49.5 mL of deionized water. Three subsamples from each diluted solution were measured for absorbance in a GENESYS 10S UV-VIS spectrophotometer (Thermo Fisher Scientific Inc., Madison, Wisconsin, USA) at 550 nm. POXC in a soil sample was calculated using the following equation:

$$\begin{aligned}\text{POXC}(\text{mg kg}^{-1}\text{soil}) = {} & [0.02\,\text{mol}\,L^{-1} - (a + b \times \text{absorbance})] \\ & \times (9,000\,\text{mg Cmol}^{-1}) \\ & \times (0.02\ \text{L solution}/0.0025\,\text{kg soil}).\end{aligned}$$

where, 0.02 mol L^{-1} is the initial solution concentration, *a* is the intercept and *b* is the slope of the standard curve, 9,000 is mg C oxidized by 1 mol of MnO_4 changing from Mn^{7+} to Mn^{4+}, 0.02 L is the volume of $KMnO_4$ solution reacted, and 0.0025 is the kg of soil used.

Soil inorganic nitrogen or KCl extractable-N (KEN) content (NH_4^+-N plus NO_3^--N) was measured in duplicates according to Maynard et al. (2008). Briefly, 5 g air-dried soil (<2 mm) was mixed with 25 mL of 2 *M* KCl, shaken in a reciprocal shaker for 30 min, and the mixture was filtered through a Whatman no. 42 filter paper. The extract was analyzed for NH_4^+ and NO_3^- concentrations colorimetrically using a phenol-nitroferricyanide method and a cadmium reduction method, respectively, in an automated micro-segmented flow Astoria analyzer (Astoria-Pacific Inc., Clackamas, Oregon, USA).

Water extractable organic carbon (WEOC) and total dissolved nitrogen (TDN) were determined by extraction of 10 g air-dried soil (<2 mm) using 40 mL deionized water (Cookson et al., 2008). The soil-water mixture was shaken in a reciprocal shaker for 1 h and then filtered through a Whatman no. 42 filter paper. The extract was frozen until analyzed for WEOC and TDN using a high-temperature combustion Torch TOC/TN analyzer (Teledyne Tekmar, Mason, OH, USA).

Carbon mineralization (Cmin) was estimated using a short-term incubation method following Sherrod et al. (2012), and Awale and Chatterjee (2017). Briefly, 100 g air-dried soil (<2 mm) was moistened to 60% WHC with de-ionized water using a pipette in a 1-L mason jar. The mason jar was closed with airtight screw-cap lid, fitted with a gas sampling port (butyl rubber septum) at the center, and was incubated at constant temperature of 25°C for 30 d. Soil moisture content was maintained at 60% throughout the incubation by monitoring the weight changes of the mason jar and adding deionized water as needed. Headspace air samples were collected from the jar on 1, 2, 3, 7, 8, 10, 13, 16, 22, and 30 d after incubation. At every sampling day, headspace air in the jar was mixed by withdrawing and injecting twice using a polypropylene syringe fitted with a 21-gauge needle and finally 30-mL air sample was collected into the syringe. The mason jar lid was then opened for at least 5–10 min to replenish with fresh air and to add deionized water (if necessary), sealed again, and returned to the incubator until 30-d. Triplicate subsamples of 7-mL air from each syringe were analyzed for CO_2 concentrations within 2 h of their collection using a LI-820 CO_2 analyzer (LICOR Inc., Lincoln, Nebraska, USA). Assuming ideal gas relations, the measured CO_2 concentrations were then converted into mass units, expressed as mg CO_2-C d^{-1} kg^{-1} soil. Cumulative CO_2-C mineralized in 30 d (Cmin) was computed by summing all the CO_2-C evolved at each time period.

Microbial biomass carbon (MBC) and nitrogen (MBN) were determined using chloroform fumigation-incubation method (Jenkinson and Powlson, 1976). Duplicate 10 g air-dried soils (<2 mm) were weighed into 60-mL French Square bottles, adjusted to 60% WHC by adding de-ionized water, and incubated at 25°C for 7 d. A set of empty bottles without soil was also incubated and processed similarly as those with soil. Following 7 d pre-incubation, one set of soils was fumigated with ethanol-free chloroform ($CHCl_3$) in a vacuum chamber in the dark for 24 h while the other set was not and remained incubated (non-fumigated). Both the non-fumigated and fumigated soils (in bottles) were then placed inside 1-L mason jars consisting 2-mL of de-ionized water at the bottom (to maintain humidity). The mason jars were sealed with lids fitted with gas sampling ports and further incubated at 25°C for 10 d. Approximately, 30-mL gas samples were collected from the mason jars through the sampling ports, and analyzed for CO_2 using infrared gas analyzer as described above. Soil MBC was calculated by dividing the difference of CO_2-C produced between fumigated and non-fumigated samples by a correction factor (k_c) of 0.41 (Collins et al., 1992). The measurement of CO_2 evolved from the non-fumigated control following pre-incubation was considered as basal respiration (mg CO_2-C kg^{-1} soil d^{-1}), and metabolic quotient (qCO_2) was calculated by dividing basal respiration with MBC (mg CO_2-C g^{-1} MBC d^{-1}). For MBN, the fumigated-incubated sample at 10 d was extracted with 50 ml of 2 M K_2SO_4 for 30 min and mineral N concentrations were determined colorimetrically as described above. Soil MBN was calculated by dividing the flush of mineral-N (NH_4^+-N + NO_3^-) released during fumigation-incubation using a correction factor (k_n) of 0.40 (Collins et al., 1992).

Data Analysis

Data were subjected to analysis of variance for a split-plot arrangement in a randomized block design using Proc Mixed of SAS (version 9.2, SAS Institute Inc., Cary, North Carolina)—assuming fixed crop and tillage effects and random replication term. We created dummy variables of GP data to conform to WP-LTE design for statistical comparisons. Treatment (tillage) means were compared using Fisher's least significant difference test when there was a significant treatment effect at 0.05 level of probability, unless otherwise stated. Univariate Pearson's correlation coefficients were used to evaluate relationships between SOM pools. Stepwise multiple linear regression analyses were conducted using Proc Reg of SAS with backward elimination to explore the relative importance of SOM pools in predicting SOC.

RESULTS

Bulk Soil Characteristics

GP had significantly ($P < 0.05$) higher levels of SOC and total nitrogen (TN) concentrations as well as stocks than all cultivated treatments in the WP-LTE (**Table 1**). Compared to GP, on average, cultivated soils had 28 and 26% less SOC and TN concentrations and had 16 and 13% less SOC and TN stocks, respectively. Within WP-LTE, there were no significant differences in SOC and TN levels among tillage treatments. However, DT/CT had slightly higher SOC concentration than FP ($P = 0.08$). Soil C:N under GP, NT, and DT/CT were similar, but both SP and FP had lower C:N than GP and NT. Soil bulk density did not differ among cultivated treatments, and averaged 1.30 g/cm^3, which was significantly higher than that of GP soil (**Table 1**). On the other hand, all cultivated treatments had significantly lower soil pH-values than GP (**Table 1**). Among the cultivated treatments, soil pH under NT was generally lower than other tillage practices ($P < 0.10$). Gravimetric water content was higher under GP than under cultivated treatments (**Table 1**).

Physical and Chemical Pools of SOM

Treatments significantly affected POM-C, POM-N, POXC, and WEOC (**Table 2**). In general, GP had the highest levels of physical and chemical C- and N-pools, which decreased with increasing tillage intensity. POM-C and POM-N were significantly lower under FP and SP than under either GP, NT, or DT/CT, which were not different among each other. On average, POM-C and POM-N were each 18% greater under reduced tillage systems (NT and DT/CT combined) than plowing (FP and SP combined). POXC and WEOC were the highest under GP. Among the cultivated treatments, POXC was similar between NT and DT/CT, but both had higher POXC than under FP. Under SP, POXC was intermediate between DT/CT and FP, but was significantly lower than NT. WEOC did not differ between NT and DT/CT soils, and averaged 182 mg kg^{-1}, which was significantly higher (14%) than WEOC of FP and SP soils. There were no significant

TABLE 2 | Treatment effects on physical and chemical pools of SOM in surface 0- to 15-cm Walla Walla silt loam near Pendleton, Oregon.

Treatments	Physical pools†			Chemical pools†				
	POM-C (g kg^{-1})	POM-N (g kg^{-1})	POM-C:POM-N	POXC (mg kg^{-1})	WEOC (mg kg^{-1})	TDN (mg kg^{-1})	WEOC:TDN (mg kg^{-1})	KEN (mg kg^{-1})
Grass pasture	4.85a‡	0.27a	17.9a	706a	223a	42.3a	9.30a	31.2a
No-till	4.48a	0.26a	17.0a	676b	181b	22.1a	9.61a	11.4a
Disk/Chisel	4.56a	0.25ab	18.1a	659bc	183b	25.0a	9.24a	14.1a
Spring plow	3.67b	0.21b	17.3a	648cd	159c	21.0a	8.80a	12.2a
Fall plow	3.72b	0.21b	17.7a	633d	153c	28.6a	7.28a	19.2a
SE§	0.37	0.02	0.8	12	12	10.3	1.91	10.2

† *Pools are POM-C, particulate organic matter carbon; POM-N, particulate organic matter nitrogen; POXC, permanganate oxidizable carbon; WEOC, water extractable organic carbon; TDN, water extractable total dissolved nitrogen; KEN, KCl extractable total inorganic (NH_4^+ + NO_3^-) nitrogen.*

‡ *Means followed by different lower case letters within a column are significantly different ($P \leq 0.05$).*

§ *Standard error (SE) values of least square mean differences provided at α =0.05.*

effects of treatments on POM-C:N, TDN, WEOC:TDN, and KEN.

Microbiological Pools of SOM

Soil microbial biomass values for C and N showed significant variation among treatments (**Table 3**). The greatest MBC was found under GP and the lowest under FP. Compared to GP, MBC was lower on average by 21% under NT, DT/CT, and SP soils. MBC among these latter three treatments was not significantly different. However, NT and DT/CT increased MBC by 27 and 36%, respectively, when compared to FP. Similar to MBC, soil MBN was the greatest under GP. On average, cultivated soils had about 55% less MBN relative to GP soil. There were no significant differences in MBN-values among cultivated treatments. The net result of the variations in soil MBC and MBN among treatments is that the ratio of microbial biomass C to N (MBC:MBN) was generally lower for GP soil than cultivated soils, in which the plow-tillage treatments exhibited slightly lower values compared to NT and DT/CT.

The values of basal respiration (BR) showed significant variation among treatments (**Table 3**). GP had the highest BR among all treatments. DT/CT and SP had similar BR and both treatments had greater BR compared to FP. Basal respiration under NT did not differ from other cultivated treatments. qCO_2 was higher under SP than under NT (by 17%) and FP (by 21%), with no statistical difference between the latter two. However, FP had lower qCO_2 compared to both GP and DT/CT treatments.

Similar to BR, mineralized CO_2-C differed significantly among treatments for all incubation sampling time periods, except for the initial 1 d of incubation (**Figure 1**, **Table 3**). However, the temporal pattern of CO_2-C mineralized among treatments generally remained similar throughout the incubation period. The values for CO_2-C mineralized were consistently highest and lowest under GP and FP, respectively, while NT, DT/CT, and SP were intermediate between them. At the end of 30 d, cumulative CO_2-C (Cmin) produced under DT/CT and SP soils were similar and averaged 637 mg CO_2-C kg^{-1}, which was 20% lower than GP but 26% higher than FP. Cmin under NT was not statistically different from any other cultivated treatments, but was about 29% lower than that of GP.

Fractions of SOM Pools

Proportions of labile C and N pools in SOM showed variation among treatments, with significant differences observed for POXC/SOC, Cmin/SOC, and POM-N/TN (**Table 4**). POXC/SOC was lower under GP than under cultivated treatments. Cmin/SOC was significantly lower under FP than under DT/CT and SP treatments, while GP and NT had intermediate levels of Cmin/SOC. POM-N/TN was higher under NT and DT/CT treatments compared to plow-tillage treatments and GP. In general, POM-C/SOC and MBC/SOC were lower, while N-pools in TN were higher under GP than under cultivated treatments, although such differences were not statistically significant ($P > 0.05$). On average, SOC had 22.8% POM-C, 3.6% POXC, 0.9% WEOC, 2.9% MBC, and 3.3% Cmin. Similarly, TN constituted about 17.1% PON, 1.9% TDN, 4.9% MBN, and 1.1% KEN.

Relationships of SOM Pools

The values of univariate correlation coefficients (r) between the SOM pools are shown in **Table 5**. Across the study, the highest correlation coefficient value ($r = 0.95$) was observed between SOC and TN. Significant positive correlations were found for all SOM pools with SOC and TN, except for soil C:N, POM-C:N, and WEOC:TDN. In general, SOM pools were also correlated among each other. Nevertheless, the C-pools (POM-C, POXC, WEOC, and MBC) were more strongly correlated with SOM than the N-pools (TDN, MBN, and KEN). Among all the SOM pools, POXC and WEOC pools demonstrated the highest correlations with both SOC and TN. Stepwise multiple regression of all the tillage-responsive SOM pools on SOC showed that POXC and WEOC pools were the best predictors of SOC stock (**Table 6**). POXC and WEOC pools, in combination, could explain nearly 70% of the total variability in the model. Bulk density was generally negatively related to SOM pools, while both pH and gravimetric water content and SOM pools had positive relationships.

DISCUSSION

Cultivation of native grasslands has led to depletion of SOC and TN levels from the 0–15 cm soil depth profile due to reduced

TABLE 3 | Treatment effects on microbiological pools of SOM in surface 0- to 15-cm Walla Walla silt loam near Pendleton, Oregon.

Treatments	Microbiological pools†					
	MBC (mg kg^{-1})	MBN (mg kg^{-1})	MBC:MBN	BR (mg CO_2-C kg^{-1} d^{-1})	qCO_2 ($\mu g\ g^{-1}$ MBC d^{-1})	Cmin (0–30 d) (mg CO_2-C kg^{-1})
Grass pasture	678a‡	135a	7.9a	32.7a	46.5ab	796a
No-till	531b	45b	15.7a	21.2bc	41.7bc	565bc
Disk/Chisel	570b	54b	15.3a	26.1b	45.3ab	661b
Spring plow	509bc	74b	12.3a	25.5b	50.4a	612b
Fall plow	418c	63b	13.6a	16.3c	39.8c	472c
SE§	50	32	3.6	6.1	4.9	55

†*Microbiological pools are MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; BR, basal respiration; qCO_2, metabolic quotient; Cmin, cumulative CO_2-C mineralized in 30-d.*
‡*Means followed by different lower case letters within a column are significantly different ($P \leq 0.05$).*
§*Standard error (SE) values of least square mean differences provided at $\alpha = 0.05$.*

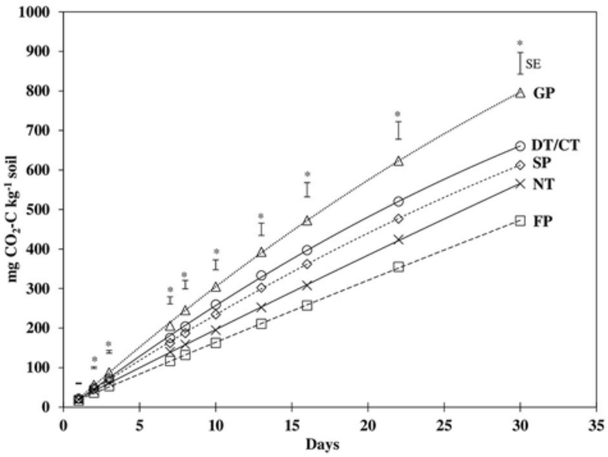

FIGURE 1 | Carbon mineralization from soils under grass pasture (GP), no-till (NT), disk/chisel tillage (DT/CT), spring plow (SP), and fall plow (FP) in 30 days of incubation. Error bars are standard error (SE) values of least square mean differences for individual days. *Indicates significant ($P \leq 0.05$) treatment differences for that day.

biomass inputs, increased exposure of physically protected SOM to microbial decomposition, and accelerated residue decay from tillage induced aeration, increased soil temperature, and depletion of water content (Six et al., 2000; Purakayastha et al., 2008). For the current study site, the mean aboveground plant biomass inputs from GP and wheat-pea systems were estimated to be about 7 and 5 mg ha^{-1} $year^{-1}$, respectively (Machado, 2011; Ghimire et al., 2015). Researchers have also asserted that undisturbed grasslands usually contain greater root density than cultivated systems (Gregorich et al., 2000; Beniston et al., 2014). Furthermore, legume-based (wheat-pea) cropping systems should result in residues that are more readily degraded than those in the GP system, which mostly consisted of annual and perennial grasses (Haynes, 2000). As a consequence of higher SOM levels, GP soil had lower bulk density and higher soil water retention (Franzluebbers et al., 1995).

Nevertheless, most studies claim that losses of SOM under arable systems can be minimized, at least within 0–15 cm top soil, by adopting reduced or conservation tillage systems (Machado et al., 2006; Dou et al., 2008; Chen et al., 2009; Awale et al., 2013). Such assertion was corroborated by our finding that DT/CT, a reduced tillage practice, tended to increase SOC content over FP. In fact, relative to GP, FP exhibited the highest reduction in SOC (33%) and TN (29%) levels, among all tillage systems. Crop residues accumulate at soil surface under reduced tillage systems, whereas intensive tillage such as FP buries crop residues and promotes their decomposition. Intensive tillage also disintegrates soil aggregates, introduces oxygen, increases soil temperature, and reduces soil water content—conditions favorable for rapid mineralization of residues and SOM (Zotarelli et al., 2007). In addition, the values of soil C:N for NT and DT/CT which were comparable to GP but higher than plow-treatments (SP and FP) further suggest that reduced tillage systems have potential to accumulate SOM and their adoption would lead to healthier soils.

NT and DT/CT increased POM-C and POM-N in soils over plow-treatments. Our results are in agreement with earlier studies that have also noticed higher POM pools with reduced tillage systems than more intensive tillage practices (Dou et al., 2008; Awale et al., 2013; Wang and Sainju, 2014). POM consists primarily of plant residues (Gregorich et al., 2006), physically protected within aggregates. Tillage breaks down these aggregates and exposes the protected POM to increased microbial consumption (Six et al., 2000; Zotarelli et al., 2007). Consequently, intensive tillage practices result in relatively less stabilization of POM than do reduced tillage systems. This is further supported by higher POM-C/SOC and POM-N/TN-values associated with reduced tillage systems than with plow-treatments. On the other hand, slightly greater assimilation of POM-N into MBN (MBN/TN) (**Table 3**) under plow-treatments might have also reduced POM-N/TN. Although weak, POM-N was significantly correlated ($r = 0.45$, $P < 0.05$) with MBN (**Table 5**). The greatest proportions of SOC and TN were found in POM-C and POM-N pools, respectively (**Table 4**). Purakayastha et al. (2008) found that POM-C was about 12.6–31% of SOC in eastern Washington with soils and management similar to this study. However, there were no significant differences in POM quality (POM-C:POM-N) among treatments because tillage induced changes in POM-C were closely matched by changes in POM-N, as demonstrated by significant correlation between POM-C and -N (**Table 5**). Higher values of C:N measured for POM (17.0–18.1) than bulk soil C:N (12.9–13.5) probably relates to the fact that POM is comprised of decomposing organic matter, often of recent origin (Gregorich et al., 2006).

The proportions of POXC in SOC measured in this study are higher than the reported range of 1.49–2.04% for soils across the iPNW by Morrow et al. (2016). Higher POXC-values obtained in this study could partly be explained by longer duration (53 years) of this study that allowed for more production of this pool when compared to shorter study periods of 3–31 years, as reported in Morrow et al. (2016). In addition, we sampled more soil (0–15 cm) compared to Morrow et al. (2016) who sampled less soil (0–10 cm). POXC levels can vary with soil depth in relation to concentration of roots and their exudation at different soil layers (Wang et al., 2017). Nevertheless, in our study, NT and DT/CT generally had more POXC compared to plow-treatments. This is in line with earlier findings that have also found higher POXC levels with reduced tillage systems than intensive tillage systems (Dou et al., 2008; Chen et al., 2009; Awale et al., 2013; Morrow et al., 2016). The POXC fraction of SOC is characterized based on its susceptibility to oxidation with weak potassium permanganate ($KMnO_4$) solution, and thereby simulates microbial oxidation (Weil et al., 2003). According to Culman et al. (2012) and Hurisso et al. (2016), POXC reflects a more stabilized fraction of SOC and reduced tillage promotes POXC in soils compared to intensive tillage because the latter increases microbial oxidation of POXC. High correlations of POXC with MBC ($r = 0.76$) and with microbial activity ($r = 0.67$) corroborate this assertion. Also, POXC demonstrated strong correlation with POM ($r = 0.73$) and

TABLE 4 | Proportions of SOM pools in soil organic carbon (SOC) and total nitrogen (TN) in treatments at surface 0- to 15-cm Walla Walla silt loam near Pendleton, Oregon.

Treatments	% of SOC[†]					% of TN[†]			
	POM-C	**POXC**	**WEOC**	**MBC**	**Cmin (0–30 d)**	**POM-N**	**TDN**	**MBN**	**KEN**
Grass pasture	19.7a[‡]	2.98a	0.92a	2.84a	3.27ab	14.8b	2.23a	7.10a	1.56a
No-till	25.4a	3.81b	1.00a	3.07a	3.20ab	19.9a	1.66a	3.26a	0.83a
Disk/Chisel	24.7a	3.65b	1.03a	3.12a	3.58a	18.2a	1.85a	3.91a	1.05a
Spring plow	21.4a	3.79b	0.94a	2.96a	3.56a	15.9b	1.55a	5.41a	0.89a
Fall plow	22.7a	3.90b	0.93a	2.91a	2.89b	16.6b	2.20a	4.70a	1.46a
SE[§]	2.4	0.15	0.05	0.21	0.23	1.41	0.56	1.64	0.56

[†] *Pools are POM-C, particulate organic matter carbon; POXC, permanganate oxidizable carbon; WEOC, water extractable organic carbon; MBC, microbial biomass carbon; Cmin, Cumulative CO_2-C mineralized in 30-d; POM-N, particulate organic matter nitrogen; TDN, water extractable total dissolved nitrogen; MBN, microbial biomass nitrogen; KEN, KCl extractable total inorganic ($NH_4^+ + NO_3^-$) nitrogen.*
[‡] *Means followed by different lower case letters within a column are significantly different ($P \leq 0.05$).*
[§] *Standard error (SE) values of least square mean differences provided at $\alpha = 0.05$.*

TABLE 5 | Pearson correlation coefficients (*r*)[†] of soil parameters across the study.

Parameters[‡]	SOC	TN	Soil C:N	POM-C	POM-N	POM-C:N	POXC	WEOC	TDN	WEOM-C:N	MBC	MBN	MB-C:N	Cmin	BR	qCO_2	KEN	Bulk density	pH
TN	0.95																		
Soil C:N	0.51	ns																	
POM-C	0.69	0.61	0.53																
POM-N	0.71	0.68	0.39	0.90															
POM-C:N	0.34	ns	0.50	0.69	0.31[§]														
POXC	0.78	0.72	0.51	0.73	0.70	0.42													
WEOC	0.78	0.71	0.53	0.78	0.73	0.47	0.79												
TDN	0.51	0.60	ns	0.35	0.47	ns	ns	0.32[§]											
WEOM-C:N	ns	ns	ns	ns	ns	ns	ns	ns	−0.75										
MBC	0.70	0.66	0.40	0.77	0.68	0.53	0.76	0.67	ns	ns									
MBN	0.51	0.64	ns	0.35	0.45	ns	0.32	0.37	0.80	−0.49	ns								
MB-C:N	−0.31[§]	−0.39	ns	ns	ns	ns	ns	−0.28[§]	−0.43	0.30[†]	ns	−0.56							
Cmin	0.69	0.61	0.50	0.79	0.62	0.68	0.70	0.77	ns	0.29[§]	0.73	ns	ns						
BR	0.66	0.62	0.40	0.75	0.58	0.66	0.67	0.70	ns	0.32[§]	0.73	ns	ns	0.93					
qCO_2	0.32[§]	0.30[§]	ns	0.40	ns	0.49	0.31[§]	0.42	ns	0.30[§]	ns	ns	ns	0.71	0.80				
KEN	0.45	0.56	ns	0.28[§]	0.41	ns	ns	ns	0.99	−0.75	ns	0.81	−0.44	ns	ns	ns			
Bulk density	−0.67	−0.66	ns	ns	ns	ns	−0.44	−0.45	−0.34	ns	−0.45	−0.34	0.34	−0.36	−0.37	ns	−0.31[§]		
pH	0.47	0.49	ns	ns	ns	0.31[§]	ns	ns	ns	ns	0.43	0.30[§]	0.28[§]	0.34	0.36	ns	ns	−0.42	
Water content	0.64	0.64	ns	ns	ns	ns	0.52	0.46	ns	ns	0.59	ns	ns	0.39	0.44	ns	ns	−0.67	0.55

[†] *Correlations significant at $P \leq 0.05$, except [§] significant at $P \leq 0.10$; ns, non-significant.*
[‡] *SOC, soil organic carbon; TN, total nitrogen; C:N, carbon/nitrogen ratio; POM-C, particulate organic matter carbon; POM-N, particulate organic matter nitrogen; POM-C:N, particulate organic matter carbon/nitrogen ratio; POXC, permanganate oxidizable carbon; WEOC, water extractable organic carbon; TDN, water extractable total dissolved nitrogen; WEOM-C:N, water extractable organic carbon/total dissolved nitrogen ratio; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; MB-C:N, microbial biomass carbon/nitrogen ratio; Cmin, cumulative CO_2-C mineralized in 30-d; BR, basal respiration; qCO_2, metabolic quotient; KEN, KCl extractable inorganic ($NO_3^- + NH_4^+$) nitrogen.*

WEOC ($r = 0.79$). To this end, relative enrichment of POXC under reduced tillage systems over plow-treatments suggests greater accumulation and stabilization of SOM under the former. Accordingly, POXC pool can serve as a useful early indicator of SOC dynamics. Nevertheless, all cultivated treatments resulted in higher POXC/SOC as compared to GP. Greater microbial biomass and activity under GP could have rapidly oxidized or converted compounds within the POXC pools into more stabilized SOC forms (Wang et al., 2017).

Lower levels of WEOC and TDN were observed under cultivated treatments than under GP, mostly due to depletion of SOM levels with soil cultivation (Gregorich et al., 2000; Haynes, 2000). WEOM reflects the equilibrium between soluble and solid phases of SOM, whereby the amounts of native SOM primarily determines the production and concentration of WEOM (Flessa et al., 2000; Gregorich et al., 2000). Higher WEOM pools under GP could also be attributed to several other factors including higher soil water content and pH that increase the solubility of SOM (**Table 1**; Chantigny, 2003). Within the cultivated treatments, NT and DT/CT had significantly higher WEOC levels than plow-treatments. This is in accordance with earlier findings of Dou et al. (2008) and Carrillo-Gonzalez et al. (2013), where intensive tillage depleted WEOC levels by 41 and 37%, respectively, compared to NT. Intensive soil mixing breaks down soil macroaggregates and exposes microaggregate protected WEOC to microbial decomposition (Six et al., 2000; Dou et al., 2008). Studies have suggested that recent additions of SOM from residues can also contribute to WEOM, apart from native and more stabilized SOM pools (Flessa et al., 2000). This could be supported by strong and significant correlation of WEOC with POM-C ($r = 0.78$, $P < 0.001$), comparable to those found with bulk SOC ($r = 0.78$) or POXC ($r = 0.79$). Moreover, the production of WEOM is also believed to be microbially mediated (Gregorich et al., 2000), which is corroborated by the observed significant correlation between WEOC and MBC ($r = 0.67$). To this end, increases in WEOC with reduced tillage systems could be attributed to greater levels of POXC, POM-C, and microbial pools. Nevertheless, despite such evidence, relative contributions of native and recent SOM to WEOM pools may be clearly distinguished using advanced technologies, such as C isotope, which deserves further investigation.

No significant tillage induced changes in TDN or KEN were found, probably suggesting similar N-cycling rates across tillage gradients. The net result of significant variation in WEOC and no effect in TDN was that the values of WEOC:TDN were generally higher under reduced tillage than plow-tillage treatments, following a trend similar to MBC:MBN (discussed below). The WEOC:TDN ratio provides a hint of the quality of WEOM where the decline in WEOC:TDN ratio is usually associated with increased bioavailability of WEOM (Cookson et al., 2008). In the present study, the values of WEOC:TDN ranged from 7.28 to 9.30, lower than the reported range of 16 $\pm$ 4 for arable soils by Christou et al. (2005). Concentrations of WEOC and TDN may differ depending upon the type of extracting solution used, presenting a challenge when comparing WEOM pools across studies (Carrillo-Gonzalez et al., 2013). In addition, lower ratios observed in this study could be due to inclusion of soluble inorganic N in the computation of WEOM, as opposed to using only soluble organic N-pool. The values for WEOC/SOC and TDN/TN measured in this study are greater than the reported ranges of 0.05–0.40% for WEOC/SOC and 0.15–0.19% for TDN/TN in agricultural soils by Haynes (2005), probably due to variations in soil type and management.

As expected, GP soil contained highest C- and N-values in microbial biomass compared to cultivated soils because GP had greater SOM content. Among the cultivated treatments, the increase in MBC under reduced tillage systems compared to FP is attributed to greater C source availability (POM-C, POXC, and WEOC) and favorable soil environmental conditions for microbial activity (Wardle, 1992; Purakayastha et al., 2009). Crop residue accumulation at the soil surface not only provided organic C substrates for microbial biomass, but reduced soil disturbance likely favored the formation of stable soil aggregates that protected microbial biomass against soil temperature and water fluctuations (Collins et al., 1992; Franzluebbers et al., 1995; Balota et al., 2003). Nevertheless, SP exhibited intermediate MBC between reduced tillage systems and FP. Under FP, residue was plowed down immediately after crop harvest in the fall, while residue was incorporated only at seeding in the following spring under SP. Therefore, delaying residue incorporation under SP provided greater C-substrate availability for microbial biomass than FP. However, soil mixing of residue under SP accelerated residue decomposition and resulted in less C-substrate availability for microbes than reduced tillage systems, where residue left at soil surface provided steady C-source to microbes.

Although not significant, soil microbial N was higher under FP and SP than under NT and DT/CT, probably due to slightly greater assimilation of N from POM-N and WEOM with plow-treatments. Similarly, no significant changes were observed on both MBC/SOC- and MBN/TN-values among treatments. Consequently, it appeared that plow-tillage systems tended to have slightly lower MBC/SOC but higher MBN/TN than corresponding values under reduced tillage treatments. In fact, the percentage of SOM as MBC and MBN followed patterns similar to the absolute values for microbial biomass among the cultivated soils. Our results follow the trend reported by Balota et al. (2003), where plowing resulted in lower MBC and MBC/SOC levels than those measured under NT. Changes in proportions of microbial biomass C and N in SOM mainly arise due to differences in organic matter inputs (both quality and amount), and their availability to microorganisms (Anderson and Domsch, 1989). Using isotopic technology, other researchers have corroborated that C and N of microbial biomass are more closely associated with C and N of added residue than bulk soil C and N, suggesting that residue provide most of the microbial energy and nutrient requirements (Flessa et al., 2000; Gregorich et al., 2000). Soil mixing of residues under plow-treatments increases accessibility and availability of substrates to soil microbes and thereby enhances residue decomposition. However, low C but high N levels assimilated by soil microbes under plow-treatments would relate to more losses of C from soil via microbial respiration and greater risk of N leakage out of the soil system. Conversely, greater conversion efficiency of C into microbial biomass but with low N assimilation under reduced tillage treatments would imply more stabilization of organic C and slow release of N in soil. Overall, soil microbes are sustained for longer periods under reduced tillage with steady supply of substrates. Nevertheless, GP generally had low MBC/SOC but high MBN/TN-values compared to cultivated treatments. Wheat-pea residues in cultivated systems are likely more biodegradable compared to residues in GP. Addition of C-rich residues (high C:N) in soil would reduce microbial utilization efficiency of C, while increasing microbial N use efficiency and retention (Mooshammer et al., 2014). In our study, MBC represented 2.84–3.12% of total SOC, and MBN represented 3.3–5.3% of TN. Comparable values were reported for the same site in an earlier study (Collins et al., 1992), and for similar soils and management systems in eastern Washington (Purakayastha et al., 2008).

The trend observed for microbial biomass proportions in bulk SOM among treatments was further reflected in corresponding

TABLE 6 | *F*-statistic and total variability (R^2) of the best stepwise multiple linear regression model for predicting soil organic carbon (SOC).

Response variable	Full model			Final model		
	Predictors†	***F*-statistic**	R^2	**Predictors**†	***F*-statistic**	R^2
SOC	POM-C, POM-N, POXC, WEOC, MBC, BR, Cmin, qCO_2	9.7	0.74	POXC, WEOC	34.9	0.69

†*Predictors are POM-C, particulate organic matter carbon; POM-N, particulate organic matter nitrogen; POXC, permanganate oxidizable carbon; WEOC, water extractable organic carbon; MBC, microbial biomass carbon; BR, basal respiration; Cmin, cumulative carbon mineralized in 30-d;* qCO_2*, metabolic quotient.*

MBC:MBN-values. The values of microbial biomass C:N were generally higher under NT and DT/CT than under SP and FP. Similar results were observed by Balota et al. (2004), where increased tillage disturbance reduced microbial biomass C:N-values. Microbial biomass C:N ratio has been frequently used to define microbial community structure. A decline in microbial C:N is correlated with a gradual shift from fungal to bacterial predominance in microbial biomass because fungi have relatively higher C-demand than bacteria, whereas bacteria are more constrained by nutrient ratios (Cleveland and Liptzin, 2007). Fungal predominance in soils would lead to increased soil aggregation, greater accumulation, and stabilization of SOM, and improved nutrient cycling (Cookson et al., 2008).

The values of basal respiration (BR) and Cmin were highly correlated and had similar trends in all treatments (**Table 5**). It is worth noting that the relationships of BR with Cmin generally improved with increasing Cmin incubation time (data not shown). This could be due to the 7-d pre-incubation used before determining BR. Cmin was computed without accounting for such pre-incubation period. In addition, other studies have indicated that disturbances during soil sampling and processing could artificially stimulate and thereby overestimate values of C mineralization by exposing protected SOM in soils, especially under reduced tillage systems (Franzluebbers et al., 1995; Balota et al., 2004). However, the amounts of CO_2-C evolution under plow-tillage treatments should reflect the field conditions.

Nevertheless, cultivated treatments had lower BR and Cmin than GP, which could be attributed to greater C availability and microbial biomass under GP (Fernandes et al., 2005). Higher pH, lower bulk density, and greater available water content of GP soils could have also favored greater soil microbial biomass and activity (**Table 1**; Franzluebbers, 1995; Jensen et al., 1997). Accordingly, among cultivated treatments, the lowest values of BR and Cmin under FP could be related to low MBC and C-availability (POXC, POM-C, WEOC) in this treatment. A similar result was observed for Cmin/SOC proportion, where FP exhibited the least value. Residue under FP was plowed under soon after crop harvest compared to SP treatment where residue was plowed down in spring of following year. Residues start decomposing immediately after incorporation under FP resulting in less C-substrate in this treatment compared to SP (Machado et al., 2006). On the other hand, higher microbial activity under reduced tillage systems can be attributed to more residues and MBC in the top soil compared to FP. Microbial activity was, however, comparable between reduced tillage treatments and SP. Recent mixing of residues under SP could have resulted in the flush of microbial activity (Franzluebbers, 1995; Franzluebbers et al., 1995). In general, high microbial activity in soil is regarded as improvement in soil health. However, studies have also suggested that the values of BR and Cmin can either provide an estimate of soil microbial index associated with the availability of large pools of C substrates, or relate to an ecological disorder (Aziz et al., 2013). Soil microbial index is considered a proxy for organic carbon cycling and its associated nutrients such as N, P, and S, indicating that higher microbial activity reflected greater soil productivity and vice-versa (Fernandes et al., 2005). Conversely, soils under ecophysiological disorder may also increase microbial respiration, as a mechanism to meet energy demand for cell integrity and maintenance by microbial biomass. Therefore, relating microbial activity with corresponding microbial biomass size (soil respiration per unit MBC or qCO_2) may explain if a particular system is aggrading or degrading SOM (Fernandes et al., 2005).

Metabolic quotient (qCO_2) showed significant variation among treatments, with FP and SP measuring lowest and highest rates, respectively, and intermediate rates under GP, NT, and DT/CT. qCO_2 represents microbial utilization efficiency of soil C or C energy usage for maintaining metabolic activity (respiration) in relation to microbial growth. Therefore, lowest qCO_2 rate under FP could be related to reduced microbial biomass (MBC) and its corresponding low microbial activity, as a result of C-substrate limitation from fall-plowing of residue (Balota et al., 2003). Such observation indicates that FP treatment would result in the lowest SOC accumulation. Compared to FP, qCO_2 rate increased slightly under NT, but significantly under other treatments and this was attributed to corresponding increases in both microbial biomass and activity. Soil microbial activity (BR and Cmin) demonstrated positive correlation with MBC (**Table 5**). But interestingly, SP had the highest qCO_2 rate among the treatments and that was significantly so when compared to qCO_2 under NT. These results imply that during the metabolism of available SOM, SP would have greater proportion of CO_2-C respiration losses and lower C assimilation into microbial biomass as compared to NT. Conversely, reduced tillage systems would likely increase SOM storage and improve nutrient cycling compared to spring plowing (Balota et al., 2003; Mooshammer et al., 2014).

It is also worth noting that neither microbial biomass nor its activity (BR, Cmin, qCO_2) had any correlation with labile N-pools, including TDN, KEN, WEON, and MBN. Instead, these microbiological pools demonstrated significant correlations with SOC pools. These results suggested that microbial activity was primarily regulated by the availability of C-substrates across tillage gradients. Accordingly, relatively higher C-availability in

NT treatment could have counter-balanced low soil pH effects on microbial biomass and its activity.

Overall, the study demonstrated that differences in bulk SOM (SOC and TN) of surface 0–15 cm soil was influenced by land use practices (GP vs. cultivated soils). However, no significant changes in bulk SOM levels were observed among cultivated treatments (tillage systems) within WP-LTE. Conversely, almost all SOC pools responded to tillage as well as to land-use. TN pools, with the exception of POM-N, were not influenced by tillage. These results suggested that tillage induced changes were probably associated more with long-term SOC sequestration than N-availability in soil under wheat-pea rotation. The SOM pools showed significant relationships among each other and with SOC and TN. These results are in accordance with those reported by Morrow et al. (2016), who observed that POXC, WEOC, WEON, MBC, MBN, Cmin (24-d), N-mineralization, acid hydrolysable, and non-hydrolysable C- and -N, SOC, and TN were all positively correlated with each other across soils under diverse agroecosystems within the iPNW. Similarly, significant interrelationships among SOM pools have also been reported in other arable soils in different agroecoregions (Cookson et al., 2008; Dou et al., 2008; Chen et al., 2009; Culman et al., 2012; Awale et al., 2013; Hurisso et al., 2016). Nevertheless, in the present study, C-pools were more strongly correlated with SOM compared to N-pools. These results corroborate previous findings that physical (POM), chemical (POXC and WEOC), and microbiological (MBC, BR, Cmin, and qCO_2) pools of SOM are relatively more sensitive to tillage disturbance than total SOC and TN (Balota et al., 2003; Cookson et al., 2008; Awale et al., 2013). Among these sensitive SOC pools, POXC and WEOC exhibited highest correlations with SOC and TN. In addition, among all the sensitive SOM pools, stepwise regression analyses selected the combination of POXC and WEOC pools as the best predictors of SOC. These results identified POXC and WEOC pools as the most sensitive SOM pools to tillage under the wheat-pea cropping system near Pendleton, Oregon.

CONCLUSIONS

Our study demonstrated that physical (POM), chemical (POXC and WEOC), and microbiological (MBC, BR, Cmin, and qCO_2) pools of SOM were more sensitive to long-term tillage management practices than bulk SOC and TN under a wheat-pea rotation. However, microbial measurements can exhibit seasonal variation due to changes in soil water content and temperature, and caution should be taken when extrapolating the results of this study to other situations (Collins et al., 1992; Fernandes et al., 2005). Analysis of microbiological SOM pools at different times during the season should provide more information needed for management decisions. Chemical pools of SOM were more sensitive than microbiological and physical indicators of tillage induced SOM dynamics. Therefore, given the complexity and time required to determine microbial pools, we recommend use of POXC or WEOC in the early detection of SOM trends for the purposes of adjusting management practices to enhance SOC accretion and improving soil health. From the perspective of long-term SOM storage, fall-plowing (FP) would likely contribute the least among all tillage systems studied. Differences in SOM storage between NT and reduced tillage (DT/CT) management are likely to continue to be negligible, reflecting the minimum disturbance nature of DT/CT. While these reduced tillage systems exhibit superiority over FP and SP in building up SOM, delaying tillage until spring (SP) sequestered more C than FP. Overall, adoption of reduced tillage systems (NT and DT/CT) should increase SOM storage under wheat-pea cropping system overtime in the iPNW.

AUTHOR CONTRIBUTIONS

RA and SM: Conceived and designed the experiment. RA and ME: Performed the experiment. RA and SM: Analyzed data and wrote the manuscript.

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Assessment of Climate Change and Atmospheric CO_2 Impact on Winter Wheat in the Pacific Northwest Using a Multimodel Ensemble

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Simulations of crop yields under climate change are subject to uncertainties whose quantification is important for effective use of projected results for adaptation and mitigation strategies. In the US Pacific Northwest (PNW), studies based on single crop models and weather projections downscaled from a few general circulation models (GCM) have indicated mostly beneficial effects of climate change on winter wheat production for most of the twenty-first century. In this study we evaluated the uncertainty in the projection of winter wheat yields at seven sites in the PNW using five crop growth simulation models (CropSyst, APSIM, DSSAT, STICS, and EPIC) and daily weather data downscaled from 14 GCMs for 2 representative concentration pathways (RCP) of atmospheric CO_2 (RCP4.5 and 8.5). All crop models were calibrated for high, medium, and low precipitation dryland sites and one irrigated site using 1979–2010 as the baseline period. All five models were run from years 2000 to 2100 to evaluate the effect of future conditions (precipitation, temperature and atmospheric CO_2) on winter wheat grain yield. Simulations of future climatic conditions and impacts were organized into three 31-year periods centered around the years 2030, 2050, and 2070. All models predicted a decrease of the growing season length and crop transpiration, and increase in transpiration-use efficiency, biomass production, and yields, but with substantial variation that increased from the 2030s to 2070s. Most of the uncertainty (up to 85%) associated with predictions of yield was due to variation among the crop models. Maximum uncertainty due to GCMs was 15% which was less than the maximum uncertainty associated with the interaction between the crop model effect and GCM effect (25%). Large uncertainty associated with the interaction between crop models and GCMs indicated that the effect of GCM on yield varied among the five models. The mean of the ensemble of all crop models and GCMs provided a robust indication of positive effects of future environmental conditions on winter wheat yield during this century at all sites studied, with greater beneficial effect under water stressed conditions than under well-watered conditions, and under RCP8.5 than RCP4.5.

Keywords: climate change, CO_2 fertilization, crop-climate models, multimodel ensemble, uncertainty, winter wheat

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INTRODUCTION

Climate change is a major concern for crop productivity. The chief elements of climate change include rising temperature, modified frequency, and severity of extreme events, and elevated atmospheric concentration of CO_2 (Rosenzweig and Tubiello, 2007). Concentrations of CO_2 are now significantly higher than in earlier years and they have been increasing continuously and rapidly (Siegenthaler et al., 2005). Agriculture is one of the sensitive sectors to climate variability and change (Slingo et al., 2005; Osborne et al., 2013). Climate change has affected crop growth, development and yield over the past few decades across the globe directly or indirectly (Nicholls, 1997; Lobell and Asner, 2003; Challinor and Wheeler, 2008a; Teixeira et al., 2013). Direct effects are due to increased CO_2 fertilization which leads to higher photosynthetic rate and water use efficiency (Challinor and Wheeler, 2008b). Indirect effects include crop responses to variability in temperature and precipitation. Higher seasonal temperature increases the risk of water stress, limits photosynthesis, and reduces light interception by accelerating crop phenological development (Tubiello et al., 2007).

Wheat is the third largest crop globally, which has shown particular sensitivity to climate change (Porter and Semenov, 2005), yet increased wheat yield has also been reported for some regions of the world because of increased growth rates and a shift of the grain filling period to a wetter part of the season (Xiao et al., 2010).

Mechanistic process-based crop models are common tools for assessing the impact of climate change on crop productivity, incorporating physiological responses of crop growth and development to environmental and management variables. Different crop models have been used to study climate change impact on crop production across the globe but with mixed results (Lobell and Burke, 2010). The assessment of climate change impacts on agriculture often has been conducted using

TABLE 1 | Modeling approaches of five models used for a study of climate change effects on crop performance in the Pacific Northwest.

Model characteristic	Crop model				
	CropSyst	**APSIM**	**DSSAT**	**EPIC**	**STICS**
Crop phenology[a]	f (TPV)	f (TPVW)	f (TPV)	f (TPV)	f (TPVO)
Leaf area development and Light interception[b]	S	D	D	S	D
Light utilization/Biomass production[c]	TE /RUE	RUE/TE	RUE	RUE	RUE
Biomass partitioning[d]	None	PCD	PCD	None	PCD
Yield formation[e]	B, HI	Prt, B, Gn, LHI	B, Gn, HI	B, HI	B, Gn, HI
Root distribution over depth[f]	LIN	EXPO	EXPO	EXPO	SIG
Stresses[g]	WNH	WAH	WN	WNO	WNH
Water stress type[h]	E	S	E	E	S
Heat stress type[i]	VR	V	–	V	VR
Water dynamics[j]	C	C	C	C	C
Water relation[k]	S	D	D	S	D
Plant N budget[l]	S	D	D	S	D
Evapotranspiration[m]	PM	PT	PM	PM	PT
Soil CN model[n]	CNP(1)	CNP(3)B	CNP(4)B	CNP(5)	CNP(3)B
CO_2 effects[o]	RUE/TE/T	RUE/TE	RUE/TE	RUE/TE	RUE
Model relative[p]	CRS	C	C	C	C
Model type[q]	P	P	P	PG	P

[a] *Crop phenology is a function (f) of: T, temperature; P, photoperiod; V, vernalization; W, water stress; O, other water stress or nutrient stress.*
[b] *Leaf area development and Light Interception: S, simple; D, detailed approach.*
[c] *Light Utilization/Biomass Production: RUE, radiation use efficiency; TE, transpiration-use efficiency.*
[d] *Biomass partitioning: PCD, detailed partitioning coefficients and more organs.*
[e] *Yield Formation: B, total above ground biomass; HI, fixed harvest index; Prt, partitioning during reproductive stages; LHI, linear increase in harvest index; Gn, grain number.*
[f] *Root distribution over depth: LIN, linear; EXPO, exponential; SIG, sigmoidal.*
[g] *Stresses: W, water; N, nitrogen; H, heat; A, air (Oxygen); O, others (e.g. EPIC model considers stresses for both above ground (water, temperature, nitrogen, phosphorus and potassium stresses) and below ground growth [Bulk density, aluminum tolerance (Soil acidity), salinity, temperature and soil aeration)].*
[h] *Water stress type: E, Eta/Etp; S, soil available water in root zone.*
[i] *Heat stress type: V, vegetative (source); R, reproductive (sink).*
[j] *Water Dynamics: C, Tipping bucket capacity approach.*
[k] *Water relation: S, simple approach includes linear increase in root depth; D, detailed approach includes root growth and water absorption.*
[l] *Plant N budget: S, simple from nitrogen dilution curve; D, detailed concentration curves for different organs over growth period.*
[m] *Evapotranspiration: PM, Penman-Monteith; PT, Priestley-Taylor.*
[n] *Soil CN model: N, nitrogen mode; P(x), x number of organic matter pools; B, microbial biomass pool.*
[o] *CO_2 effects: RUE, radiation use efficiency; TE, transpiration efficiency; T, stomatal conductance.*
[p] *Model relative: CRS, CropSyst; C, CERES.*
[q] *Model type: P, point model (site specific); G, global or regional model.*

a combination of weather downloaded from general circulation models (GCM) and crop responses evaluated with cropping systems models (CSM), often one crop model and a few GCM projections. This approach has been applied to the US Pacific Northwest (PNW) with projections suggesting mostly beneficial effects of climate change on wheat production, especially winter varieties (Thomson et al., 2002; Stöckle et al., 2010). However, recent studies (e.g., Asseng et al., 2013; Martre et al., 2015; Ruane et al., 2016) have shown large variation in both GCM and CSM projections, which can introduce significant uncertainty in assessments of climate change impact on agriculture.

Based on results of a 27-wheat model comparison study, Asseng et al. (2013) reported that crop models were able to produce acceptable yield estimates compared to observations from single-year experiments for four diverse sites when properly calibrated. However, when changes in precipitation combined with increases in temperature and atmospheric CO_2 concentration were imposed on the same sites, a large variation in yield projections was obtained. Thus, Asseng et al. (2013) recommended the use of crop model ensembles, particularly when limited information about the crops and cropping systems involved is available, suggesting that at least five models should be used for reliable assessment of yield impacts for temperature increases up to 3°C and 540 ppm of CO_2, with fewer models needed for lower temperature increases and vice versa. Similar results have been reported for maize models (Bassu et al., 2014) and rice models (Li et al., 2015), where model ensembles appeared to perform better than individual models when compared with observations. Martre et al. (2015) concluded that there was no additional advantage of a model ensemble including more than 10 models. Bassu et al. (2014), in a study involving 23 maize models, concluded that a single model may not be able to simulate well absolute yields while an ensemble of 8–10 models is more likely to perform better if a small amount of information is available for calibration. Li et al. (2015) evaluated 13 rice models against experimental information and found that individual models were not consistent in reproducing observed yields, but an ensemble of five models properly calibrated was able to approximate measured yields within the uncertainty of well-controlled experiments.

Studies such as those of Asseng et al. (2013), Bassu et al. (2014), and Li et al. (2015) that include a large number of crop models for a given crop species are possible by the direct involvement of modelers and user groups. The customary use of large crop model ensembles as a standard practice in climate change assessments would be time consuming and costly (at least for now), and will require significant cooperation. In the meantime, securing adequate information on some key crop characteristics such as crop phenology, canopy cover [e.g., maximum leaf area index (LAI)], and rooting depth along with the use of a few models, well-documented and tested under a large range of conditions around the world, appears to be a reasonable approach.

With the interest of corroborating or disputing previous findings regarding climate change impacts on wheat production in the PNW, USA, in this study we evaluated the uncertainties in yield projections related to crop-climate models using 5 CSMs and 14 GCMs. Our primary focus was on the usefulness of applying a multimodel ensemble in the examination of future climate change in the IPNW. Toward this end, we excluded consideration of rotational effects and other effects related to farm management decisions.

MATERIALS AND METHODS

The impacts on winter wheat productivity at six dryland and one irrigated sites were evaluated using five well-established CSM (CropSyst, APSIM-Wheat, DSSAT CERES Wheat, EPIC, and STIC) and downscaled weather projections from 14 GCMs and 2 RCPs (RCP4.5 and 8.5).

TABLE 2 | General circulation models used to study dryland crop response to future climate change in the Inland Pacific Northwest.

General Circulation Model	Source	References
BCC-CSM1.1	Beijing Climate Center	Wu et al., 2014
BNU-ESM	Beijing Normal University Earth System Model	Ji et al., 2014
CanESM2	Canadian Centre for Climate Modeling and Analysis	Chylek et al., 2011.
CNRM-CM5	Centre National de Recherches Me'te'orologiques—Groupe d'e'tudes de l'Atmosphe're Me'te'orologique and Centre Europe'en de Recherche et de Formation Avance'e	Voldoire et al., 2013
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation and Queensland Climate Change Centre of Excellence	Jeffrey et al., 2013
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory Earth System Models	Dunne et al., 2013
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Models	Delworth et al., 2006
HadGEM2-CC	Hadley Global Environment Model 2—Carbon Cycle	Martin et al., 2011
HadGEM2-ES	Hadley Global Environment Model 2—Earth System	Martin et al., 2011
INMCM4	Institute for Numerical Mathematics, Moscow, Russia	Voldin et al., 2010
MIROC5	Model for Interdisciplinary Research on Climate	Watanabe et al., 2010
MIROC-ESM	Model for Interdisciplinary Research on Climate, Earth System Model	Watanabe et al., 2011
MIROC-ESM-CHEM	Model for Interdisciplinary Research on Climate, Earth System Model	Watanabe et al., 2011
MRI-CGCM3	Meteorologcical Research Institute	Yukimoto et al., 2012

TABLE 3 | Characteristics of seven study sites used for a study of climate change effects on crop performance in the Pacific Northwest.

Characteristics	Study site						
	Pullman	**Kambitsch**	**Wilke**	**St. John**	**Lind**	**Moro**	**Moses Lake (irrigated)**
Position latitude/longitude/altitude m.a.s.l	46°78′/–117°09′/ 796.75	46°58′/–116°95′/ 848.86	47°65′/–118°14′/ 743.71	47°09′/–117°58′/ 598.00	47°00′/-118°56′/ 505.35	45°48′/-120°72′/ 566.92	47°31′/–119°54′/ 389.00
Average annual precipitation (mm year^{-1})	590.3	685.2	354.7	437.4	261.1	296.3	205.0
Simulation period precipitation (mm)	474.7	561.6	323.0	407.6	216.1	229.5	192.7
Average annual temperature (°C)	7.2	6.9	5.5	6.6	7.1	7.1	8.7
Soil texture	Silty Clay Loam	Silty Clay Loam	Coarse Silt Loam	Coarse Silt Loam	Coarse Silt Loam	Coarse Silt Loam	Sandy Loam
Sand (%)	12.0	7.6	11.0	11.0	21.7	14.2	48.9
Silt (%)	69.3	63.6	68.6	68.6	70.8	71.8	21.1
Clay (%)	18.7	28.7	20.4	20.4	7.5	14.0	30.0
Bulk density (g cm^{-3})	1.3	1.3	1.3	1.3	1.3	1.4	1.4
Soil water at field capacity in the root zone (m^3 m^{-3})	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Soil water at wilting point in the root zone (m^3 m^{-3})	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Soil name	Mollisol	Mollisol	Mollisol	Mollisol	Aridisol	Aridisol	Aridisol

TABLE 4 | Target results for a series of five cropping system models used in a study of climate change effects on crop performance at several locations in the Pacific Northwest.

Study site	Crop trait	Predicted					
		Target range	APSIM	CropSyst	DSSAT	EPIC	STICS
Pullman	Emergence (DOY)[†]	295	295	295	295	295	295
	Anthesis time (DOY)	162	160	162	162	–	160
	Maturity time (DOY)	215	214	216	215	215	214
	$LAI^{†}_{max}$	4.5–6.0	4.5–6.9	2.2–6.3	3.5–6.5	4.8–5.4	4.5–6.2
	Biomass at harvest (t ha^{-1})	11.2–16.0	10.0–16.3	6.3–17.6	8.8–16.3	12.9–15.0	9.4–15.9
	Grain yield (t ha^{-1})	4.5–7.2	3.5–7.8	2.6–7.8	3.1–7.5	5.4–6.2	5.0–7.5
	HI[†]	0.40–0.45	0.35–0.45	0.41–0.44	0.36–0.45	0.40–0.42	0.35–0.46
Wilke	Emergence (DOY)	260	260	260	260	260	260
	Anthesis time (DOY)	150	149	150	150	–	150
	Maturity time (DOY)	200	199	200	200	200	200
	LAI_{max}	3.5–5.0	2.1–5.0	3.0–5.7	2.5–6.0	3.3–4.2	3.2–5.4
	Biomass at harvest (t ha^{-1})	9.0–12.0	8.0–15.2	5.4–14.3	8.1–15.5	5.3–13.8	8.5–12.5
	Grain yield (t ha^{-1})	3.3–5.00	2.69–7.2	2.2–6.2	2.5–7.2	2.1–5.8	3.5–7.0
	HI	0.38–0.43	0.30–0.49	0.41–0.44	0.30–0.46	0.40–0.42	0.39–0.44
Lind	Emergence (DOY)	251	251	250	251	251	251
	Anthesis time (DOY)	143	143	143	143	143	143
	Maturity time (DOY)	191	191	191	191	191	191
	LAI_{max}	2.5–3.5	1.6–3.4	2.5–3.5	2.5–3.0	2.5–3.8	2.5–3.3
	Biomass at harvest (t ha^{-1})	2.6–8.0	1.7–9.5	2.1–9.0	2.1–8.5	2.4–11.9	2.7–8.9
	Grain yield (t ha^{-1})	1.0–3.5	0.7–4.0	1.0–4.0	0.8–3.6	0.9–5.0	1.1–4.0
	HI	0.38–0.43	0.38–0.46	0.40–0.43	0.39–0.42	0.38–0.42	0.38–0.44
Moses Lake	Emergence (DOY)	251	251	251	251	251	251
	Anthesis time (DOY)	143	143	143	143	–	143
	Maturity time (DOY)	191	191	191	191	191	192
	LAI_{max}	6.0–7.0	4.5–6.5	4.9–7.0	5.5–6.5	4.6–5.3	5.9–7.0
	Biomass at harvest (t ha^{-1})	16.5–20.0	14.4–22.2	14.5–21.7	12.3–21.9	14.2–21.0	16.0–20.6
	Grain yield (t ha^{-1})	7.5–9.5	6.0–9.0	6.5–11.4	5.0–10.6	6.0–8.9	7.1–8.2
	HI	0.45–0.48	0.35–0.45	0.44–0.45	0.38–0.48	0.41–0.42	0.37–0.49

[†] *DOY, day of year; LAI_{max}, maximum leaf area index; HI, harvest index.*

Crop Models

CropSyst

CropSyst is a multi-year, multi-crop, daily time-step cropping system model developed as an analytical tool to study the effect of climate, soil, and management on the productivity and environmental impact of cropping systems (Stöckle et al., 2003). The model can simulate crop development, growth and yield in response to weather, atmospheric CO_2 concentration, and management (crop rotations, fertilization, irrigation, tillage), and soil processes such as soil water dynamics, nitrogen budgets, soil erosion by water, and salinity. Details on the use, parametrization and execution of CropSyst are given on the website (http://modeling.bsyse.wsu.edu/CS_Suite_4/CropSyst/index.html).

APSIM

The APSIM (Agricultural Production Systems Simulator) is a modeling framework developed by the Agricultural Production Systems Research Unit (APSRU) in Australia (Keating et al., 2003). APSIM was developed to simulate biophysical processes in farming systems, in particular where there is interest in the economic and ecological outcomes of management practice in the face of climatic risk (Keating et al., 2003). It was constructed on a modular modeling framework based on biophysical processes in farming systems with many plant, soil and management modules for a diverse range of crops, pastures and trees, soil processes including water balance, nitrogen and phosphorus transformations, soil pH, erosion, and a full range of management controls. Details of the model are included on the APSIM web site (https://www.apsim.info/Documentation.aspx). The APSIM-Wheat model version 6.1 (Wang et al., 2002; Keating et al., 2003) was used in this study.

DSSAT_CERES_Wheat

The CERES wheat model included in the DSSAT (Decision Support System for Agrotechnology Transfer) family of models is a complex model used to integrate knowledge about crops, soil, climate, and management for making appropriate decisions under a wide range of climatic conditions. It can be used to design

TABLE 5 | Performance of five crop models under historical weather conditions (1979–2010) in simulating mean maximum leaf area index (LAI_{max}), above-ground biomass, grain yield and harvest index (HI) with standard deviation and coefficient of variation at three sites not used for model calibration in the Pacific Northwest.

Study site	Crop trait	APSIM			CropSyst			DSSAT			EPIC			STICS		
		Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
Kambitsch	LAI_{max} (m^2 m^{-2})	5.8	0.4	0.1	6.0	0.3	0.1	5.5	2.3	0.4	5.8	1.1	0.2	5.5	1.2	0.2
	Biomass (t ha^{-1})	13.9	2.5	0.2	16.4	2.1	0.1	13.6	3.2	0.2	14.0	2.7	0.2	14.6	2.1	0.2
	Yield (t ha^{-1})	5.8	1.2	0.2	7.2	1.0	0.1	6.0	1.2	0.2	5.7	1.1	0.2	6.6	1.0	0.2
	HI	0.42	0.04	0.10	0.44	0.01	0.02	0.45	0.05	0.11	0.40	0.01	0.02	0.46	0.06	0.13
Moro	LAI_{max} (m^2 m^{-2})	2.9	0.4	0.2	3.5	1.5	0.4	2.7	2.4	0.9	3.2	0.4	0.1	3.3	1.4	0.4
	Biomass (t ha^{-1})	6.5	1.6	0.3	6.2	2.6	0.4	6.7	3.3	0.5	6.7	2.6	0.4	6.3	2.6	0.4
	Yield (t ha^{-1})	2.7	0.7	0.3	2.6	1.1	0.4	2.8	1.5	0.5	2.8	1.1	0.4	2.9	1.6	0.6
	HI	0.42	0.02	0.04	0.42	0.01	0.02	0.42	0.05	0.12	0.42	0.05	0.11	0.47	0.19	0.40
St. John	LAI_{max} (m^2 m^{-2})	5.0	0.9	0.2	4.9	1.0	0.2	4.5	1.3	0.3	4.6	0.7	0.2	4.7	0.8	0.2
	Biomass (t ha^{-1})	15.2	1.4	0.1	11.0	2.7	0.3	12.0	2.6	0.2	10.4	2.3	0.2	11.7	1.4	0.1
	Yield (t ha^{-1})	6.2	1.1	0.2	4.7	1.2	0.3	5.3	1.3	0.2	4.3	1.0	0.2	4.7	0.8	0.2
	HI	0.41	0.04	0.10	0.43	0.01	0.03	0.45	0.08	0.18	0.41	0.01	0.02	0.40	0.04	0.10

optimum crop management practices, precision agriculture, and pest management. Similarly, it can be used to quantify responses to climate change and variability impacts on crop yield and to study long term sustainability, environmental pollution and genomics (Hoogenboom et al., 2012; http://dssat.net/).

EPIC

The EPIC (Environmental Policy Integrated Climate) model is a field scale soil and crop model originally designed to quantify the effects of erosion on soil productivity (Williams et al., 1984). It is a complete agroecosystem model that can simulate crop growth under different rotations while simulating detailed soil management operations. EPIC version 0810 was used in this study. Additional information on the EPIC model can be found at http://epicapex.tamu.edu/epic/.

STICS

The STICS crop growth model was developed by INRA, France (Brisson et al., 2003). The model can simulate carbon, water and nitrogen dynamics as well as a number of different environmental and agricultural variables in response to weather, soil, crop, and management practices. STICS is a generic model that can simulate various kinds of crops and environmental conditions. Options for plant parameters associated with detailed ecophysiological characteristics are adjusted to define a specific crop. Additional parameters are used to simulate physical and biological processes occurring in the soil-crop system and define soils, crop management and climate. In this work, we used STICS version v8.4. The detailed description of all parameters used in the model is available in the document freely downloadable with the model from http://www6.paca.inra.fr/stics_eng/.

A general description of the approaches used by each of the five crop models is presented in **Table 1**.

General Circulation Models (GCMs)

Many GCMs have been evaluated for use in climate change studies (Randall et al., 2007; Flato et al., 2013). The fourteen GCMs listed in **Table 2** were used in this study due to their suitability for use in North America (Rupp et al., 2013; Sheffield et al., 2013). The methodology used for generation of the weather data for these GCMs is found in Abatzoglou (2013) and Abatzoglou and Brown (2012). Specific datasets are available at http://thredds.northwestknowledge.net:8080/thredds/reacch_climate_MET_catalog.html.

Emission Scenarios

Representative concentration pathways (RCP) are climate change research scenarios that contain trajectories of emissions, GHG concentrations and land-use patterns based on alternative responses of future socio-economic, technological, energy use, and emissions patterns (Van Vuuren et al., 2011). Four RCPs have been developed that provide distinct trajectories of radiative forcing and GHG concentrations (Moss et al., 2010). For this research, we used RCP4.5 which stabilizes at a radiative forcing of 4.5 W m^{-2} and 650 ppm CO_2-equiv in the year 2100, and RCP8.5 which develops a radiative forcing of 8.5 W m^{-2} and 1,370 ppm CO_2-equiv at 2100 (Moss et al., 2010). RCP4.5 is characterized by policies that, among other things, reduce energy use, reduce fossil fuel use, increase renewable and nuclear energy, employ CO_2 capture and storage, expand forests, and reduce beef consumption by a world population of 8.7 billion in 2100 (Thomson et al., 2011). RCP8.5 is characterized by minimal climate change policies, global population of 12 billion in 2100, slow income growth, high energy demand mostly from fossil fuels and declines in forested area (Riahi et al., 2011).

Study Sites

Seven diverse agro-ecological sites were selected for CSM and GCM models ensemble study. These sites are in the main

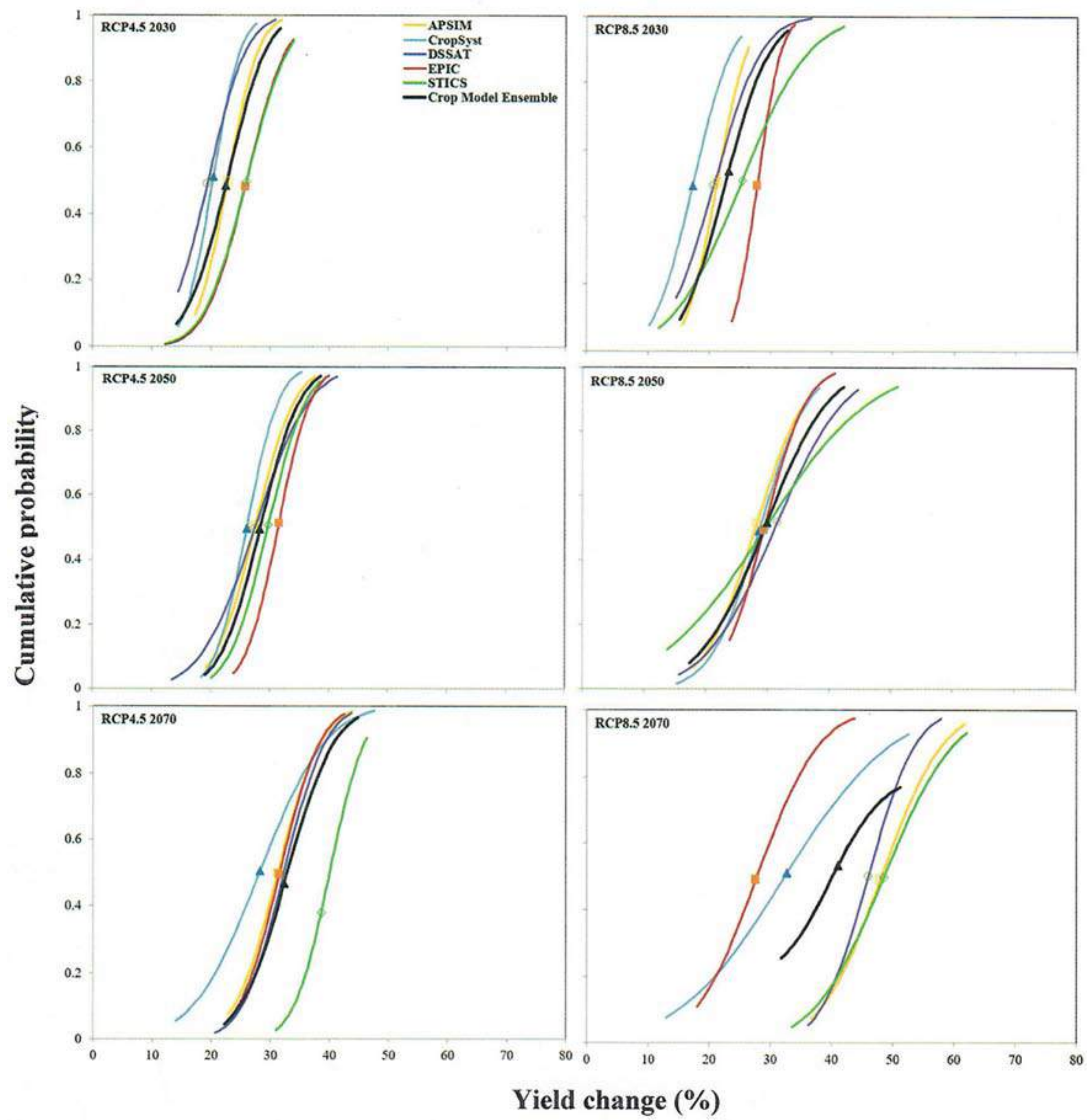

FIGURE 1 | Cumulative probability distribution for simulated winter wheat yield changes during three 31 year time periods, centered on 2030, 2050, and 2070, relative to the baseline period (1979–2010) under two representative concentration pathways (RCP4.5 and 8.5) and five crop models with ensembles of crop models at high rainfall site Pullman. Symbols on curves are at the curve's inflection point and represent the most probable yield change.

winter wheat production region in the IPNW. Average annual precipitation ranges from 125 to 700 mm on moving from west to east (Schillinger et al., 2010). Basic features of the study sites are summarized in **Table 3**.

Model Simulation Targets

To establish reasonable historical baselines for all five CSMs, four study sites were selected: Pullman (high precipitation), Wilke (intermediate precipitation), Lind (low precipitation), and Moses Lake (irrigated). Baseline simulations (1979–2010) were conducted for all models to meet targets for crop phenology (emergence, anthesis, and maturity dates), maximum LAI, biomass at maturity, and yield derived from literature and extension reports focused on winter wheat in the study region (Papendick, 1996; Schillinger et al., 2006; Schillinger, personal communication; WSU Extension variety trials). The model parameters used were as suggested for winter wheat by the respective models, with adjustments to phenology, and minor adjustments to leaf area development and biomass production parameters within the range provided by each model so as to conform to the targets, with the same set of parameters (except for phenology) used in all sites.

Although, winter wheat in the region is rotated with other cereals and legumes, to avoid adding complexity to

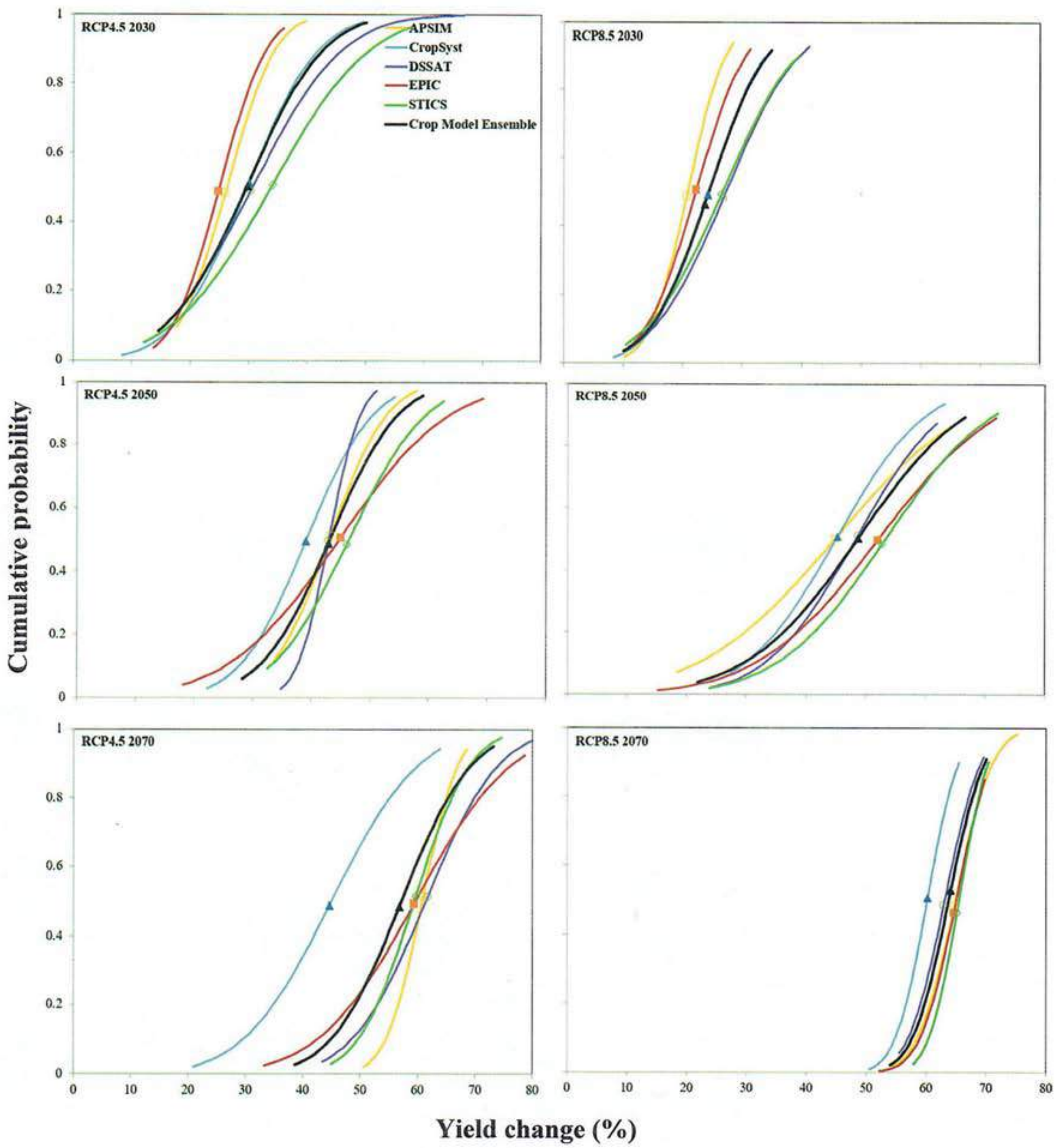

FIGURE 2 | Cumulative probability distribution for simulated winter wheat yield changes during three 31-year time periods, centered on 2030, 2050, and 2070, relative to the baseline period (1979–2010) under two representative concentration pathways (RCP4.5 and 8.5) and five crop models with ensembles of crop models at low rainfall site Lind. Symbols on curves are at the curve's inflection point and represent the most probable yield change.

the comparison of models and to focus on the simulated responses of wheat to climate variation and atmospheric CO_2, continuous winter wheat was simulated. The profile soil water content was reset to a set low value at the end of the summer each year, so that cumulative effects were not a factor. To focus our concern only on CSM and GCM, we removed the confounding effects of crop rotation and carryover. **Table 4** shows targets and baseline results after parameter adjustments.

Simulations and Analysis

In total, 140 simulations were generated for each study site (14 GCMs × 5 crop models × 2 RCPs), with outputs separated into three time periods (2030s, 2015–2045; 2050s, 2035–2065; and 2070s, 2055–2085). PROC ANOVA in SAS, Version 9.2 (SAS Institute Inc., 2010), was used to obtain the sums of squares for targeted effects, and an Uncertainty Index (UI) was calculated by dividing the treatment sums of squares by the total sums of squares (Holzkämper et al., 2015). The resulting UI is a measure

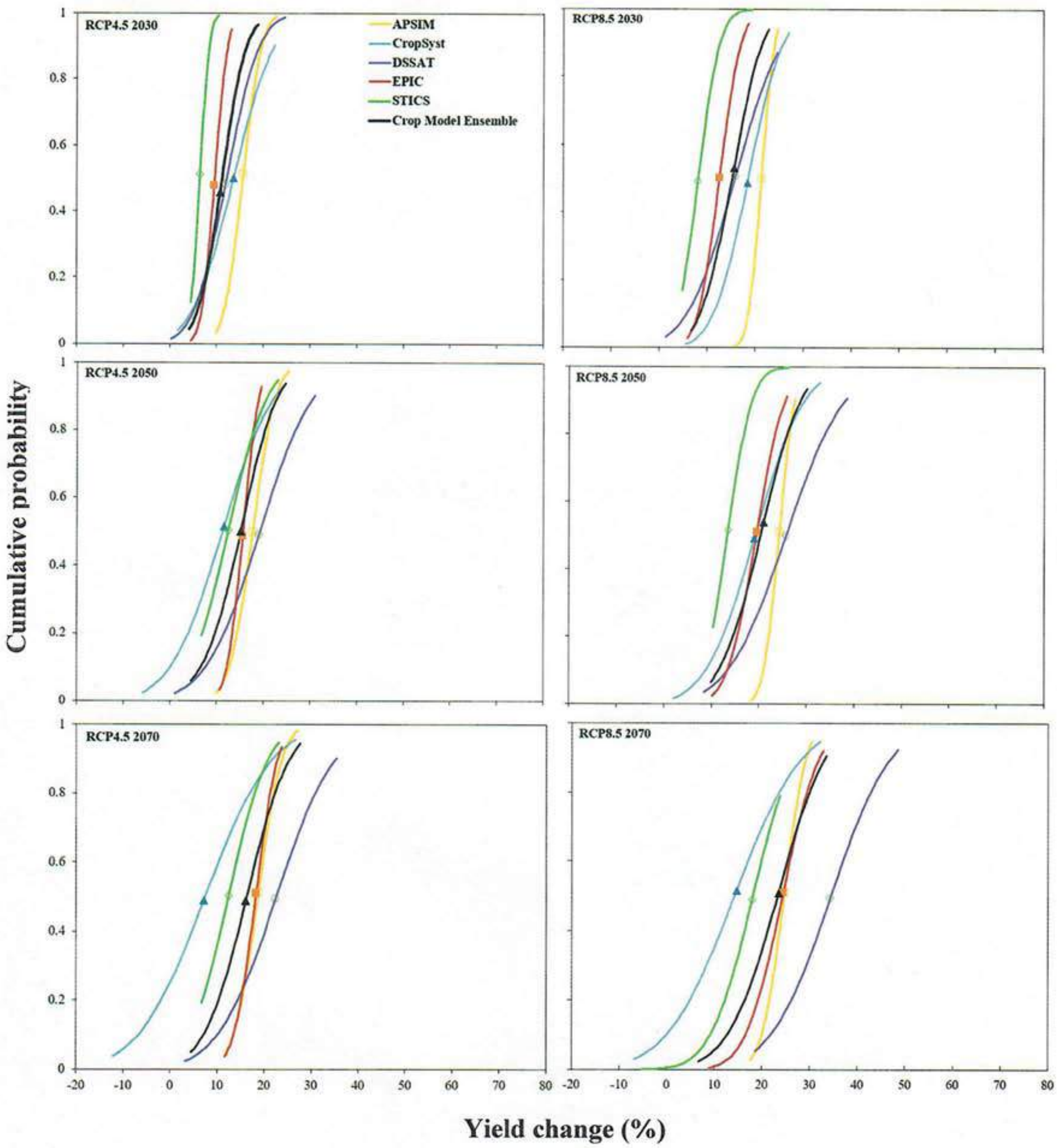

FIGURE 3 | Cumulative probability distribution for simulated winter wheat yield changes during three 31-year time periods, centered on 2030, 2050, and 2070, relative to the baseline period (1979–2010) under two representative concentration pathways (RCP4.5 and 8.5) and five crop models with ensembles of crop models at an irrigated site, Moses Lake, WA. Symbols on curves are at the curve's inflection point and represent the most probable yield change.

of the proportion of the total variation explained by the effect of interest.

The cumulative probability distributions (CPDs) for yield changes (see Section Results) were generated using a multi-step process. First the average yield was calculated for the historic period within location for each CSM. Then the average yield over all GCMs was calculated within location, CSM and year. The percentage change between this average projected yield (within location, CSM, and year) and its respective baseline yield was calculated, [percent change = ((future yield/baseline yield)−1) × 100]. This last calculation resulted in 41 percentage yield changes, one for each year within a given time period, location and CSM. The mean and standard deviation of these 41 values were used to generate the normal density distribution for the values and the CPD by applying the NORMDIST function in Microsoft Excel. The maximum value on the normal density distribution thus represents the percentage yield change with the highest probability of occurrence and

TABLE 6 | Percent changes with respect to baseline (1979–2009) values of selected process components contributing to changes in winter wheat yield during the 2070 period (2055–2085) and representative concentration pathway 8.5.

Study site	Response variable	Crop model				
		CropSyst	DSSAT	APSIM	STICS	EPIC
		(Percentage change from baseline)				
Lind	Length of growing season	−34.8	−16.9	−20.6	−30.9	−33.6
	$LAI_{max}^{\dagger}$	1.8	44.0	6.9	21.7	5.9
	Transpiration	−7.2	−2.3	−6.8	−2.2	−8.6
	Biomass	34.4	49.2	44.1	52.2	53.4
	Transpiration-use efficiency	41.8	46.8	39.8	33.0	36.3
Pullman	Length of growing season	−21.0	−15.7	−13.6	−20.2	−17.5
	$LAI_{max}^{\dagger}$	2.8	11.6	5.6	16.9	9.9
	Transpiration	−2.1	−5.3	−4.6	−5.7	−0.4
	Biomass	20.0	24.1	4.2	32.1	21.2
	Transpiration-use efficiency	25.0	25.6	20.9	23.0	18.3
Moses Lake	Length of growing season	−6.6	−12.6	−21.8	−12.7	−5.5
	$LAI_{max}^{\dagger}$	13.1	9.8	11.1	4.8	3.5
	Transpiration	−7.5	−10.8	−8.9	−2.1	−7.2
	Biomass	15.7	23.8	17.8	6.5	19.2
	Transpiration-use efficiency	18.4	22.8	16.5	10.8	16.6

† *LAI_{max}, maximum leaf area index.*

corresponds to the inflection point on the CPD. Rather than present both the normal and cumulative curves, we present only the cumulative curve with its inflection point identified.

RESULTS AND DISCUSSION

Baseline Period (1979–2010)

Three sites, Kambitsch, Moro and St. John, were not used for parameter adjustments/calibration. The relative performance of the five crop models using historical weather at these three sites is shown in **Table 5**. The results showed that the simulated LAI fluctuated within a relatively narrow range, while biomass and grain yields showed more variation among the models, except at the driest site, Moro, where better agreement existed. Nevertheless, most models were still within a narrow range of biomass and yield values at Kambitsch and St. John.

Probability Distribution of Crop-Climate Model Projections

The CPD of future winter wheat yield changes projected by the 14 GCMs for the five CSMs and three sites (Pullman, Lind, and Moses Lake) are presented in **Figures 1–3**, where the thicker line is the mean of the CSMs ensemble. All CSMs projected a positive impact of climate change and atmospheric CO_2 concentration on future winter wheat yields, but with significant variation. This variation was larger for RCP8.5 (more warming and higher atmospheric CO_2) than RCP4.5, and increased significantly with increasing time periods. The most probable yield change for the CSMs in Pullman (**Figure 1**), identified by the inflection point on the curves, ranged from 19 to 26% (RCP4.5) and from 17 to 28% (RCP8.5) for the 2030s, with the range increasing to 28 to 39% (RCP4.5) and 27 to 49% (RCP8.5) for the 2070s. The range of yield increases spanned by the CPD curves tended to increase from the 2030s to the 2070s, indicating increasing spread among GCM projections later in the century. The most probable yield change of the ensemble of all CSMs and CGMs indicated a 23% (2030s), 30% (2050s), and 41% (2070s) increase in projected vs. baseline yields for RCP8.5 (**Figure 1**). A similar pattern of increasing yield gains was obtained for RCP4.5.

Figure 2 shows the CPDs for Lind, the site with the lowest precipitation. Inflection points ranged from 25 to 34% yield increase for RCP4.5 in the 2030s, and from 21 to 27% for RCP8.5 in the 2030s. By the 2070s, the range had increased to 45–62% under RCP4.5 and 61–66% under RCP8.5. The tighter clustering of models under RCP8.5 late in the century in Lind was probably due to the dominant effect of water stress, and the high percent yield increase was likely due to the direct effect of CO_2 having a higher relative impact under more limited water supply. The crop-climate model ensemble at Lind projected increased yield under both RCPs but the effect was greater under RCP8.5 than RCP4.5 (**Figure 2**). The percentage yield increase under RCP8.5 was substantial, jumping from 23% in the 2030s to 64% in the 2070s (**Figure 2**).

At the wettest site, Moses Lake, the ensemble of all crop model and GCMs projected a wheat yield increase for both RCP4.5 and RCP8.5 (**Figure 3**) but the increase was not as large as at the

TABLE 7 | Uncertainty Index (UI) for projected winter wheat yield at seven sites in the Pacific Northwest modeled under 14 general circulation models (GCMs) averaged over 2 representative concentrations pathways in each of 5 cropping system models (CSMs).

Study site	Source of variation	Time period		
		2030 (UI)	2050 (UI)	2070 (UI)
Lind	GCMs	0.091	0.063	0.050
	CSMs	0.509	0.684	0.630
	GCMs*CSMs	0.223	0.075	0.046
Moro	GCMs	0.127	0.077	0.089
	CSMs	0.549	0.510	0.351
	GCMs*CSMs	0.175	0.161	0.183
Wilke	GCMs	0.073	0.064	0.126
	CSMs	0.530	0.652	0.564
	GCMs*CSMs	0.302	0.194	0.165
St. John	GCMs	0.034	0.067	0.107
	CSMs	0.791	0.662	0.576
	GCMs*CSMs	0.141	0.207	0.217
Pullman	GCMs	0.011	0.021	0.048
	CSMs	0.858	0.792	0.710
	GCMs*CSMs	0.086	0.105	0.116
Kambitsch	GCMs	0.029	0.053	0.101
	CSMs	0.695	0.625	0.520
	GCMs*CSMs	0.203	0.201	0.192
Moses Lake	GCMs	0.050	0.130	0.155
	CSMs	0.733	0.550	0.381
	GCMs*CSMs	0.135	0.180	0.252

Results are presented for three 31-year time periods, centered on 2030, 2050, or 2070.

rainfed sites. The ensemble yield change under RCP8.5 went from 15% in the 2030s to 24% in the 2070s. This smaller increase was due to a lower direct effect of CO_2 when water was not a limiting factor. The effect of the different CO_2 responses among models is perhaps evident in these responses under irrigation. Free-Air CO_2 Enrichment (FACE) experiments have demonstrated well-watered wheat yield increases of 7–9% when CO_2 was elevated from 350 to 550 ppm (Tubiello et al., 1999), and ∼10% when CO_2 was elevated from 365 to 645 ppm (Manderscheid and Weigel, 2007). Photosynthetic response to CO_2 follows a typical saturation response, and biomass gain of wheat shows a similar response saturating (plateau response) at about 25% gain (compared to 370 ppm) when CO_2 exceeds 1,000 ppm (Reuveni and Bugbee, 1997). For the conditions during the 2070s and RCP8.5, atmospheric CO_2 concentration fluctuated from 570 to 801 ppm, while baseline conditions were set at 360 ppm. Thus, it is unlikely that yield gains greater than ∼15% should be obtained with these CO_2 concentrations for the 2070s, particularly when the effect of warming is considered. However, the 50% CPD of most models and the ensemble exceeded this figure, implying that not only differences in temperature responses but also in CO_2 responses contribute to the spread of projections among CSMs.

In all crop-climate model ensembles, the most probable yield increase was shifted rightward with time, indicating a high probability of yield increase. Although results for only the wettest (Moses Lake, Pullman), and the driest (Lind) sites are presented here, all seven sites evaluated showed similar responses, modulated mainly by the extent of water limitations. Overall, the behavior of all CSMs was similar in terms of direction of change in process components leading to yield estimations but with variations in magnitude, as shown in **Table 6** for the 2070s period and RCP8.5 compared to baseline values. The growing season was shorter during the 2070s at all sites as predicted by all CSMs, with the percentage reduction being largest at Lind and smallest under irrigation at Moses Lake. These differences reflect the different magnitude of projected temperature changes in these contrasting environments. All CSMs predicted increased biomass at all sites late in the century under RCP8.5. This increase was due in part to the CO_2 fertilization effect and to the warmer winter temperatures. Not surprisingly, with more biomass, all CSMs predicted higher LAI at all locations (**Table 6**). As expected under higher atmospheric CO_2 concentrations (Ainsworth and Rogers, 2007) and warmer temperatures (shorter growing season), all CSMs projected a decrease in transpiration, fluctuating from 0.4 to 11%. On the other hand, consistent with increased biomass and decreased transpiration, transpiration use efficiency increased at all locations and with all CSMs (**Table 6**), being greatest in the driest location, Lind, and least in the wettest.

Partitioning of Projection Uncertainties

Substantial uncertainty/variation was found among GCM and CSM projections. We present here results of the uncertainty analysis for yield only (**Table 7**). The UI revealed that the uncertainty attributable to CSMs was substantially larger than that from GCMs at all study sites during all three time periods. This is in agreement with previous finding by Asseng et al. (2013). The maximum UI for CSM was over 0.85 during the 2030s at Pullman whereas the maximum UI for GCM was 0.15 during the 2070s at Moses Lake. At a majority of locations, the UI associated with GCM tended to increase with time, but the UI for CSM tended to decrease with time at most locations (**Table 7**). Although the largest proportion of uncertainty was associated with CSM, the relatively large UI associated with the interaction of GCM and CSM indicated that the amount of uncertainty associated with GCM depended on which of the five models was under consideration.

Model (CSM and GCM) Ensemble Projection of Winter Wheat Biomass Production and Yield

An ensemble of all GCMs and CSMs showed a consistent trend of beneficial effects of climate change on biomass production and wheat yields in all sites studied under the two RCP scenarios (**Figure 4**). The model ensemble depicted increasing trends for biomass and grain yields under RCP4.5 at the seven study sites, but the increasing trend was more prominent at low

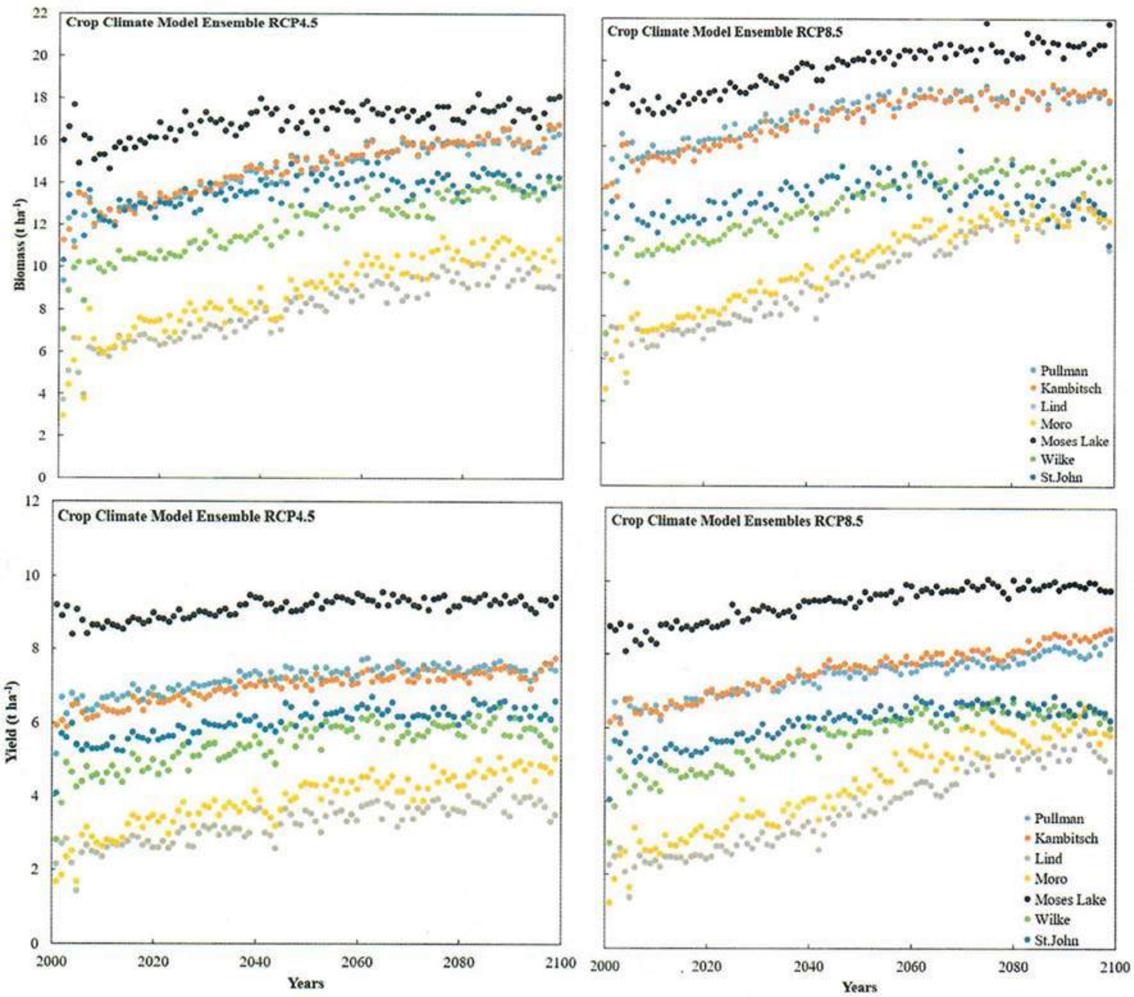

FIGURE 4 | Winter wheat biomass (t ha^{-1}) and grain yield (t ha^{-1}) trends by the crop climate model ensemble approach using two representative concentration pathways (RCP4.5 and 8.5) at seven diverse agroecological sites in the Inland Pacific Northwest.

rainfall sites (Lind and Moro) than at the wetter sites, Pullman, Kambitsch, and Moses Lake. A somewhat steeper increasing trend was observed under RCP8.5 for all sites. Over the twenty-first century, the benefit to yield of climate change appeared to be positively correlated to water stress. The driest site, Lind, saw a benefit of over 3 t ha^{-1} under RCP 8.5 whereas the least water-stressed sites, Pullman, Kambitsch and Moses Lake, experienced yield increases of at most about 2 t ha^{-1} (**Figure 4**). Also, there was a trend for biomass and yields to plateau toward the end of the century, more so for wetter sites.

There is certainly large uncertainty (**Table 7**) associated with each trajectory in **Figure 4**, implying many possible pathways toward future crop performance in the region. But the overall beneficial trend resulting from the combination of climate change and elevated CO_2 appears strong and in agreement with previous studies conducted in the region (Thomson et al., 2002; Stöckle et al., 2010). Overall, positive effects have been also projected for the northern Great Plains of the US (Izaurralde et al., 2003). Similar findings indicating increased suitability for wheat production under climate change of high northern Europe latitudes have been reported (Eckersten et al., 2001; Richter and Semenov, 2005; Balkovič et al., 2014). The winter wheat producing region of China is also expected to move northward (Sun et al., 2015).

Many additional factors will affect crop production in the future. Weeds, insect pests and diseases (Rosenzweig and Tubiello, 1996; Scott et al., 2014; Junk et al., 2016) will all influence crops, and these influences will all be impacted one way or another by climate change. Additionally, management decisions made by farmers in response to climate change will certainly affect future crop production.

CONCLUSIONS

In this study we assessed climate change impacts on winter wheat crop yield in the PNW using five CSMs and 14

GCMs. It was found that the uncertainty due to the variability of GCM and CSM projections can be substantial with the uncertainty attributed to CSMs being larger than that attributed to GCMs. Nevertheless, despite substantial variations, all CSMs consistently projected decrease in growing season length and transpiration and increase in transpiration-use efficiency, biomass, and yields. Overall, the mean of the ensemble of all CSMs and GCMs provided a robust indication of positive effects of future environmental conditions on winter wheat yield during this century at all sites studied, with greater beneficial effect under water stressed conditions than under well-watered, less stressed conditions.

AUTHOR CONTRIBUTIONS

MA conduct simulations, data reduction, draft manuscript; CS project conception and supervision, manuscript revision, RN programming, project realization; SH advise analyses, manuscript revision.

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Carbon and Water Budgets in Multiple Wheat-Based Cropping Systems in the Inland Pacific Northwest US: Comparison of CropSyst Simulations with Eddy Covariance Measurements

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Accurate carbon and water flux simulations for croplands are greatly dependent on high quality representation of management practices and meteorological conditions, which are key drivers of the surface-atmosphere exchange processes. Fourteen site-years of carbon and water fluxes were simulated using the CropSyst model over four agricultural sites in the inland Pacific Northwest (iPNW) US from October 1, 2011 to September 30, 2015. Model performance for field-scale net ecosystem exchange of CO_2 (NEE) and evapotranspiration (ET) was evaluated by comparing simulations with long-term eddy covariance measurements. The model captured the temporal variations of NEE and ET reasonably well with an overall r of 0.78 and 0.80, and a low RMSE of 1.82 g C m^{-2} d^{-1} and 0.84 mm d^{-1} for NEE and ET, respectively. The model slightly underestimated NEE and ET by 0.51 g C m^{-2} d^{-1} and 0.09 mm d^{-1}, respectively. ET simulations showed better agreement with eddy covariance measurements than NEE. The model performed much better for the sites with detailed initial conditions (e.g., SOC content) and management practice information (e.g., tillage type). The CropSyst results showed that the winter wheat fields could be annual net carbon sinks or close to neutral with the net ecosystem carbon balance (NECB) ranging from 92 to −17 g C m^{-2}, while the spring crop fields were net carbon sources or neutral with an annual NECB of −327 to −3 g C m^{-2}. Simulations for the paired tillage sites showed that the no-till site resulted in lower CO_2 emissions for the crop rotations of winter wheat-spring garbanzo, but had higher carbon loss into the atmosphere for spring canola compared to the conventional tillage site. Water budgets did not differ significantly between the two tillage systems. Winter wheat in the high-rainfall area had higher crop yields and water use efficiency but emitted larger amounts of CO_2 into the atmosphere than in the low-rainfall area. Based on model evaluations in this study, CropSyst appears promising as a tool to simulate field-scale carbon and water budgets and assess the effects of different management practices and local meteorological conditions for the wheat-based cropping systems in this region.

Keywords: CropSyst, eddy covariance, tillage practices, rainfall, fallow, carbon and water budgets

INTRODUCTION

Carbon and water cycles are two critical biophysical processes within the biosphere-atmosphere exchanges (Law et al., 2002) and agriculture plays an important role in global carbon and water dynamics (Bondeau et al., 2007; Running, 2012). CO_2 is one of the major greenhouse gases in the atmosphere affecting the processes of global warming. CO_2 emissions from agricultural soils are estimated to be 13 Pg C per year globally, accounting for 13% of total soil respiration (Bond-Lamberty and Thomson, 2010). Agricultural systems have also been considered as potential net carbon sinks to mitigate CO_2 in the atmosphere resulting from photosynthesis. Examining the contribution of carbon budgets by agriculture systems is crucial to understand the global carbon cycle with respect to climate change (Sauerbeck, 2001). Agricultural carbon and water cycles are greatly affected by local meteorological conditions and management practices (Bernacchi et al., 2005; Aubinet et al., 2009; Vuichard et al., 2016). Meteorological variables, such as photosynthetically active radiation (PAR) and air temperature, play vital roles in photosynthesis and respiration processes (Rabinowitch, 1951; Lloyd and Taylor, 1994). In addition, local meteorological conditions also influence farming practices. For example, in dry cropping areas where rainfall is insufficient, crop-fallow is one management practice used to increase productivity (Schillinger, 2001). Farming activities can also alter carbon and water dynamics; for example, tillage practices can change soil structure and aggregation which eventually changes soil bulk density, soil water retention capacity, and hydraulic conductivity of soil, as well as accelerate soil organic carbon (SOC) decomposition (e.g., Ball et al., 1999; West and Post, 2002; Regina and Alakukku, 2010). As a result, there is a critical need to quantify the effects of different climatic conditions and management practices on agricultural carbon and water cycles to better understand how the underlying biophysical processes, and thus carbon and water dynamics, respond to a changing environment.

Cropping system simulation models have been widely used to predict the effects of weather conditions, crop rotations, site characteristics, and management practices on crop growth as well as water and nutrient dynamics in agro-ecosystems (Benli et al., 2007). Through crop simulations under different scenarios, the models can be utilized as a practical tool to help improve the efficacy of decision making for agriculture not only under the current conditions but also for the future changing climate. CropSyst is a cropping system simulation model that is structured in modular systems (Stöckle et al., 1994, 2003). It has been used to provide a better understanding of ecological interactions to help guide relevant areas of research in a wide range of crops (Donatelli et al., 1997; Confalonieri et al., 2009), management practices (Jalota et al., 2012; Marsal and Stockle, 2012), climatic scenarios, (Tubiello et al., 2000; Lehmann et al., 2013), and simulation scales (Stöckle et al., 2014). However, the simulation of real ground conditions is a challenge for cropping system models due to the spatial complexity and variability of factors that are difficult to capture in initial conditions (Holzworth et al., 2015).

On the other hand, methods, such as the eddy covariance technique have been widely used to directly measure agricultural carbon and water budgets over the field-scale but have their own limitations. The eddy covariance method measures net exchanges of water and carbon between the surface and the atmosphere (Baldocchi, 2003), and uses models to partition these net fluxes into different components (Reichstein et al., 2005; Lasslop et al., 2010). Furthermore, the uncertainties due to random measurement errors and data-processing procedures can be large for annual or multi-year cumulative carbon or water budgets determined via eddy covariance. From a practical standpoint, long-term field scale eddy covariance measurements can be expensive and it is not feasible to deploy eddy covariance towers in every ecosystem, while cropping models can provide scenario analysis and field-scale simulations for cropping systems under various conditions. Therefore, it is beneficial to combine both modeling and measurement methods to first evaluate model performance and then apply the model to assess the agricultural carbon and water dynamics under different scenario conditions.

In this study, carbon and water fluxes were simulated using the CropSyst model at four agricultural sites in the inland Pacific Northwest (iPNW) region of the United States. To evaluate the model performance, net ecosystem exchange of CO_2 (NEE) and evapotranspiration (ET) were measured using eddy covariance flux towers. The iPNW region is a major wheat production area in the US and covers several agro-ecological classes (AECs) classified by integrating different biophysical (e.g., climate, soils, and terrain) and socioeconomic factors (e.g., commodity prices) (Douglas et al., 1992; Huggins et al., 2011). Traversing from the west to the east of the iPNW region, the AECs include dynamic- and stable- irrigated, crop-fallow, annual crop-fallow transition, and annual crop zones (https://www.reacchpna.org). Thus, the iPNW region is a unique study area to investigate the performance of wheat-based cropping systems under different water regimes and management practices. Consequently, the primary goal for this paper is to apply the CropSyst model to assess carbon and water dynamics at selected sites in the iPNW. Specific objectives are to (1) evaluate the CropSyst model performance with corresponding eddy covariance NEE and ET measurements, (2) determine the seasonal and inter-annual variability of carbon and water budgets in wheat-based cropping systems, and (3) discuss the implications of management practices and local meteorology on carbon and water budgets.

METHODS

Site Description

The four study sites are located in the iPNW region across a precipitation gradient of 250–600 mm and a variety of agricultural management practices (**Table 1**). Briefly, LIND is situated in a low-rainfall, crop-fallow area. Two paired sites are located in the high-rainfall zone (550 mm annually), with the same crop rotation and similar meteorological conditions but different tillage types. One site has been in continuous no-till management (CAF-NT) since 1998 while the other site has been under conventional tillage practice (CAF-CT) over the same period. MMTN is located in a higher rainfall zone (>600 mm annually), 10 km southeast of CAF-NT and CAF-CT.

Field Measurements

Each site has identical eddy covariance flux tower set-ups, including a 3D sonic anemometer (CSAT3A, Campbell Scientific, Inc.), an open-path infrared gas analyzer (IRGA, EC 150, Campbell Scientific, Inc.), net radiometer (NR-Lite2, Kipp&Zonen), air temperature and humidity sensor (HMP155A, Vaisala Inc.), PAR sensor (LI190SB, LI-COR Biosciences), wind vane (034B Windset, Met One Instruments), and soil temperature and moisture probes (5TM, Decagon Devices). Crop phenology is monitored using a time-lapse camera (WCT-00122, Wingscapes). Carbon content in the above-ground biomass is determined from the bi-weekly collected biomass samples using a TruSpec Carbon/Nitrogen Determinator (630–100–100, Leco Corporation), based on the method described in Law et al. (2008). The eddy covariance technique directly measures NEE and ET between the atmosphere and the surface. Uncertainties due to random measurement errors and gap-filling in annual sums of NEE and ET are estimated based on the method described in Richardson and Hollinger (2007). Full details of instrumentation, flux computation, quality assurance and quality control, data gap-filling, and uncertainty analysis are presented in Waldo et al. (2016) and Chi et al. (2016). The eddy covariance systems measure exchange over a homogeneous but fluctuating area, typically 1.5–2.5 ha, depending on wind direction and speed as well as atmospheric stability.

Cropsyst Model

At each of the four sites, the CropSyst model simulated carbon and water flux components in daily time step and field-scale spatial resolutions. Similar to the eddy covariance assumption, within the modeling domain (approximately 1.0 ha), it was assumed to have homogeneous soil, crop, meteorological and management conditions at the field-scale, although the "rolling hill" area in the iPNW is heterogeneous at the landscape scale. The CropSyst model simulates potential and actual ET partitioned into transpiration (T) and soil water evaporation (E) components, and based on transpiration-use efficiency determines biomass accumulation, which is partitioned into straw and grain yield (Stöckle et al., 2003). In addition, the model simulates CO_2 emissions from SOC oxidation and residue decomposition. Using daily biomass production simulated by CropSyst, crop respiration (R_a), including growth and maintenance components, gross primary productivity (GPP) can be obtained as discussed below, which is the sum of biomass and R_a. Total ecosystem respiration (R_{eco}) is the sum of R_a plus soil and residue respiration (R_h) associated with microbial decomposition activity. NEE is calculated as the difference between GPP and R_{eco}. Based on Chapin et al. (2006), net ecosystem carbon balance (NECB) is determined by combining NEE and the exported harvest biomass carbon content (EXP). In

TABLE 1 | Site characteristics, local meteorology, and management practices at each site.

Site	LIND	CAF-NT	CAF-CT	MMTN
Latitude	46°59′N	46°47′N	46°46′N	46°45′N
Longitude	118°35′W	117°04′W	117°04′W	116°56′W
Elevation (masl)	475	807	799	817
Date tower installed	10/18/2011	8/19/2011	6/27/2012	7/11/2012
Soil type[a]	Mollisols	Mollisols	Mollisols	Mollisols
Soil texture[a]	Silt loam (Shano and Ritzville Series)	Silt loam (Naff, Thatuna and Palouse Series)	Silt loam (Naff, Thatuna and Palouse Series)	Silt loam (Latahco-Thatuna complex, Southwick, and Larkin Series)
Annual temperature (°C)[b]	10	9	9	9
Annual precipitation (mm)[b]	280	550	550	680
Crop rotation[c]	TF-WW-TF-WW	WW-SG-WW-SC	WW-SG-WW-SC	SB-SP-WW
Tillage practices[d]	RT	NT	CT	CT
Nearby weather station[e]	LIND, AgWeatherNet	Pullman NE, AgWeatherNet	Pullman NE, AgWeatherNet	Crumarine Creek, University of Idaho

[a]*Soil types and textures were from Soil Survey Staff (1999) and Web Soil Survey (2013).*
[b]*Annual temperature and precipitation were averaged based on historical records from 1981 to 2010, National Centers for Environmental Information, NOAA.*
[c]*TF (Tillage fallow), WW (winter wheat), SG (spring garbanzo), SC (spring canola), SB (spring barley), SP (spring pea).*
[d]*RT (reduced tillage), NT (no-till), CT (conventional tillage).*
[e]*Nearby weather stations are the AgWeatherNet stations (AgWeatherNet, 2016).*

this study, we used the sign convention that positive carbon fluxes indicate carbon loss from the ecosystem, and *vice versa*.

Model input includes hourly or daily local meteorological data, such as air temperature, precipitation, vapor pressure deficit (VPD), PAR, solar radiation, wind speed, as well as agricultural management information, such as tillage, fertilization and irrigation. Daily meteorological data are from nearby weather stations in the AgweatherNet network which provides access to current and historical weather data measured at 177 automated weather stations (AgWeatherNet, 2016). The weather data are filtered with a range test (Estévez et al., 2011). Gaps in the weather data are filled by averaging data over a period of adjacent 5 days. Parameters used to define each crop species are taken from the CropSyst default values based on Stöckle et al. (2012) (Appendix I in Supplementary Material) and thermal time accumulation is used to determine different crop phenological stages, which are based on observations by time-lapse cameras in the field (Bater et al., 2011). All the simulations are initialized in the fall of 2,000, providing 12 years to make the simulations independent of initial conditions before the period of comparisons with eddy covariance flux measurements. However, the crop history during the 12 years was not available and was assumed similar to the crop rotation during the period of measurements.

Crop Growth and Transpiration

To simulate crop growth, the CropSyst model incorporates crop phenology, canopy development, potential transpiration and biomass production (assuming no stress), factors of stress, and partitioning of the actual biomass (leaves, stems, grain, and roots). Crop phenology is determined by a thermal time scale, which is also adjusted for water stress (Stöckle et al., 2003). The daily potential biomass production is determined under unstressed conditions as the minimum of potential transpiration-dependent and PAR-dependent biomass gain (Monteith, 1977; Sinclair et al., 1984). The actual biomass gain is then determined by the most limiting of two stress factors: water and nitrogen. The reference and potential evapotranspiration is calculated using the Penman-Monteith equation (Monteith, 1965). Potential transpiration is part of the potential evapotranspiration adjusted by the fraction of solar radiation intercepted by the crop canopy. Root biomass and density are simulated by layer, which are used to determine the actual water and nitrogen uptake from soil layers. Partitioning of the tissues (leaves, stems, and root biomass) is determined by dynamic partitioning coefficients (**Table 2**). Crop yield is a function of the harvest index at maturity stage. Crop growth and transpiration are set to zero during the periods including (1) prior to seeding, (2) post-harvest, and (3) fallow.

Crop Respiration

Crop respiration, or autotrophic respiration (R_a), is the sum of maintenance (R_m) and growth (R_g) respiration (Thornley, 1970; Penning de Vries, 1974; Amthor, 2000; Cannell and Thornley, 2000). R_m is the amount of CO_2 released due to maintenance per unit of existing biomass per time and R_g is the amount of CO_2 released due to biomass growth per unit time. According to Amthor (2000); Penning de Vries (1974), and van Iersel and Seymour (2000), R_m and R_g (g CO_2 m^{-2}) are calculated using the biomass data and respiration coefficients (**Table 2**), as presented in Equations (1) and (2):

$$R_m = WC_m \tag{1}$$

where W is the existing biomass (g B m^{-2}) which is equal to the cumulative biomass by tissue (see Section Crop Growth and Transpiration); and C_m (g CO_2 g B^{-1}) is the maintenance respiration coefficient, which is determined using a Q_{10} value of 1.8 for each 10°C increase in tissue temperature (Confalonieri et al., 2009). Daily mean air temperature is used as an approximation of the tissue temperature.

$$\begin{aligned} R_g &= WC_g \\ C_g &= \frac{1 - Y_g}{Y_g} \end{aligned} \tag{2}$$

where C_g (g CO_2 g B^{-1}) is the growth respiration coefficient and Y_g (g CO_2 g B^{-1}) represents the units of carbon appearing in new biomass per unit of glucose carbon utilized for growth (Thornley, 1970).

Soil and Residue Respiration

In order to simulate heterotrophic respiration (R_h), the CropSyst model apportions residue carbon into three fractions (fast- and slow-cycling, and lignified fractions) with distinctive decomposition rates; and SOC into either single (Kemanian and Stöckle, 2010) or multiple (Stöckle et al., 2012) pools. Residue pools are initialized with the estimated contents of surface, root and residues from previous crops, while the SOC pool (single-pool model) is initialized based on the observed soil organic matter (**Table 3**). The pools are updated each day with a specified potential decomposition rate (d^{-1}), adjusted as a function of soil temperature and moisture in each soil layer. Tillage effects on the decomposition rates are determined based on a soil conditioning index (USDA-NRCS, 2002), which describes the soil disturbance levels. Different soil disturbance levels as a result of tillage practices and clay content are used to determine tillage factors that adjust the SOC oxidation rate in the SOC pool (Kemanian and Stöckle, 2010). Soil and residue respiration is determined as the amount of CO_2 released to the atmosphere via SOC oxidation and decomposition of residue carbon pools.

Model Evaluation

We used the Willmott index of agreement (d) (Willmott, 1982) to evaluate the CropSyt performance for simulating cumulative above-ground biomass, daily NEE and ET by comparing with the field measurements at four sites. As defined in Equation (3), d ranges from 0 to 1 where a value of 1 indicates perfect agreement.

$$d = 1 - \frac{\sum_{i=1}^{N} (CS_i - EC_i)^2}{\sum_{i=1}^{N} (|CS_i| + |EC_i|)^2} \tag{3}$$

where CS_i and EC_i are the CropSyst simulations and the field measurements, respectively. N is the total number of data points. In addition, correlation coefficient (r), root mean square error (RMSE), and bias are also calculated to estimate the degree of

TABLE 2 | Coefficients of maintenance respiration (C_m) and growth respiration (C_g) of vegetative organs at a temperature of 20°C (adapted from Penning de Vries et al., 1989).

	C_m (g CO_2 g B^{-1})		C_g (g CO_2 g B^{-1})	
	Non-legume	Legume	Non-legume	Legume
Leaves	0.016	0.019	0.461	0.790
Stems and storage	0.010	0.020	0.406	0.540
Roots	0.015	0.017	0.406	0.537

TABLE 3 | Organic matter (%) at different depths used for initial conditions at each site (adapted from Purakayastha et al., 2008).

Depth (m)	LIND	CAF-NT	CAF-CT	MMTN
0.05	0.7	3.8	2.8	0.5
0.1	0.7	3.2	2.8	1.8
0.2	0.7	2.7	2.8	1.6
0.3	0.5	2.5	1.8	1.1
0.4	0.3	1.5	1.5	1.0
0.5	0.1	1.3	1.3	0.8
0.6–2	0.1	0.4–0.1	0.4–0.1	0.5

association and the average differences between simulations and measurements.

The annual period, or one water year, is defined from October 1 to September 30. According to Schmidt et al. (2012), the main growing season (MGS) is defined as the period when the measured NEE is less than the median NEE during each water year, with the remainder of the annual period defined as the off-main growing season (oMGS). The way of defining the MGS in this study, rather than from seeding to harvest, emphasizes the period where photosynthesis is significant and excludes the wintertime where little carbon uptake by winter wheat occurred.

RESULTS

Evaluation of Modeled Above-Ground Biomass

As the core engine for modeling carbon and water budgets heavily relies on biomass simulations in CropSyst, accuracy in the CropSyst biomass results directly affects the model performance. The overall Willmott index of agreement (d) between biomass simulations and measurements was 0.98 for all 12 site-years (not including the two fallow years), indicating good agreement between CropSyst simulations and field measurements. Other statistical evaluation results also suggested good model performance for biomass simulations, illustrated by the relatively low bias and RMSE, as well as correlation coefficient (r) and slope close to 1 (**Table 4**). CropSyst performed best at CAF-CT, followed by CAF-NT, MMTN, and LIND (**Figures 1A–D**). The magnitudes of RMSE and bias ranged from 44 to 88 g C m^{-2} and −40 to 57 g C m^{-2}, respectively, with CAF-CT and LIND having a relatively smaller magnitude compared to CAF-NT and MMTN.

TABLE 4 | Evaluation of modeled cumulative above-ground biomass, daily net ecosystem exchange of CO_2 (NEE), and evapotranspiration (ET) for all 14 site-years.

	Slope	r	RMSE[a]	Bias[b]	d
Above-ground biomass	0.90	0.92	82	25	0.98
NEE	0.69	0.78	1.82	0.51	0.87
ET	0.98	0.80	0.84	-0.09	0.93

[a,b]Units for RMSE bias of above-ground biomass are in g C m^{-2}. Units for RMSE and bias of NEE and ET are in g C m^{-2} d^{-1} and mm d^{-1}, respectively.

For each site-year, the simulated above-ground biomass generally agreed well with the observed biomass data (**Figure 2**). CropSyst results captured the above-ground biomass accumulation rates reasonably well for all the crop species at both no-till and conventional tillage sites (CAF-NT 2012–2015 and CAF-CT 2013–2015), winter wheat at the low-rainfall site during 2013 (LIND 2013), and the spring barely field (MMTN 2013). At LIND, the model slightly overestimated the above-ground biomass by 50–120 g C m^{-2} during the early growth stages in 2015 (**Figure 2A**). While at MMTN, CropSyst overestimated the above-ground biomass of spring pea by 50–80 g C m^{-2} during the MGS of 2013 and underestimated winter wheat biomass by 10–130 g C m^{-2} during the MGS of 2015 (**Figure 2D**).

Evaluation of Modeled NEE and ET

Overall Accuracy

Compared to the eddy covariance measurements for the four sites, the modeled daily NEE and ET agreed well with a high agreement index of 0.87 and 0.93, respectively, indicating a slightly better performance for ET simulations than NEE (**Table 4**). Statistical evaluation also showed a high correlation coefficient of 0.78 and 0.80, as well as a low RMSE of 1.82 g C m^{-2} d^{-1} and 0.84 mm d^{-1} for NEE and ET, respectively. Overall, the model resulted in less negative NEE (bias = 0.51 g C m^{-2} d^{-1}) and slightly underestimated ET (bias = −0.09 mm d^{-1}).

Evaluation of NEE and ET by Site

Focusing on each site individually, the highest agreement index for NEE simulations was found at CAF-CT (d = 0.92), accompanied by a high correlation coefficient (r = 0.86), a small RMSE (1.59 g C m^{-2} d^{-1}), and a low bias (0.36 g C m^{-2} d^{-1}) (**Figure 1G**). At CAF-CT, the modeled NEE captured the NEE peak values during each MGS and showed very good agreement for the growing seasons of winter wheat and spring canola in 2014 and 2015, respectively (**Figure 3C**). NEE simulations at CAF-NT were also in good agreement with the eddy covariance measurements, followed by MMTN and LIND (**Figures 1E–H**, **3A,B,D**). The largest RMSE (2.18 g C m^{-2} d^{-1}) was found at MMTN and was primarily attributed to the large discrepancies during each MGS, where the model underestimated the carbon sink strength of spring barley, spring pea, and winter wheat by 100–185 g C m^{-2} $month^{-1}$ (**Figure 3D**). Even though LIND had the lowest RMSE (1.40 g C m^{-2} d^{-1}), the other evaluation parameters, such as slope and correlation coefficient indicated fair performance (**Figure 1E**),

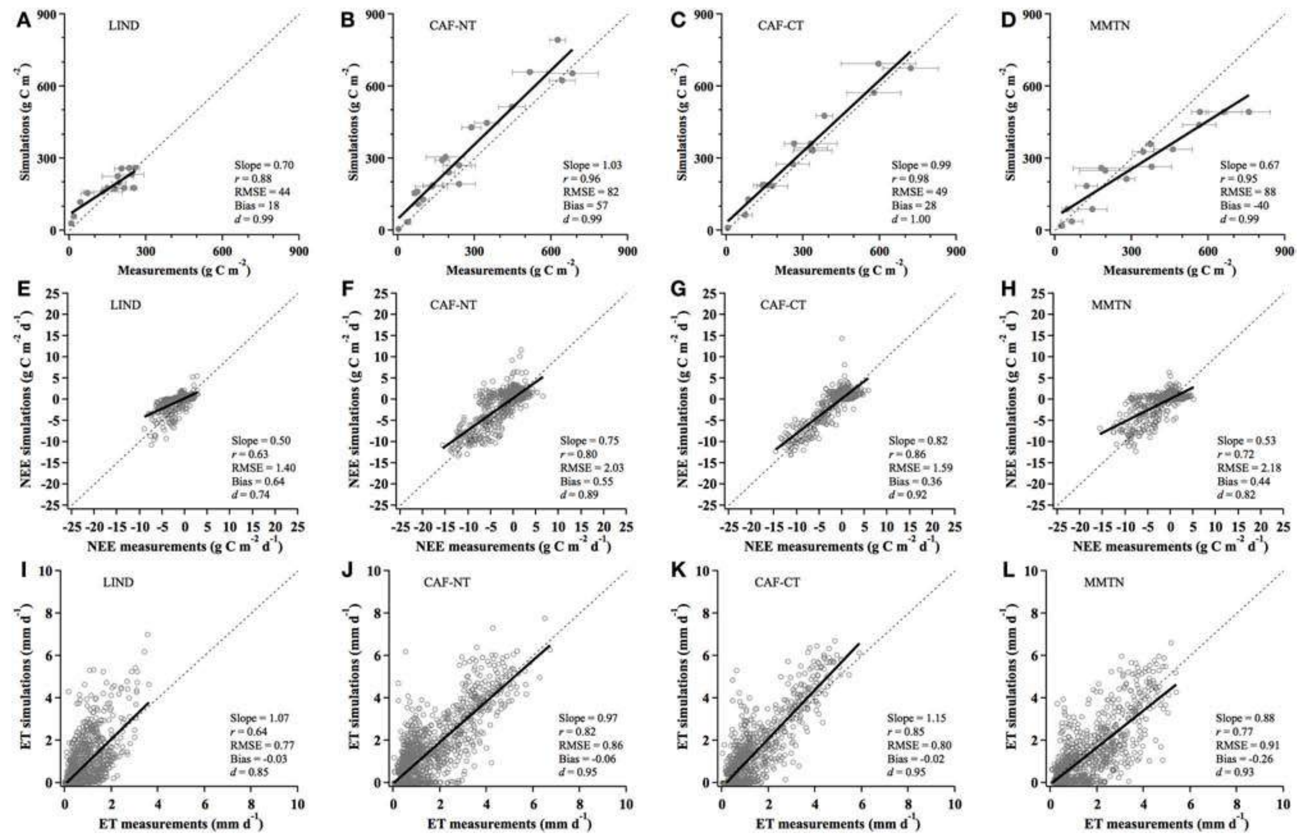

FIGURE 1 | Scatter plots of the simulated and the measured cumulative above-ground biomass (A–D), daily net ecosystem exchange of CO_2 (NEE, **E–H**), and daily evapotranspiration (ET, **I–L**) at four sites.

therefore further in-depth comparisons (e.g., by site-year) are still needed to better evaluate the model performance for determining annual or MGS carbon sink or source for all sites.

For ET simulations, the model had very good agreement with the measured ET at each site, particularly at the three high-rainfall sites (**Figures 3E–H**), with $d > 0.85$ and r ranging from 0.64 to 0.85 (**Figures 1I–L**). The highest agreement index was found at CAF-NT and CAF-CT throughout the entire evaluation period. At MMTN, the model also captured the particular ET seasonal patterns during 2013 and 2014, where two ET peak periods occurred during both early spring and the MGS (**Figure 3H**). During these two ET peak periods, the simulated ET was slightly lower compared to the measurements for the first peak, but simulated the measurements well for the second peak period. In contrast, at LIND, even though the simulated ET values were comparable to the corresponding measured ET on average, the correlation coefficient ($r = 0.64$) was still relatively small compared to the three high-rainfall sites (**Figure 1I**). The lower r at LIND was most likely attributed to the slightly underestimated ET values over the winter wheat field during 2013 (**Figure 3E**).

Evaluation of Annual and MGS Cumulative NEE and ET by Site-Year

Two site-years (CAF-CT 2013 and MMTN 2014) had very comparable annual NEE magnitudes between simulations and measurements, with differences of only 6 and 38 g C m^{-2} for CAF-CT and MMTN, respectively. For the remaining 12 site-years, CropSyst underestimated the CO_2 sink strength or overestimated the CO_2 source amount by an annual difference of 63–461 g C m^{-2} (**Figure 4A**). This annual difference range was greater than the uncertainties in the measured annual NEE (6–47 g C m^{-2} $year^{-1}$). In terms of determining if a site was a net CO_2 sink, source, or neutral over an annual basis, the modeled results were consistent with the measurements for 8 out of 14 site-years. However, CropSyst did a better job on estimating the MGS cumulative NEE than the annual NEE (**Figure 4B**). The differences in the MGS-cumulative NEE between CropSyst and eddy covariance were 95–303 g C m^{-2} and the model showed agreement with the measurements for all the growing seasons, where both simulations and measurements indicated these sites were all net CO_2 sinks during the MGS (**Figure 4B**).

With respect to simulating the annual ET, the model performed well for 10 out of 14 site years with a small difference (2–7%) between the CropSyst simulations and the eddy covariance measurements (**Figure 4C**). A relatively greater annual ET difference (10–24%) was found at MMTN for all 3 years and at LIND during 2015. Differences in the MGS-cumulative ET between simulations and measurements varied greatly with sites and crops, and ranging between 1% and 31%.

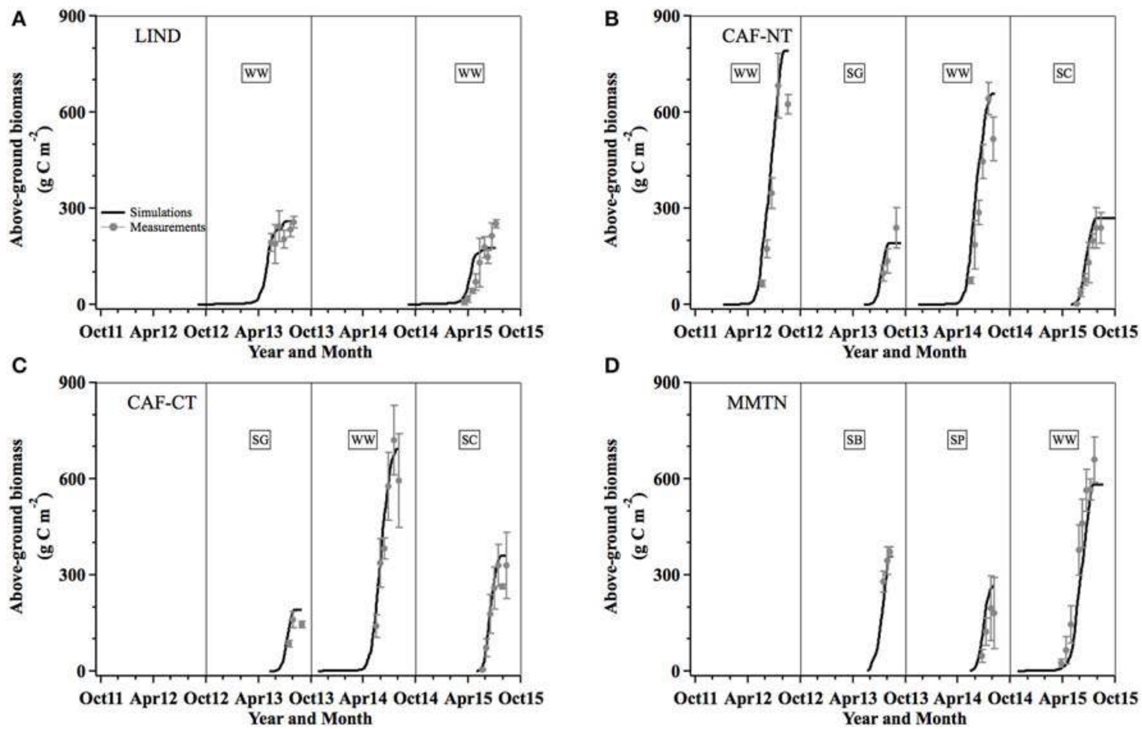

FIGURE 2 | CropSyst modeled and field measured above-ground biomass carbon content at LIND (A), CAF-NT **(B)**, CAF-CT **(C)**, and MMTN **(D)**. WW, winter wheat; SG, spring garbanzo; SC, spring canola; SB, spring barley; SP, spring pea.

Simulations for the MGS-cumulative ET had better agreement (1–6% difference) with the measurements for the winter wheat fields at CAF-NT and CAF-CT, as well as the spring canola field at CAF-CT. While for the remaining 8 site-years, the modeled MGS-cumulative ET was smaller than the measured values by a MGS difference of 13–27%. Uncertainties due to random measurement errors and gap-filling uncertainty in the measured annual ET were around 2 mm year^{-1}, accounting for a very small portion of annual ET (<1%).

Seasonal and Inter-Annual Variabilities of Modeled Carbon and Water Fluxes

CropSyst was also used to simulate other flux components to assess the seasonal and inter-annual variabilities of carbon and water budgets at each site. The simulated carbon (NEE, R_{eco}, and GPP) and water (ET, E, and T) fluxes showed a typical seasonal pattern of larger magnitudes during the MGS and lower fluxes during the oMGS at each site (e.g., **Figures 5**, **6**). As a result of CropSyst stomatal-related flux components (GPP and T) being set to zero prior to seeding, after harvest, and during fallow, NEE and ET were equivalent to the non-stomatal parameters, R_{eco} (or R_h) and E, and all sites were small net CO_2 sources and water was lost into the atmosphere directly during these periods. During the MGS, NEE (or ET) was affected by both GPP (or T) and R_{eco} (or E) at all sites with GPP (or T) contributing the most (e.g., **Figures 5**, **6**). By averaging all the non-fallow years, 96% of GPP and 99% of T occurred during the MGS. For R_{eco} and E, the MSG fractions were 67% and 22%, respectively.

The inter-annual variabilities of carbon and water fluxes were greatly dependent on crop rotations and water availability at each site. The crops grown at the four sites encompassed typical crop rotations for the iPNW region: winter wheat-spring crops and winter wheat-tillage fallow (**Table 1**). Winter wheat generally had larger flux magnitudes compared to the spring crops (i.e., canola, garbanzo, barely, and pea; e.g., **Figures 5**, **6**). Due to the different annual rainfall amounts, the high-rainfall sites (CAF-NT, CAF-CT, and MMTN) always had relatively larger magnitudes of carbon and water fluxes compared to the low-rainfall site (LIND), regardless of crop species (e.g., **Figures 7**, **8**).

Among the 14 site-years of carbon flux simulations, the CropSyst model showed that all the spring crop fields and the tillage fallow years were net carbon sources or close to carbon neutral over an annual basis, with an annual NECB ranging from −327 to −3 g C m^{-2} (**Table 5**). The annual NECB for the winter wheat fields ranged from 92 to −17 g C m^{-2}, suggesting either net carbon sinks or near carbon neutral annually. As the ratio of T/ET is one index indicating the proportion of water utilized for crop growth, the CropSyst water budgets implied that less water was utilized by crops than directly lost into the atmosphere at the high-rainfall spring crop fields and the low-rainfall site, with the annual T/ET less than or close to 0.5. While for the high-rainfall winter wheat fields, their annual T/ET values were >0.6 (**Table 5**).

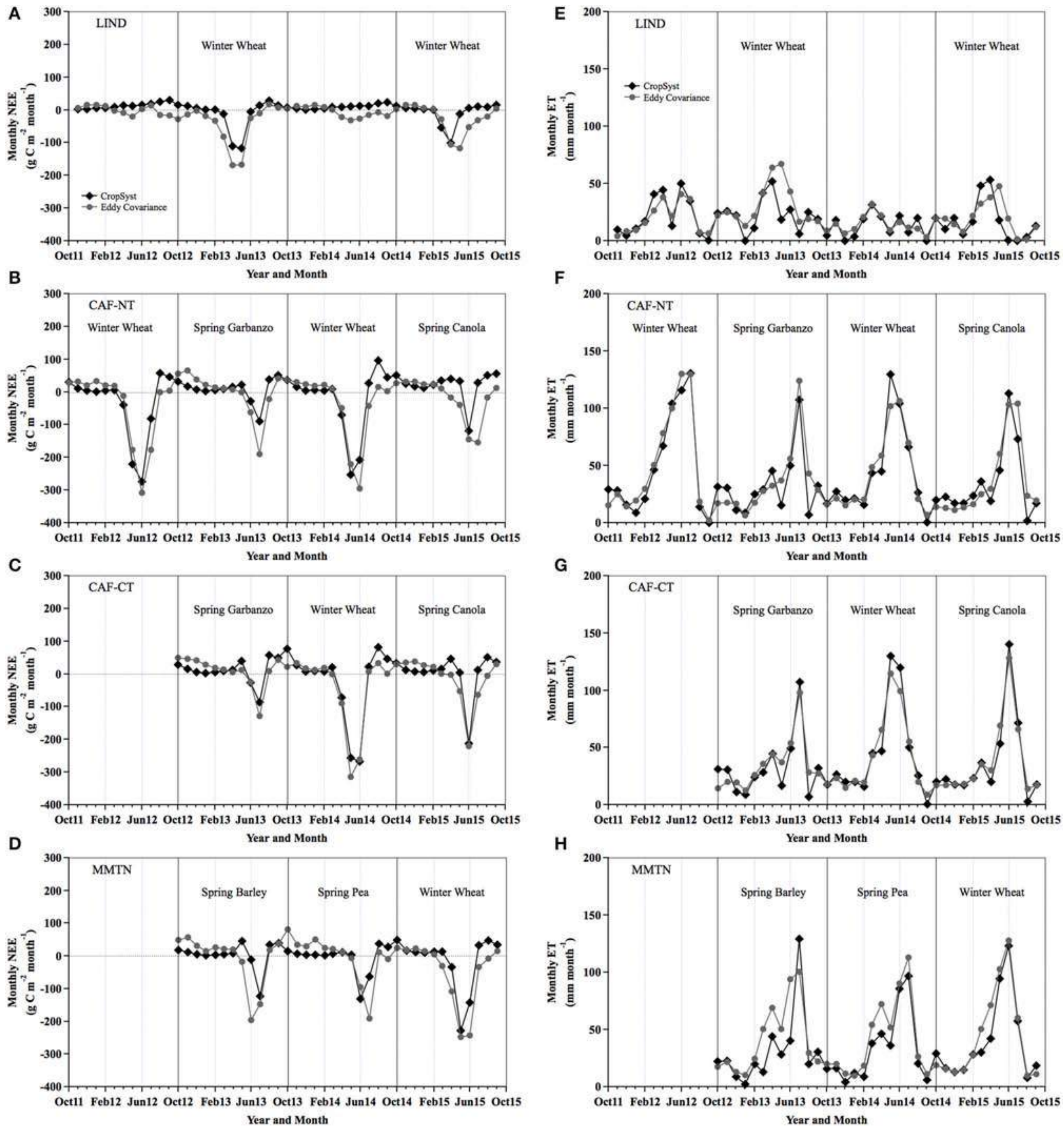

FIGURE 3 | CropSyst and eddy covariance monthly net ecosystem exchange of CO_2 (NEE, **A–D**) and evapotranspiration (ET, **E–H**) at four sites from October 2011 to September 2015.

Carbon and Water Budgets at No-Till and Conventional Tillage Sites

The simulated annual NECB suggested that the no-till site was a slightly smaller net carbon source over the spring garbanzo field (−132 vs. −201 g C m^{-2}) but was a stronger carbon source over the spring canola field (−327 vs. −104 g C m^{-2}), compared to the conventional tillage site (**Table 5**). For winter wheat field, the no-till site was a net carbon sink (61 g C m^{-2}) while the tilled site was close to carbon neutral (−17 g C m^{-2}). Over the three water years, the average annual NECB differed by 25 g C m^{-2} between the two sites.

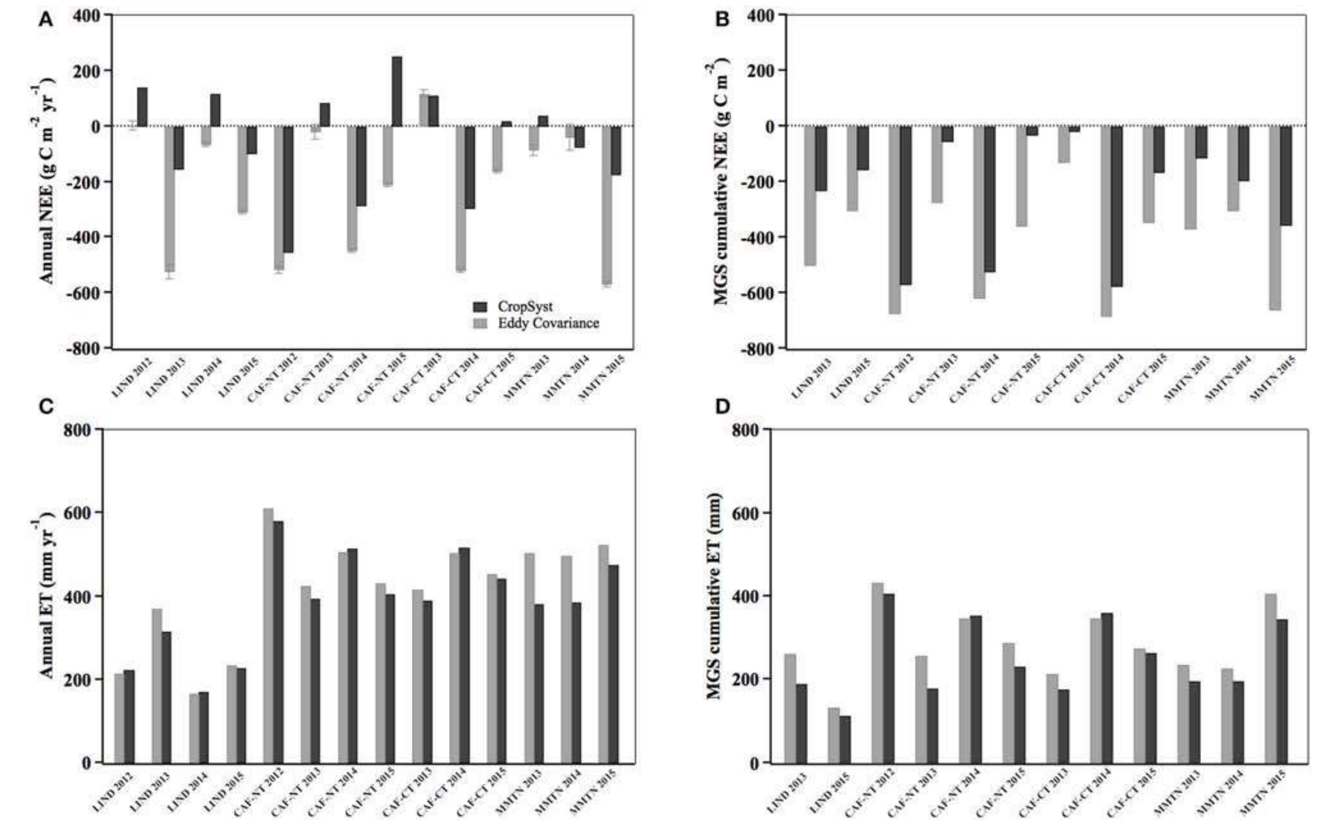

FIGURE 4 | CropSyst and eddy covariance annual (A,C) and main growing season (MGS, **B,D**) cumulative net ecosystem exchange of CO_2 (NEE) and evapotranspiration (ET) for each site-year. Error bars are the uncertainties in the eddy covariance annual NEE **(A)**.

Comparing the carbon simulations between the two sites (CAF-NT and CAF-CT), major differences in their carbon budgets were attributed to the oMGS R_{eco} and the MGS GPP (**Figure 5**). The CropSyst results showed that the no-till site had comparable annual R_{eco} during the 2013 spring garbanzo year, 55 g C m^{-2} lower annual R_{eco} during 2014 (winter wheat), and 152 g C m^{-2} greater annual R_{eco} during 2015 (spring canola), compared to the conventional tillage site (**Figure 5E**, **Table 5**). Respiration simulations over the spring garbanzo field showed that the no-till management practice resulted in an increased amount of R_a but a comparable reduced amount of R_h compared to the conventional tillage scenario runs. For winter wheat, the no-till site had both smaller R_a and R_h compared to the conventional tillage site by an annual difference of 23 and 32 g C m^{-2}, respectively (**Table 5**). While for spring canola, the modeled results suggested that the no-till practice enhanced R_{eco} with larger contributions by R_h rather than R_a. Due to the large R_{eco} difference over the spring canola fields, the mean annual R_{eco} only differed by 32 g C m^{-2} yr^{-1} (5%) between CAF-NT and CAF-CT over a 3-year crop rotation of spring garbanzo-winter wheat-spring canola. Based on the paired t-test, R_{eco} and R_h were significantly different ($p < 0.05$) during 2015 over the spring canola field (**Table 5**).

Differences in the modeled GPP and EXP varied with crop rotations. During the 2013 spring garbanzo year, the modeled GPP did not differ much between the two sites and CAF-NT had 41 g C m^{-2} lower EXP compared to CAF-CT. During 2014 and 2015, the conventional tillage site had more negative GPP throughout the two growing seasons and eventually had 66 and 79 g C m^{-2} more carbon uptake and 89 and 8 g C m^{-2} greater EXP relative to the no-till site for winter wheat and spring canola, respectively (**Figures 5C,F**, **Table 5**). The GPP and EXP differences in winter wheat and spring canola between the two tillage practices were also noticeable in the biomass measurements (**Figure 2**). During the end of the growing seasons for spring garbanzo and spring canola, CAF-NT was harvested 1-to-2 weeks later than CAF-CT and therefore resulted in a slightly longer growing simulation period compared to CAF-CT (**Figure 5C**).

The simulated ET, E, and T was not significantly different ($p > 0.05$) between CAF-NT and CAF-CT over the three water years (**Table 5**). For spring garbanzo and winter wheat, the modeled annual sums of ET, T, and E were similar at the two sites (**Figure 6**). While during 2015 (spring canola), CAF-CT had 36 mm greater annual ET than CAF-NT, primarily a result of the higher annual T (**Table 5**, **Figures 6D–E**). As a result, CAF-NT and CAF-CT had very similar T/ET ratios for spring

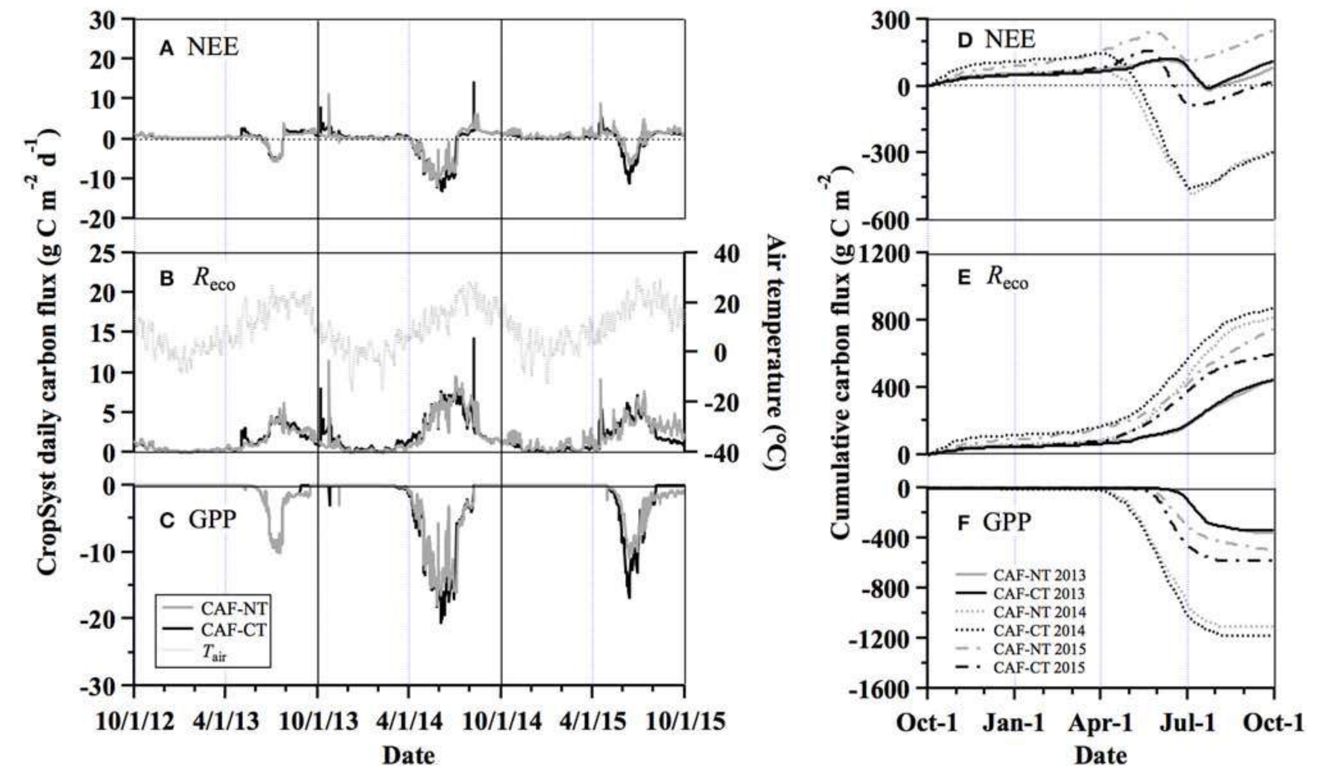

FIGURE 5 | CropSyst daily (A–C) and cumulative **(D–F)** net ecosystem exchange CO_2 (NEE), total ecosystem respiration (R_{eco}), and gross primary productivity (GPP) at the no-till (CAF-NT) and the conventional tillage (CAF-CT) sites from October 1, 2012 to September 30, 2015. Daily mean air temperature (T_{air}) was only plotted for CAF-NT to represent the general temperature conditions at CAF.

garbanzo and winter wheat and CAF-CT had a slightly greater ratio for spring canola. Even though the annual water budgets did not vary much between the two sites, there were some subtle differences in each water flux component illustrated in the daily step simulations (**Figure 6**). For instance, CAF-CT had greater E compared to CAF-NT during some of the oMGS rainfall events (**Figure 6B**). Several small differences in T were mostly seen during the winter wheat growing season; for example, T at CAF-CT was higher than CAF-NT during the early growth stages, but slightly lower during the later MGS (**Figure 6C**). These small differences in T also corresponded with the GPP patterns.

Carbon and Water Budgets at Low- and High-Rainfall Winter Wheat Fields

Winter wheat was grown at both high- and low-rainfall sites (MMTN and LIND) during 2015. All CropSyst carbon and water flux components differed greatly between MMTN and LIND, with R_{eco}, GPP, ET, and T significantly different ($p < 0.05$) between the two sites (**Table 5**). Limited by the water availability, the magnitude of R_{eco} was much smaller at LIND compared to MMTN over the entire water year (**Figures 7B,E**), thus resulting in 492 g C m^{-2} lower annual R_{eco} relative to MMTN (**Table 5**). The rainfall influence on the simulated R_{eco} was relatively small during the oMGS, as respiration rates were primarily inhibited by the low air temperature during this period. While during the MGS, the modeled R_{eco} at LIND was <30% of the R_{eco} at MMTN, which was mostly attributed to the different rainfall amounts at the two sites, even though the majority of the rainfall occurred during the oMGS (**Figures 7B**, **8B**). Similar to the R_{eco} patterns at the two sites, MMTN annual GPP (−887 g C m^{-2}) was estimated to be much greater in magnitude compared to LIND (−317 g C m^{-2}). LIND also had a shorter growing season compared to MMTN due to the influence of rainfall (**Figure 7C**). In CropSyst, winter wheat at LIND began growing earlier and faster than MMTN during March and April, due to the warmer weather conditions and the stored soil water content from the previous fallow year (**Figure 7C**). Influenced by both R_{eco} and GPP flux components, winter wheat at MMTN had a larger annual NEE magnitude (−177 g C m^{-2}), compared to LIND (−99 g C m^{-2}). In terms of EXP simulations, the high-rainfall site obtained a much higher crop yield (114 g C m^{-2}) compared to the low-rainfall site (39 g C m^{-2}). Combining annual NEE and EXP together, over the water year of 2015, both sites were estimated as net carbon sinks with a similar annual NECB magnitude, 60 and 63 g C m^{-2} for LIND and MMTN, respectively.

In 2015, the simulated annual ET was 229 and 475 mm at LIND and MMTN, respectively, with an annual T difference contributing the most (**Table 5**). From October 2014 to March 2015, the cumulative ET did not vary much between the two sites

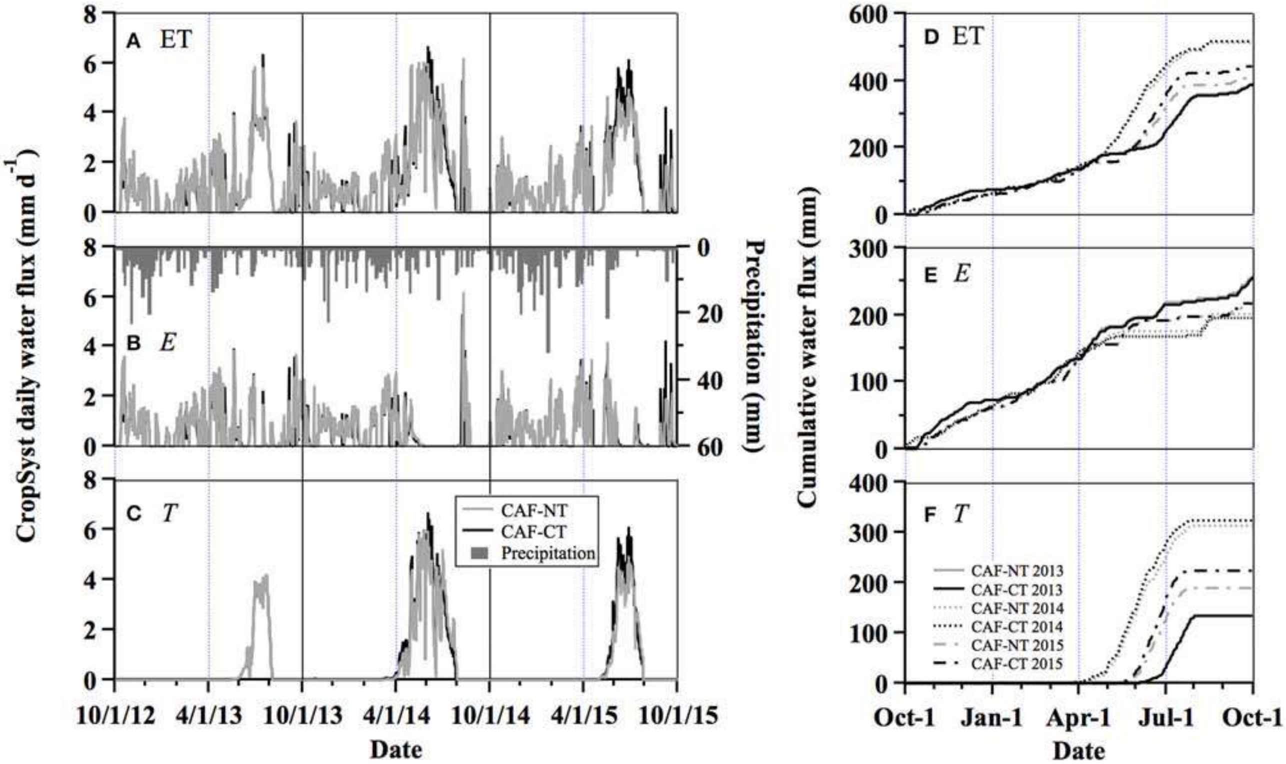

FIGURE 6 | CropSyst daily (A–C) and cumulative **(D–F)** evapotranspiration (ET), soil water evaporation (*E*), and crop transpiration (*T*) at the no-till (CAF-NT) and the conventional tillage (CAF-CT) sites from October 1, 2012 to September 30, 2015. Daily precipitation measurements were only plotted for CAF-NT to represent the general precipitation conditions at CAF.

and the slightly higher ET at MMTN was primarily attributed to the relatively higher *E* flux component (**Figures 8D,E**). Starting in April 2015, *T* increased quickly at LIND as a result of earlier crop growth compared to MMTN and therefore resulted in a comparable cumulative ET to MMTN in May 2015 (**Figure 8D**). However, starting in June, both cumulative *T* and *E* started increasing at MMTN, while water fluxes at LIND remained nearly constant due to the dry conditions and the short growing season. The estimated *T*/ET ratio was 0.34 and 0.61 for LIND and MMTN, respectively, with a higher fraction of water directly evaporating into the atmosphere at LIND.

DISCUSSION

Model Performance and Evaluation

Through model evaluations for all 14 site-years, we found that CropSyst performed well for simulating biomass and water budgets, as well as determining if a site was an annual carbon sink or source. Therefore, CropSyst can provide reliable daily, annual, and long-term simulations for agricultural carbon and water dynamics over a field-scale.

Overall, the model had better performance for CAF-NT and CAF-CT sites, compared to LIND and MMTN. Both CAF-NT and CAF-CT are located at the research site operated by Washington State University (WSU), vs. the LIND and MMTN sites that are managed by local growers cooperating with WSU. As a result, the more detailed site-specific management practices, such as seeding and harvest dates, tillage types and depths, and fertilization types and rates, were available at CAF-NT and CAF-CT compared to the other two sites. These management practices greatly affected the carbon and water budgets, as the inter-annual variability of carbon and water fluxes is mainly driven by these indirect effects (e.g., the altered soil microbial community by tillage), rather than the direct effects from the short-term environmental forcing, such as temperature and moisture (Chu et al., 2016). Additional conditions that may contribute to reduced model performance include site history, which is critical for setting the model initial conditions (e.g., soil organic matter and residue contents). This model input information should ideally be based on specific field measurements, which was partially available at CAF-NT and CAF-CT in this study. Uncertainties in the initial SOC and residue conditions affected the R_h simulations and thus carbon budget simulations in CropSyst.

Because CropSyst does not provide R_a simulations directly, R_a was estimated based on simulated biomass production and coefficients of growth and maintenance respiration per unit of biomass produced. Therefore, R_a simulations are sensitive to the values chosen for the respiration coefficients. Due to the lack of specific crop variety information, crop parameters were set

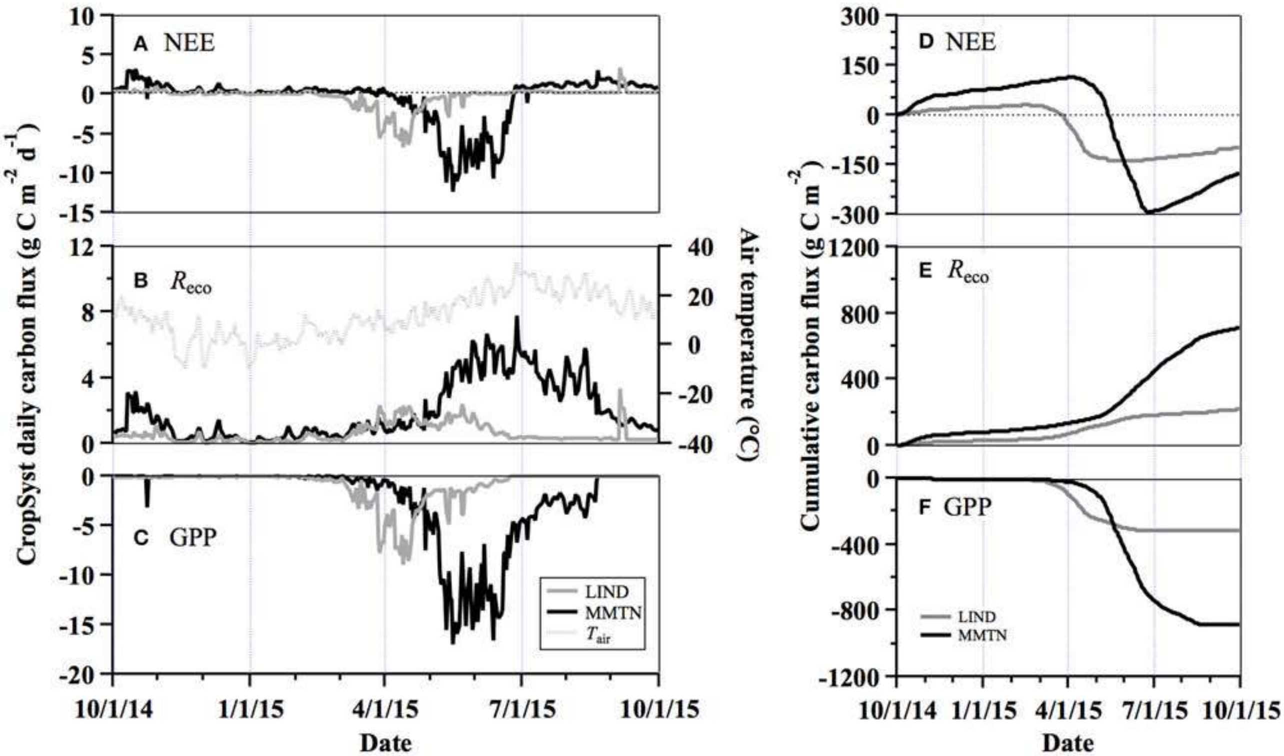

FIGURE 7 | CropSyst daily (A–C) and cumulative **(D–F)** net ecosystem exchange of CO_2 (NEE), total ecosystem respiration (R_{eco}), and gross primary productivity (GPP), at the low-rainfall (LIND) and high-rainfall (MMTN) winter wheat fields during the water year of 2015. Daily air temperature (T_{air}) was only plotted for LIND.

identically for the same crop species at all sites. For example, crop parameters for winter wheat were the same for CAF and MMTN, resulting in earlier simulated maturity of winter wheat at MMTN and insufficient accumulation of biomass at harvest compared to the measurements. Adequate information for crop model parameterization reduces sources of modeling uncertainty (Confalonieri and Bechini, 2004; Singh et al., 2013). One known weakness of this work is the lack of CropSyst simulations of weed growth during the oMGS or the fallow periods at all sites, which contributed to an underestimated carbon sink strength during these periods. Particularly during the fallow years, there was an important amount of carbon uptake by weeds with an annual GPP of -519 ± 21 g C m^{-2} (Waldo et al., 2016).

Uncertainty related to the input parameters may be even larger for some crops that have not been well studied (e.g., spring garbanzo or canola), but this can be improved by model validation and calibration using more measurement data over multiple cropping systems. On the other hand, uncertainties in the eddy covariance measurements may also affect the model performance evaluation, such as gap-filling uncertainties and uncertainties during stable and calm nighttime conditions.

Tillage Practice Effects on Annual Cropping Area

CropSyst was used to assess the tillage effects on carbon and water budgets in this study. The simulations for the paired till and no-till sites had identical model inputs (e.g., crop species, meteorological variables, and seeding rates) with the exceptions of soil conditioning indices and initial conditions for soil organic matter. The different settings for soil conditions were used to account for the tillage effects within CropSyst (Stöckle et al., 2012). As few monitoring studies have been done to investigate the long-term tillage effects on carbon and water budgets, the CropSyst simulations provide an insight of the feasibility of implementing a certain tillage practice over different crop species. The modeled results showed that the difference in the mean annual NECB between CAF-NT and CAF-CT was relatively small and within the uncertainty range of both model simulations and eddy covariance measurements over agricultural ecosystems. The measurement uncertainty in annual carbon budgets is in the range of 18–50 g C m^{-2} (e.g., Béziat et al., 2009; Schmidt et al., 2012; Chi et al., 2016; Waldo et al., 2016) and the modeling uncertainty is even larger, 50–110 g C m^{-2} in annual carbon budget or 10–15% in grain yields (Rotter et al., 2012; Chen et al., 2015). Therefore, differences in the long-term averaged carbon budgets between no-till and conventional tillage practices may become less significant under the crop rotations of winter wheat-spring crops in the long run.

By investigating the tillage effects on each carbon flux component over different crops, CropSyst showed greater crop yields for spring garbanzo, winter wheat, and spring canola associated with the conventional tillage practice, most likely resulting from precipitation interception by the residue cover in

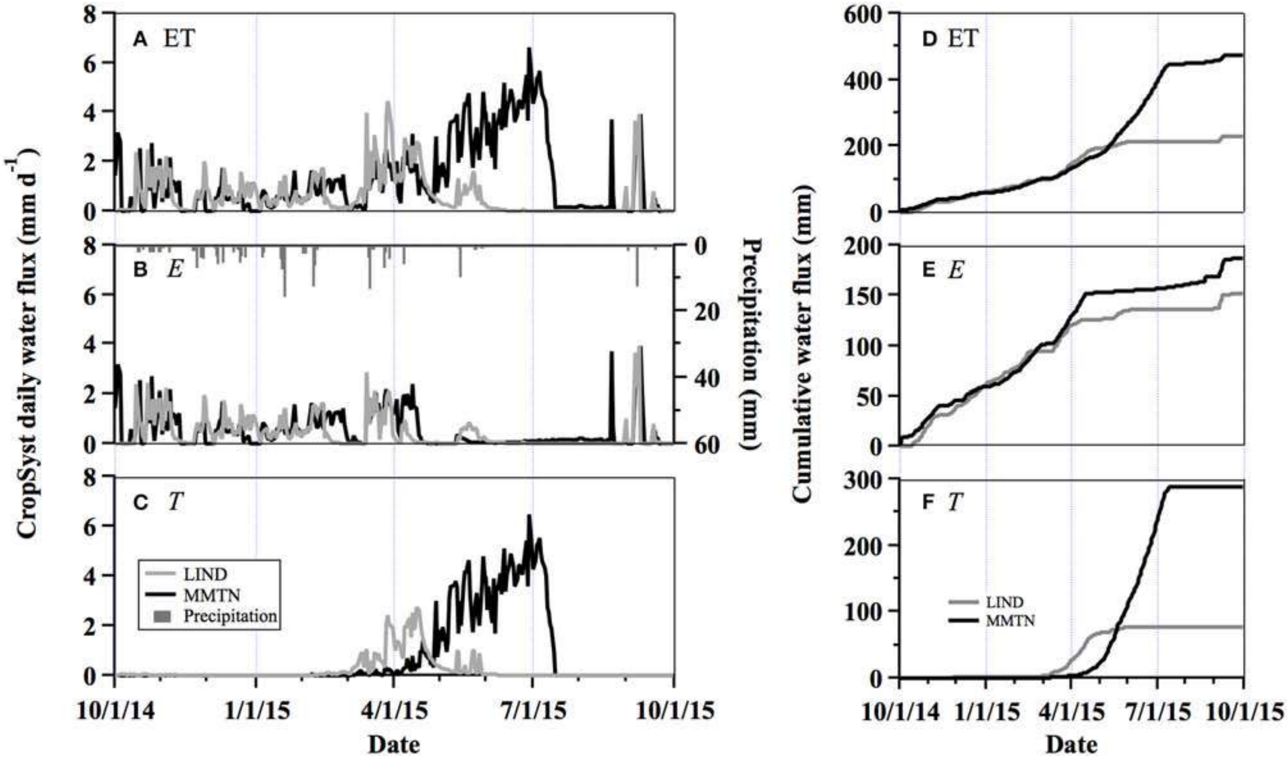

FIGURE 8 | CropSyst daily (A–C) and cumulative **(D–F)** evapotranspiration (ET), soil water evaporation (*E*), and crop transpiration (*T*) at the low-rainfall (LIND) and high-rainfall (MMTN) winter wheat fields during the water year of 2015. Daily precipitation data were only plotted for LIND.

TABLE 5 | CropSyst annual carbon (g C m^{-2}) and water (mm) budgets for 14 site-years.

	2012		2013				2014				2015			
	LIND (TF)	**CAF-NT (WW)**	**LIND (WW)**	**CAF-NT (SG)**	**CAF-CT (SG)**	**MMTN (SB)**	**LIND (TF)**	**CAF-NT (WW)**	**CAF-CT (WW)**	**MMTN (SP)**	**LIND (WW)**	**CAF-NT (SC)**	**CAF-CT (SC)**	**MMTN (WW)**
R_{eco}	142	734	314	445	446	552	119	821	876	361	218[b]	749[a]	597[a]	710[b]
R_a	0	464	195	181	154	186	0	441	464	182	122[b]	227	210	383[b]
R_h	142	270	119	264	292	366	119	380	412	179	96[b]	522[a]	387[a]	327[b]
GPP	−1	−1190	−470	−361	−334	−513	−1	−1108	−1174	−438	−317[b]	−498	−577	−887[b]
NEE	141	−456	−156	84	112	39	118	−287	−298	−77	−99	251[a]	20[a]	−177
EXP	0	364	80	48	89	192	0	226	315	80	39	76	84	114
NECB	−141	92	76	−132	−201	−231	−118	61	−17	−3	60	−327	−104	63
ET	223	580	316	394	391	381	171	515	518	386	229[b]	406	442	475[b]
T	0	357	126	134	134	166	0	312	323	172	77[b]	190	225	288[b]
E	223	223	190	260	257	215	171	203	162	214	152	216	217	187
Precip	250	496	278	539	539	584	175	455	455	536	208	467	467	793
T/ET	0	0.62	0.40	0.34	0.34	0.44	0	0.61	0.62	0.45	0.34	0.47	0.51	0.61

[a]*significant difference between CAF-NT and CAF-CT ($p < 0.05$).*

[b]*significant difference between LIND and MMTN ($p < 0.05$).*

TF, tillage fallow; WW, winter wheat; SG, spring garbanzo; SB, spring barley; SP, spring pea; SC, spring canola. NT, no-till; CT, conventional tillage. EXP, carbon content in the exported harvest materials. Precip, precipitation.

no-till practice, decreasing the amount of water reaching the soil. Similar results were also found in other studies (Dalrymple et al., 1993; Rasmussen et al., 1997; Kettler et al., 2000; Lopez-Bellido et al., 2000; Rieger et al., 2008; Ogle et al., 2012).

The no-till benefits of reduced R_{eco} and R_h over the spring garbanzo and the winter wheat fields was primarily due to the fact that no-till practice reduces soil-residue contact, and slows down SOC oxidation and residue decomposition (Kessavalou et al., 1998; Koga et al., 2003; Dong et al., 2008; Li et al., 2010; Chang et al., 2013; Gollany, 2016; Hu et al., 2016; Lu et al., 2016). Comparing CropSyst to the DayCENT model showed that over the winter wheat field, the R_h difference between the two sites in CropSyst is comparable to the DayCENT model simulations as reported by Chang et al. (2013). However, CropSyst results showed that no-till management practice resulted in increased R_{eco} for spring canola and almost identical R_{eco} for spring garbanzo, indicating that crop rotations also affected agricultural CO_2 emissions, especially during the growing season (Omonode et al., 2007). As there were very few studies in the literature review related to tillage impacts on CO_2 emissions from the spring garbanzo and the spring canola fields, the only available comparison was with R_{eco} modeled based on corresponding eddy covariance NEE and other data. The R_{eco} derived from the measurements showed that the no-till site had a significant lower annual R_{eco} compared to the conventional tillage over the spring garbanzo field (Chi et al., 2016) and the spring canola field. Therefore, more studies on tillage impacts on R_{eco} over spring crops are needed to validate the modeling results. In summary, the modeled results suggested that no-till can either increase or decrease R_{eco}, greatly depending on crop species. As the increased R_{eco} by no-till practice for spring crops offset the reduced R_{eco} over winter wheat field, the model showed the mean annual R_{eco} did not vary much between the two tillage sites over the three water years. A similar finding was also reported in Campos et al. (2011) where they found no significant difference in annual average CO_2 emissions between tilled and no-till systems.

Comparing the simulated daily R_{eco} between the two sites over the course of three water years, the R_{eco} at the conventional tillage site reacted more intensely to the rainfall events, which was presumably due to the “Birch Effects”, where rainfall events after a drought period can induce respiration pulses (Birch, 1958). This was also found in other studies, such as Fierer and Schimel (2003), Jarvis et al. (2007), Unger et al. (2010), and Ma et al. (2012). The impact of rainfall events under no-till management is somewhat reduced due to residue interception of rainfall, particularly with infrequent and low amount rainfall events. Higher R_{eco} at the conventional tillage site after each seeding event was attributed to the enhanced R_h under the warmer and tilled soil conditions, which was also observed in other studies (Dwyer et al., 1995, 1996; Ben Moussa-Machraoui et al., 2010; Derpsch et al., 2010; Aziz et al., 2013).

The similar modeled water budgets at the two sites suggested that tillage practices had insignificant effects on ET, which has also been found over different crop fields, such as winter wheat, spring garbanzo, canola, corns, and soybean (Borstlap and Entz, 1994; Tan et al., 2002; Liu et al., 2013; Zhang et al., 2013; Guan et al., 2015; Chi et al., 2016). Daily E differences between the two sites were a good indicator of how the different soil conditions affect the direct water losses from the soil surfaces. Similar to the previous studies, we found that during the oMGS rainfall events, the simulated E was suppressed by the residue cover layer at the no-till site compared to the bare and disturbed soils at the conventional tillage site (Salado-Navarro and Sinclair, 2009; van Donk and Klocke, 2012; Wang et al., 2014). This amount of reduced E at CAF-NT was mostly affected by rainfall frequency rather than rainfall amounts, which was also supported by van Donk et al. (2010) where they found the different magnitude in E between residue-covered and bare soils increased during the infrequent and light rainfall events. One example of this is the September 2015 rain events on the 6, 17, and 18th (10.2, 1.5, and 4.6 mm rainfall, respectively) that resulted in the largest difference in simulated E between CAF-NT and CAF-CT (**Figure 6B**). The simulated daily T was only influenced by tillage practices during the winter wheat growing season and the difference between CAF-NT and CAF-CT was consistent with the finding in Guan et al. (2015) where they concluded that ET (mostly T during MGS) under tilled conditions was greater than ET under no-till from seeding to flowering stages, but smaller at the ripening stage.

Rainfall Effects on Winter Wheat Fields

In 2015, winter wheat was grown at the low- and high-rainfall sites (LIND and MMTN), and comparing the CropSyst results between these two sites provided a direct comparison of carbon and water budgets between different rainfall zones in the iPNW region during the same year. Through validating the model performance for assessing the rainfall effects, CropSyst can be applied to study the impacts of future climatic conditions on the field-scale carbon and water cycling. As expected, the high-rainfall area had greater winter wheat crop yield and the limited rainfall in the crop-fallow area greatly restricted crop productivity (Musick et al., 1994; Lindwall et al., 1995). Large rainfall amounts and frequent rainfall events increased the simulated R_{eco} by enhancing R_h during the oMGS and R_a during the MGS at MMTN. The frequent rainfall events during the oMGS greatly enhanced soil microbial activity under the disturbed soil conditions at MMTN, which was also observed by Calderon and Jackson (2002); Zhou et al. (2006); Jiang et al. (2013), and Gong et al. (2015). In addition, MMTN had sufficient water for winter wheat growth, therefore R_a was also much higher compared to LIND where both crop growth and crop respiration were limited by the dry summer. On an annual basis, both sites were net carbon sinks with a comparable NECB magnitude. Higher yields at MMTN enhanced GPP, but larger soil (higher SOC content) and crop (higher biomass) respiration offset GPP and resulted in a relative smaller NEE compared to other high-rainfall winter wheat fields. However, the larger amount of residues produced at MMTN maintained a larger SOC stock.

Based on Liu et al. (2002), the average total water consumption for winter wheat is approximately 450 mm assuming no water stress conditions. The amount of water available at LIND during 2015 was only half of this, even though LIND stored some soil water content from the previous fallow year. According to the CropSyst results, winter wheat was growing under water stress conditions at LIND during 2015, therefore resulting in a much smaller annual ET compared to MMTN and the average value (450 mm). Because of sufficient rainfall during 2015, annual ET at MMTN was comparable to the average water consumption of winter wheat. Based on the difference between annual ET and annual precipitation at MMTN, more than 40% of annual rainfall amount was either stored in the soil or lost via surface runoff. According to the field measurements during 2013–2015, the average runoff was typically <10% of the precipitation and the year of 2015 had 71 mm (9%) surface runoff.

Due to the water stress at LIND, T/ET was significantly lower compared to other studies on winter wheat water use efficiency, where annual T typically accounts for 60–75% of annual ET (Gregory et al., 1992; Liu et al., 2002; Sun et al., 2006; Chen et al., 2010; Aouade et al., 2016). More than 60% of ET was estimated to be lost directly into the atmosphere, which was likely due to the less dense crop coverage at LIND compared to MMTN (seen in the biomass measurements and the time-lapse camera), as E typically increases with the winter wheat row spacing (Sun et al., 2006; Chen et al., 2010). T/ET at MMTN was within the average water use efficiency range (0.60–0.75), with the majority of evaporation occurring during the early MGS (March and April). Therefore, the seasonal rainfall distribution also greatly affected the annual water budget and water use efficiency.

CONCLUSIONS

Compared to the eddy covariance measurements, the CropSyst model performed well in simulating NEE and ET at all sites with an overall r of 0.78 and 0.80 and a RMSE of 1.82 g C m^{-2} d^{-1} and 0.84 mm d^{-1}, respectively. Overall, the model slightly underestimated the carbon sink strength and the total water consumption by 0.51 g C m^{-2} d^{-1} and 0.09 mm d^{-1}, respectively. Carbon budget simulations showed that the winter wheat fields in the iPNW region were either net carbon sinks or near carbon neutral (NECB, 92 to −17 g C m^{-2}), while the fallow site and the spring crop fields were net carbon sources or neutral (NECB, −327 to −3 g C m^{-2}) over an annual basis. Annual water budget simulations indicated that water use efficiency (T/ET) was significantly lower over the spring crop fields and the low-rainfall winter wheat field (0.34–0.51), compared to the high-rainfall winter wheat fields (0.61–0.62).

The seasonal and inter-annual variability of carbon and water budgets also agreed well with the eddy covariance measurements. The inter-annual variations of each flux component were greatly affected by crop rotations and meteorological conditions, with winter wheat and high-rainfall sites typically having larger magnitudes of carbon and water fluxes, compared to the spring and the low-rainfall site.

CropSyst output was used to assess the impacts of tillage practices and rainfall on agricultural carbon and water budgets in the iPNW region. The modeled results suggested that no-till practice resulted in lower carbon losses from the winter wheat and spring garbanzo fields but higher CO_2 emissions from the spring canola field compared to the conventional tillage. Tillage practices showed varied effects on crop yields, strongly depending on crop species. Therefore, more studies will be needed to further investigate the tillage effects on different crop species. Water budget simulations did not differ significantly between the two tillage systems. Compared to the low-rainfall winter wheat field, the high-rainfall site obtained greater winter wheat crop yield and higher water use efficiency but had higher CO_2 emissions.

In summary, the CropSyst model can be used as a practical tool to assess the field-scale carbon and water budgets. Future work associated with improving the model performance for site-specific simulations includes using more detailed management practices as model input, calibrating the model with measurements over various crop species, obtaining adequate model initial conditions for each site-year.

AUTHOR CONTRIBUTIONS

PO, SW, JC, and EB contributed to the field data collection. JC, SW, SP, and BL contributed to eddy covariance data processing. FM and CS provided the modeling results. JC and FM prepared the figures and tables. JC, FM, SW, SP, CS, BL, WP, DH, and EB conducted the data analysis and interpretation. All authors contributed to the writing of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fevo.2017.00050/full#supplementary-material

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Agroclimatology and Wheat Production: Coping with Climate Change

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Cereal production around the world is critical to the food supply for the human population. Crop productivity is primarily determined by a combination of temperature and precipitation because temperatures have to be in the range for plant growth and precipitation has to supply crop water requirements for a given environment. The question is often asked about the changes in productivity and what we can expect in the future and we evaluated the causes for variation in historical annual statewide wheat grain yields in Oklahoma, Kansas, and North Dakota across the Great Plains of United States. Wheat (*Triticum aestivum* L.) is adapted to this area and we focused on production in these states from 1950 to 2016. This analysis used a framework for annual yields using yield gaps between attainable and actual yields and found the primary cause of the variation among years were attributable to inadequate precipitation during the grain-filling period. In Oklahoma, wheat yields were reduced when April and May precipitation was limited ($r^2 = 0.70$), while in Kansas, May precipitation was the dominant factor ($r^2 = 0.78$), and in North Dakota June–July precipitation was the factor explaining yield variation ($r^2 = 0.65$). Temperature varied among seasons and at the statewide level did not explain a significant portion of the yield variation. The pattern of increased variation in precipitation will cause further variation in wheat production across the Great Plains. Reducing yield variation among years will require adaptation practices that increase water availability to the crop coupled with the positive impact derived from other management practices, e.g., cultivars, fertilizer management, etc.

Keywords: temperature, precipitation, yield gaps, agroclimatic indices, historical yields

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INTRODUCTION

Agricultural ecosystems convert light, water, carbon dioxide, and nutrients into a variety of diverse plant products, e.g., carbohydrates, proteins, starch, etc. However, the changing climate, affects water availability, temperature, and atmospheric CO_2 concentrations which in turn directly influences the plant growth processes and ultimately the ability of plants to efficiently produce the protein, starch, and other plant products that the human race requires as food. These effects are especially critical in cereal crops because of the importance in the human food supply. It is important to understand the role climate has on crop productivity and on individual plants and plant communities as part of agroecosystems.

Production variability in cereal crops in Queensland, Australia has been related to availability of precipitation and temperatures during the growing season (Yu et al., 2014). They found precipitation during the vegetative stage was the positive factor and most beneficial in determining grain yield, while exposure to high maximum temperatures depressed grain yields. Assessments of the future impacts of climate on agricultural productivity have been the subject of several recent summaries (Hatfield et al., 2011). These summaries have fostered extensive efforts to model the effects of future climate and have revealed that the continual increase in temperatures will depress wheat yields by 6% per °C increase (Asseng et al., 2015). Increasing carbon dioxide levels will increase growth; however, the positive effects are often offset by exposure to high temperatures and reduced precipitation (Hatfield et al., 2011). The Great Plains of the United States represent one of the most extensive areas of wheat (*Triticum aestivum* L.) production. Historical yields across the Great Plains provide an opportunity to evaluate the change in production relative to climate trends and to determine the effect of a changing climate on grain yields. One potential avenue to evaluate yield response is to examine the change in the yield gap, defined as the difference between the potential and actual yield. Licker et al. (2010) and van Brussel et al. (2015) have shown the value of yield gaps in being able to assess productivity in crops across the globe. Hatfield et al. (2017) utilized yield gap analysis across the Midwest for corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] to determine the relationship between yield gaps and the meteorological conditions during the growing season. They found that July maximum, August minimum, and July–August precipitation totals were the dominant factors explaining yield gaps in these two crops across the Midwest. They utilized these relationships to estimate the potential impact of a changing climate across the Midwest and found with increasing temperatures and more variable summer precipitation there would be significant decreases in corn and soybean production.

Yield gap analysis was applied to the Great Plains of the United States using Kansas, Oklahoma, and North Dakota statewide yield data as examples of the changes in wheat productivity. These states were selected because Kansas and Oklahoma wheat yields at the state-wide production have shown a decline since 2000 with a recovery in yields in 2016 to near record levels (**Figure 1**). These trends are in contrast to wheat yields in in North Dakota that have continued to exhibit a yield increase with the typical annual variation due to variable weather during the growing season (**Figure 1**). Our goal was to evaluate the yield gaps in these three states and relate these yield gaps to the meteorological conditions during the growing season.

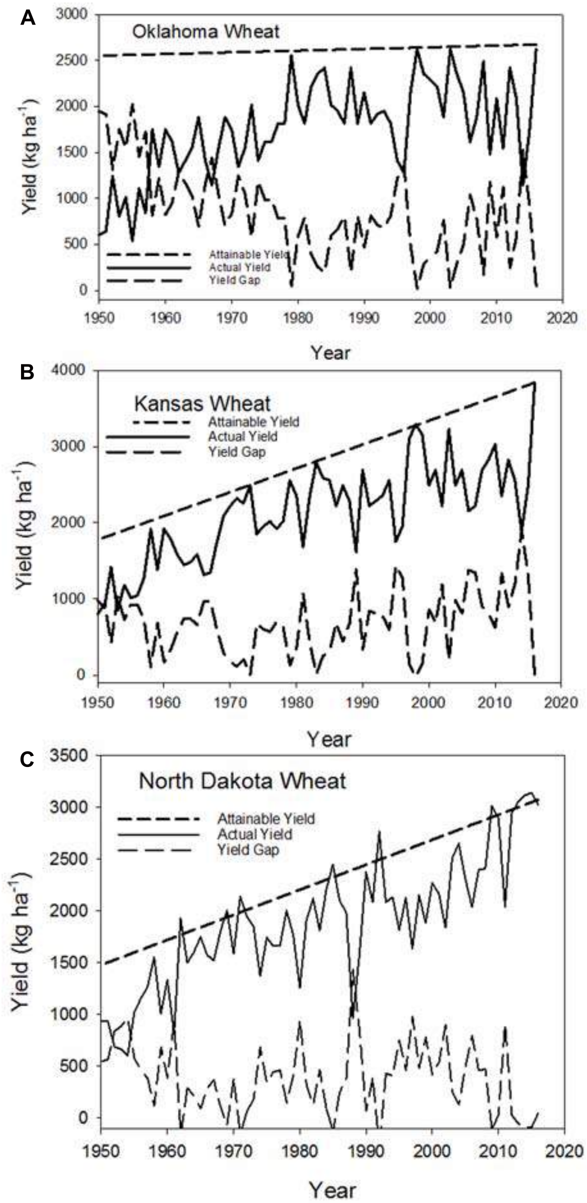

FIGURE 1 | Attainable yield, actual yield, and yield gap for **(A)** Oklahoma, **(B)** Kansas, and **(C)** North Dakota statewide wheat yields since 1950 (data obtained from www.nass.usda.gov, accessed 2-December-2016).

YIELD GAPS IN CEREALS

Throughout the history of agriculture, there has been the development of indices that describe how crops respond to the weather or how climate affects the distribution of crops around the world. Temperature and precipitation have been the two primary variables used in the development of these indices because of the availability of these data from public sources; however, the relationship of these indices to yield gaps has not been conducted. A recent study by Holzkämper et al. (2013) incorporated six factors into a crop suitability index that included average daily minimum temperatures below 0°C for frost impacts, daily mean temperature to determine plant growth, average daily maximum temperature above 35°C for heat stress, average daily soil water availability (precipitation–reference evapotranspiration), and length of the phenological period (days) to account for the effects of changing phenological development on biomass accumulation and crop yield. They were able to relate their index to maize yields for a number of locations around the world with a positive relationship between productivity and the suitability index. This approach is a refinement of the original approach by Neild and Richman (1981) to add more factors into their index to more closely match crop physiological responses.

Temperature impacts crop phenology and each species has a specific lower temperature value or base temperature, an optimum temperature value, and an upper temperature limit (Hatfield et al., 2011). Increases in temperature above the optimum have shown a negative impact on wheat yield with a projected 5.3% (Innes et al., 2015), and 6% (Asseng et al., 2015) yield reduction per 1°C rise. In wheat, exposure to frost or high temperatures during pollination has a significant effect on yield (Prasad and Djanaguiraman, 2014; Rezaei et al., 2015).

Adequate soil water supplies to the crop can offset the impacts of temperature extremes that are projected to increase during the growing season (Hansen et al., 2012; Collins et al., 2013; Walsh et al., 2014). These are difficult concepts to evaluate; however, understanding the linkage between historical yields and climate provides a foundation for future management scenarios.

To evaluate this framework, we computed the yield gaps for wheat production in Kansas, Oklahoma, and North Dakota following the approach of Egli and Hatfield (2014a) and Hatfield et al. (2017) using state level yield data since 1950. We selected 1950 as the beginning point in these analyses because this represents the agricultural era with modern technology. Yield gaps are computed as the difference between attainable yield, defined as the highest yields observed over the period of record, and the actual yield. Attainable yields are assumed to represent wheat yields under conditions that are non-limiting during the production year and a regression line is fit through these yields to obtain an attainable yield for each year. In this case study we used statewide yields rather than county yields to show the impact of climate variables at a large scale. It is evident for these three states that the attainable yield varies among states. For example, in Oklahoma, state level yields have shown only a modest increase since 1980 while Kansas and North Dakota have shown significant increases in grain production (**Figure 1**). Yield gaps for all three states showed variation from 1950 to 2016 and a statistical analysis of the yield gap with monthly maximum and minimum temperatures and precipitation observations was conducted. Regression analysis of monthly statewide average maximum and minimum temperatures and precipitation (data obtained from the Regional Climate Center) for the months of October, November, April, May, and June for Oklahoma and Kansas and April, May, June, and July for North Dakota against yield gaps for these three states revealed that precipitation was the only consistent and significant factor explaining yield gaps. For Oklahoma, the yield gap was explained by total April and May precipitation with a $r^2 = 0.7$ and in Kansas the yield gap was due to May precipitation ($r^2 = 0.78$). In North Dakota, with the later maturing crop, June and July precipitation was the dominant factor explaining 0.65 of the yield gap. Temperature for these three states showed no significant relationship to the variation in yield gap, even though there were years with temperatures that deviated from normal, these deviations were not sufficient to cause a change in statewide yields. Precipitation amounts below normal increased the yield gap and while low precipitation events are often associated with high temperatures, the phenology of the wheat crop with the grain-filling period earlier in the year reduces the potential for high temperature events. Although there were years in which the temperatures were above normal, these were not above the maximum temperature range for wheat for a significant period of time to become a significant factor reducing yield. Evaluating the effect of increasing temperatures has to account for the temperature increase relative to the temperature ranges of the crop. For example, Ahmed et al. (2017) showed an

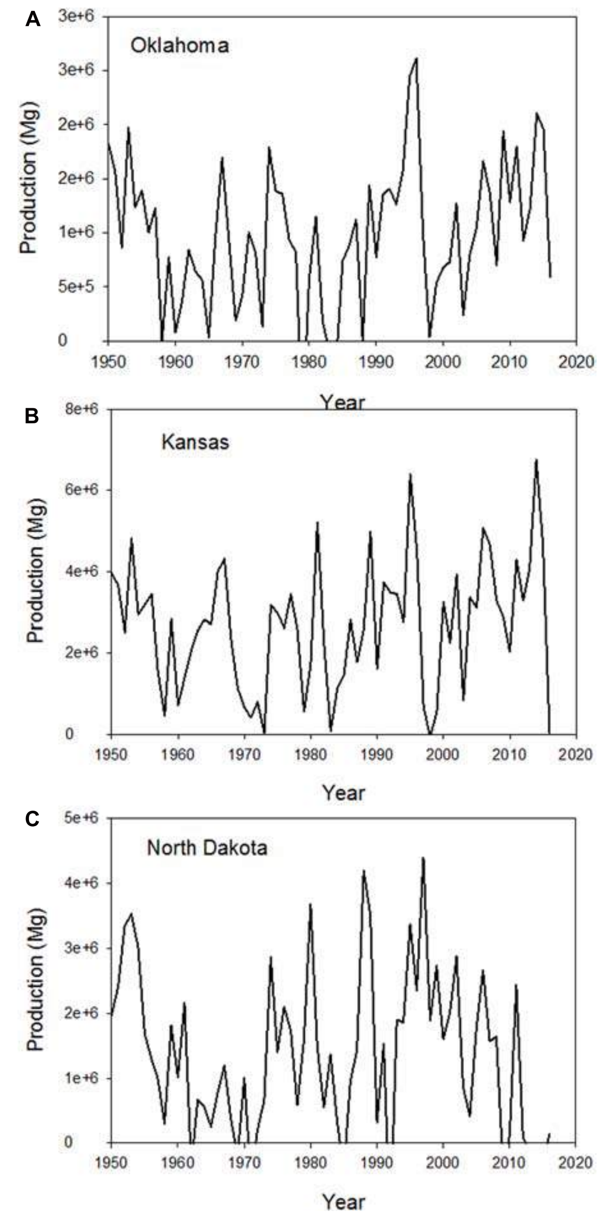

FIGURE 2 | Production lost due to yield gaps occurring in **(A)** Oklahoma, **(B)** Kansas, and **(C)** North Dakota since 1950.

increase in wheat yields in the Pacific Northwest; however, these temperature increases are still within temperature ranges for the crop. We evaluated temperature effects using different temperature parameters for these data and found no consistent and significant relationships. This could be related to the fact that high temperature events or frost occur over short time periods, e.g., less than 5 days, and in more localized areas that are not detectable in monthly average data at the statewide scale, but can have significant impacts on local productivity (Prasad and Djanaguiraman, 2014; Rezaei et al., 2015). This does raise a caution about the scale being used in analysis of climate impacts on agriculture.

The primary inability to close the yield gap in the Great Plains was the lack of soil water to meet the water requirements of the wheat crop and insufficient precipitation amounts to recharge the soil profile during the grain-filling period. Egli and Hatfield (2014a,b) demonstrated that maize and soybean productivity were directly related to the ability of the soil to supply water during the grain-filling period. The dynamics of this response has been described by Hatfield (2012) to show the largest effect on maize yields in the central United States was the lack of sufficient water availability during the grain-filling period to meet the evaporative demand. The increase in precipitation variability with climate change will increase variation in crop yield (Hatfield et al., 2011). Soil water becomes the dominant factor affecting vegetative productivity in both cultivated and natural systems and the ability of the soil to infiltrate and store precipitation will become a critical factor to offset the impact of increasing variability in the changing precipitation regime. Increases in soil organic matter and the resultant impact on soil water holding capacity will increase the ability of a soil to store water and increase the infiltration rate. Both of these factors will increase the efficiency of a soil to offset variation in precipitation due to climate change.

The magnitude of the yield gaps creates a large loss in wheat production across the Great Plains (**Figure 2**) and average about 20% of the attainable yield. The largest lost production in a given year was over 3 million Mg in Oklahoma, 6 million Mg in Kansas, and 4 million Mg in North Dakota during this period. This is a significant economic factor in each of these state economies. Since 1950, the production lost in these three states exceeds 65 million Mg in Oklahoma, 180 million Mg in Kansas, and 91 million Mg in North Dakota. These represent extremely large losses across the Great Plains and can be partially offset by management practices to increase climate resilience in our cropping systems. These management practices encompass how we manage the soil for water and nutrients, along with cultivar selection, and agronomic practices related to crop management for weeds, pests, and diseases.

COPING WITH CLIMATE CHANGE

Variation in cereal production is directly linked with variations in precipitation and temperature and evident in the historical yield records. Projections of future changes in climate with warming temperatures and more variable precipitation will have impacts on crop productivity (Tao et al., 2009; Hao et al., 2013) and the recent analysis by Hatfield et al. (2017) for maize and soybean revealed that a combination of July maximum temperatures, August minimum temperatures, and July–August precipitation explained yield gaps across the Corn Belt. In this research study, we found for wheat in the Great Plains of the United States that precipitation was the dominant factor, with amounts during the grain-filling period the most critical in terms of affecting yield. Projections of precipitation for the critical months for wheat production in the Midwest obtained from https://climatetoolbox.org/tool/future-climate show that amounts will increase coupled with increased variation. We could expect yield variation among years to increase; however, the tendency to increase total amounts would suggest years with low yields may decrease leading to an overall increase in wheat productivity across the Great Plains until temperature increases become the dominant factor affecting grain yields. The projection that precipitation will become more variable during the spring months creates a situation in which management of soil water for the crop will be a necessary adaptation strategy to cope with climate change (Melillo et al., 2014). Protection of the soil resource to ensure available soil water will be critical to overcoming these impacts.

There is evidence in the literature to suggest that increasing temperatures will become more significant in affecting wheat productivity; however, some of this impact can be offset by ensuring these crops have an adequate soil water supply. Although, precipitation was a dominant factor in historical yields for these states, the recent results by Prasad and Djanaguiraman (2014), Tack et al. (2015), Karimi et al. (2017), and Kaur et al. (2017) suggest that we need to devote more attention to the effects of temperature on wheat productivity and suggest analyses and simulation models be utilized to evaluate the potential growing regions and productivity for wheat under future climate scenarios. To ensure continual advances in wheat productivity will require an integrated approach combining genetic improvement along with management practices and the approach we have outlined in the paper provides a framework for evaluating how we are progressing toward reducing the gap between genetic potential and actual yield.

AUTHOR CONTRIBUTIONS

This paper is a contribution from United States Department of Agriculture, Agricultural Research Service. JH wrote the paper and conducted the analysis. CD reviewed the materials and offered insights on the dynamics of environmental interactions.

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Estimating the Impacts of Climate Change and Potential Adaptation Strategies on Cereal Grains in the United States

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Climate change induced alterations from historical patterns of precipitation, temperature, and atmospheric gases as well as increases in the frequency of extreme events is leading to alterations in global cereal production and its spatial distribution. Using a US agricultural sector model, we examine effects and acreage adaptation with an emphasis on wheat and the Pacific Northwest region. Use of a national sector model allows for analysis at the national as well as regional level. Generally, under climate change we find that the incidence of wheat production shifts northward in the Southern Great Plains, westward in Northern Great Plains and eastward in Oregon and Washington, all of which are moves to cooler conditions. Total wheat acreage in the Pacific Northwest is expected to decline from 6 million acres under no climate change to 5.4–5.7 million acres over the study period. Additionally, we consider impacts on price, production, and consumer, producer, and foreign welfare finding losses to consumer welfare and gains to producer welfare with overall losses in surplus. Recommendations are made for future research and alternative ways that adaptation strategies can be integrated into models to predict long-term impacts.

Keywords: climate change, adaptation, agriculture production, ASM, Pacific Northwest, cereal crops

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INTRODUCTION

Crop production is sensitive to climate and weather patterns. According to the 2016 NOAA State of the Climate report (NOAA, 2017), (1) globally 2016 was the warmest year on record, and (2) Every one of the 5 warmest years in the climate record have occurred since 2010. Further, the observed pace of temperature increase since 1970 is 2.5 times greater than the pace since 1880. Such increases in temperature have affected agriculture and society in general (IPCC, 2014a). Lobell and Field (2007) estimate the magnitude of the yield loss due to increased temperatures between 1981 and 2002 finding that for barley, wheat and maize production was decreased by 2–3% with market losses of about $5 billion per year. Additionally Cho and McCarl (2017) examine historical data showing that this is stimulating farmers to change crop mix with many crops moving northward and up in elevation while Mu et al. (2013) show land moving from cropland to pasture.

Climate change is expected to continue to evolve further affecting agriculture. The Inter-Governmental Panel on Climate Change (IPCC) projects even greater future effects including: increased surface temperatures, changes from historical precipitation patterns, loss of soil moisture in select regions and an increase in the frequency of extreme events among other items (IPCC, 2013). This will impact future global crop production.

The production effects will also manifest in altered prices and demand levels (Adams et al., 1995). In turn, climate change will affect agricultural income and general economic conditions.

Here we simulate the impacts that projected climate change will have on United States agriculture including examining changes in the spatial incidence of crops along with the agricultural, income, production and market effects. In doing this we will place particular emphasis on wheat and the US Pacific Northwest.

The United States (US) is one of the top wheat producing countries. Its production is only surpassed by China, the European Union, India, and Russia (USDA ERS, 2016). States that produced the most wheat in 2015 were: North Dakota (370 million bushels), Kansas (321 million bushels), Montana (185 million bushels) and Washington (112 million bushels) (USDA NASS, 2016).

There is a long history of wheat production in the Pacific Northwest (PNW)—Washington, Oregon, and Idaho (Schillinger and Papendick, 2008). Sales from wheat production in Washington for 2012 were $1.1 billion (USDA NASS, 2015) and $786 million in Idaho in 2011 (IFBF, 2017). Further, three of the top 10 wheat selling counties in the US were in Washington and one in Oregon (USDA NASS, 2015).

Many studies indicate that warmer temperatures, shifts in water availability, and increased atmospheric carbon dioxide have impacted wheat yields with different effects spatially (Chen et al., 2004; Lobell and Field, 2007; McCarl et al., 2008; Attavanich and McCarl, 2014). In particular, warmer temperatures in hotter areas stress plants and lead to reduced yields (Asseng et al., 2011). But in higher latitudes or at higher elevations, warmer temperatures increase frost free days and growing degree days thereby lengthening the growing season (Kane et al., 1992). However, increased variability of temperatures has been shown to reduce wheat yields (Wheeler et al., 2000). Also, for non-irrigated crops, climate change alters precipitation patterns which will affect yields. Finally, Chen and McCarl (2001) show that climate change has increased pesticide usage and production costs. Additionally increased carbon dioxide concentrations stimulate wheat yields (Attavanich and McCarl, 2014). Overall there are both yield decreasing and increasing forces under climate change depending on location, crop and CO_2 sensitivity.

Farmers' reactions to climate change is and will continue to shift land allocation between crops and other uses plus the incidence of crops spatially. The land may shift to other crops, pasture or forest. Mu et al. (2013) projected cropland in the US (especially in the central and southern region of US) would shift to pasture under the four General Circulation Models (GCMs) they tested while many studies have projected latitude and elevation shifts in crop incidence (Adams et al., 1990; Reilly et al., 2001, 2002; Cho and McCarl, 2017).

This paper will explore the impact of projected global climate change on the US with a focus on wheat production and the Pacific Northwest (PNW) taking into account the total US agricultural market. Additionally, since the magnitude of future climate change and related emissions control is uncertain, this study will use multiple climate projections across multiple mitigation scenarios to generate results on the range of possible impacts.

MATERIALS AND METHODS

In order to carry out our study, we need estimates on the effect of varying degrees of climate change on crop yields. This information will then be used to see what these changes do to economically driven land allocation, production and markets.

Due to the expertise of this study team we did not generate our own simulation based crop yield estimates; rather choosing to use ones from the peer reviewed literature. Specifically, yield responses from Beach et al. (2015) were used because they were available for all FASOM regions across the entirety of the continental US and were reflective of the climate models used in the most recent IPCC Report (2013).

The study used crop yield sensitivity estimates obtained from Beach et al. (2015) who estimated crop yield changes using the Environmental Policy Integrated Climate (EPIC) crop simulation model nationwide for nine crops under alternative climate projections[1]. The climate projections arose from two GCMs (MIROC and IGSM-CAM hereafter called IGSM). Each run included two greenhouse gas mitigation scenarios (aggressive mitigation—hereafter called the policy scenario and no mitigation—hereafter called the reference scenario). The specific GCMs used were selected by Beach et al. (2015) because of their varying characteristics in terms of precipitation. In particular, the MIROC projections show a relatively drier future and the IGSM projections show a wetter one, particularly for the Eastern and Central US (Beach et al., 2015).

Yield estimates from Beach et al. (2015) are comparable to yield projections obtained from other cropping studies conducted specifically in the PNW. Stockle et al. (2017) showed wheat productivity increasing under climate change in the inland PNW until approximately 2050 and then declining to current levels by the end of the twenty-first century with increased carbon dioxide positively impacting yields. Karimi et al. (2017) simulated grain yields in the inland PNW suggests that grain yields will increase under climate change projections. Specifically, Karimi et al. (2017) included cropping practices and showed that yields in 2070 are projected to increase 18–48% under representative concentration pathway (RCP) 4.5 and 30–65% under RCP 8.5. Results from these regional studies support the results from the EPIC projections by Beach et al. (2015) suggesting that the EPIC projections are suitable for use in this assessment.

In terms of mitigation, the threat of climate change has caused the international community to dialog and in cases addresses emissions reductions. Since the future extent of mitigation is uncertain, Beach et al. (2015) utilized two scenarios reflecting different levels of GHG mitigation. In the no mitigation or business as usual, reference scenario, global GHG emissions are not greatly reduced and by year 2100 total radiative forcing is 10 Wm^{-2} (Beach et al., 2015). This corresponds most closely to the IPCC RCP 8.5 scenario which predicts temperature change

[1]The crops included in Beach et al. (2015) are barley, corn, cotton, hay, potatoes, rice, sorghum, soybeans, and wheat.

TABLE 1 | Average change in percentage yield for top field crops in the US and PNW.

		IGSM-Pol		IGSM-Ref		MIROC-Pol		MIROC-Ref	
		Dryland	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland	Irrigated
National	Soybean	8.5	4.6	3.4	−5.3	−7.1	−0.2	−15.7	−8.3
	Corn	24.2	12	16.1	1.4	5.4	7.9	−6.9	−0.9
	Wheat	18.2	9.2	11.4	−0.7	6.2	7.2	−8.1	−4.7
	Hay	−37.8	17.2	−34.1	17.1	−44.8	17.5	−46.1	17.7
	Cotton	25.8	12.8	19.8	1.6	−2.3	9.0	−18.0	−3.7
PNW	Wheat	13.2	2.7	6.1	−5.9	13.8	5	10.7	−0.5
	Hay	−28.2	20.1	−23.3	25.8	−33.5	21.0	−29.5	24.9
	Barley	41.6	19.1	31.7	0.6	18.8	18.3	24.9	12.1
	Potatoes	28.3	11	13.4	−10.1	11.5	11.3	10.4	2.8
	Corn	47.5	15.2	42.9	5.9	25.1	16.6	32.1	14.7

These are calculated by the authors over the data from Beach et al. (2015).

TABLE 2 | Percentage change in crop yield standard deviations across climate projections relative to MIROC-Ref.

	Dryland			Irrigated		
	MIROC	IGSM		MIROC	IGSM	
	Pol	Ref	Pol	Pol	Ref	Pol
Barley	−49.947	−5.478	−34.743	−44.088	−22.886	−58.337
Corn	−41.726	13.834	−29.526	−49.408	−26.064	−67.842
Cotton	−27.830	18.402	−28.196	−41.745	−19.940	−61.318
Hay	31.763	119.933	112.333	−60.467	−15.983	−66.586
Potato	−26.268	−10.115	−26.211	−26.076	−23.076	−35.441
Rice	15.532	31.441	54.350	−22.971	−41.626	−33.694
Sorghum	−33.814	18.133	−33.268	−37.207	−15.083	−55.801
Soybean	36.211	102.785	8.644	−43.044	−26.154	−66.336
Wheat	118.682	158.126	94.555	−55.447	−48.737	−71.968
Average	2.511	49.674	13.104	−42.272	−26.617	−57.480

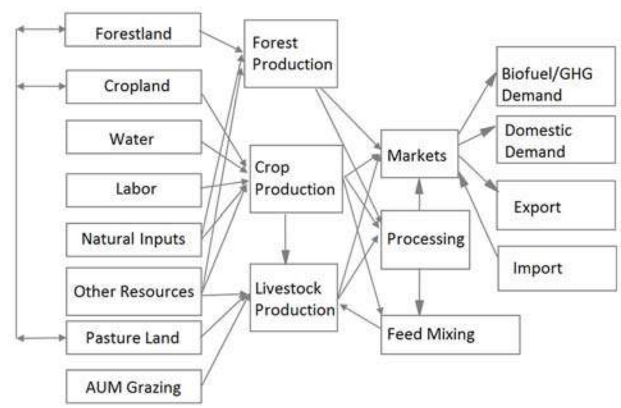

FIGURE 1 | FASOM structure. Source: Adams et al. (2005) Unpublished paper Texas A&M University on web at http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf.

of about 3.7°C by 2100 (IPCC, 2014b). Conversely, the aggressive mitigation, policy strategy, assumes GHG emissions are reduced to levels that lower total radiative forcing to 3.7 Wm^{-2}. This case corresponds most closely to the IPCC RCP 4.5 which results in about a 1.8°C temperature change (IPCC, 2014b). These two mitigation strategies were applied to the GCMs resulting in four combinations of climate/mitigation scenarios (IGSM-Ref, IGSM-Pol, MIROC-Ref, MIROC-Pol) which Beach et al fed into EPIC to simulate crop yield effects.

The Beach et al. (2015) yield results predict increased yields for many crops. In particular: (1) the yields under the MIROC simulations are lower than those arising from the IGSM projection; (2) Generally, the MIROC reference scenario projected a national decline in yields but positive yields in the PNW (**Table 1**). Nationally, corn and cotton showed the largest percentage increase under IGSM projects with wheat yields showing a slightly lower increase. Under the MIROC scenarios, corn and wheat were the best performing crops; (3) Hay showed different responses to climate change in comparison with the other crops. Increasing temperature under climate change caused dryland hay yields to decrease under all scenarios but irrigated hay yields increased; (4) The yield change for dryland and irrigated crops was negative under the drier MIROC scenarios but positive under the IGSM scenarios; and (5) In the PNW, corn and barley yields showed dramatic increases under all climate scenarios. However, the PNW average corn yield in 1980-2009 was much lower than the national average. Also barley, hay, and potatoes had a higher yield response to climate change than the national average.

Further, we investigated the variability present in the data set across the GCM and mitigation scenarios. To do this, we analyzed the relative variation in yields between scenarios by computing a relative percentage change. For each scenario we computed the standard deviation of yields for each crop and irrigation status across all the subregions. Then we computed a percentage change between each scenario and MIROC-Ref. The resultant data are given in **Table 2**.

TABLE 3 | Average cropland and wheat land use in US and PNW under climate change (2010-2100).

Scenarios	Total cropland use (Million acres)		Wheat land use (Million acres)	
	National	PNW	National	PNW
No climate change	283.0	12.2	56.8	6.0
IGSM-Pol	252.3	10.9	52.6	5.4
IGSM-Ref	266.8	12.1	55.3	5.7
MIROC-Pol	283.2	11.7	56.7	5.5
MIROC-Ref	299.7	12.6	58.2	5.7

TABLE 4 | National top 5 field crops average harvested acreage as percentage of total harvested cropland acreage (2010-2100).

Scenarios	Corn (%)	Soybeans (%)	Wheat (%)	Hay (%)	Cotton (%)
No climate change	22.20	23.18	20.06	17.20	3.99
IGSM-Pol	20.65	23.97	20.84	16.36	3.57
IGSM-Ref	21.12	23.50	20.73	16.68	3.48
MIROC-Pol	21.24	23.69	20.00	16.93	3.31
MIROC-Ref	22.02	23.63	19.43	17.38	3.38

TABLE 5 | PNW top 5 field crops average harvested acreage as percentage of total harvested cropland acreage (2010-2100).

Scenarios	Wheat (%)	Hay (%)	Barley (%)	Potatoes (%)	Corn (%)
No climate change	49.29	27.14	10.39	5.75	1.94
IGSM-Pol	49.48	27.38	9.55	6.02	2.04
IGSM-Ref	46.95	29.25	10.21	6.08	2.02
MIROC-Pol	46.91	31.09	8.74	5.44	2.19
MIROC-Ref	45.41	32.26	9.32	5.40	2.10

We found that for the dryland yields, the relative yield variation in the IGSM climate projections compared to MIROC are mixed in sign but are substantially larger for hay, wheat, soybeans and the overall average. We also found that the relative yield variation was smaller for most crop with strong mitigation (Pol) as opposed to little mitigation (Ref) but with a slightly larger overall average largely due to wheat. For irrigated yields, MIROC-Ref had the highest amount of variability with IGSM generally having less variation than MIROC and the policy scenarios having less than the reference (limited mitigation) ones. Further, percentage change in standard deviation are mostly stable and relatively constant across crops showing irrigation is reducing the variability and making the crops closer in behavior.

In turn, to address land allocation, production and market effects, the agricultural part (ASM) of the Forestry and Agricultural Sector Optimization Model (FASOM), a US agriculture sector model, was used. ASM is a non-linear programming model that simulates production, processing, transporting and marketing in the US agricultural sector in an equilibrium year (Baumes and McCarl, 1978; Adams et al., 1996, 2005). ASM simulates a perfectly competitive agricultural market in equilibrium by maximizing the total social welfare subject to resource constraints. The model simulated the maximum social welfare constrained by scarce resources, such as land, water, labor, capital and others. ASM simulates the optimal land allocation among crops, livestock and forests plus results on crop and livestock mix, total production, processing activity, bioenergy production, exports, domestic consumption and commodity prices. **Figure 1** illustrates the geographic scope of the FASOM model where ASM has all components portrayed but the forestry related ones. Note ASM does not in this form treat uncertainty in the crop yield projections under a given GCM/mitigation scenario. Also, it does not simulate CO_2 effects, rather that is manifest in the crop simulation results as discussed in Beach et al. (2015). Use of ASM allows us to examine impacts of the alternative climate projections on the US agricultural sector and related markets. ASM has been widely used in climate change related studies as discussed in Beach et al. (2010). For example previous studies have looked at the impact of climate change on crop yields, livestock productivity, transportation, land conversion and greenhouse gas net emission reductions (Adams et al., 1990, 1995; Reilly et al., 2001, 2002; Murray et al., 2005; Attavanich et al., 2013).

ASM encompasses the entire US with production broken up into 63 smaller production regions (subregions) and 11 market regions. The trade of commodities can occur between US regions, or into the international market the representation of which contains supply and demand curves for 27 countries or foreign regions (Adams et al., 1996, 2005; Beach et al., 2010). Additionally, ASM simulates production of 30 crops. To capture the effect of climate change on the crops not simulated with EPIC, we used expert opinion to assign the yield sensitivities of the simulated crops to the other crops that were not simulated. For example, silage is proxied by corn. Also, we assumed all five types of wheat face the same regional yield changes although geographic incidence varied by type.

Predicting future population, technology, economic and market conditions for the next 100 years based on current economic and social structure information is difficult at best. Also, variations in projected future conditions may enlarge or offset the effects of climate change. Therefore, following many other similar studies, ASM was run as a static model for each climate scenario with the scenario climate change effects applied to current year (2015) economic and market conditions.

We also simulated the effects of adaptation strategies including: increasing irrigation or managing water allocation in response to drier environments (Howden et al., 2007), changing crop mixes (Adams et al., 1999; Barros et al., 2014), shifting crop production and varieties to higher latitudes or elevations (Reilly et al., 2002; Cho and McCarl, 2017), shifting land between cropping and grasslands to support livestock (Mu et al., 2013), changing livestock species (Seo et al., 2010) and reducing livestock stocking rates (Mu et al., 2013). In ASM, all available adaption strategies are allowed but are constrained by resources and cropping pattern. For example, irrigation and water management is limited by water availability. Crop mixes are constrained to be a convex combination of regional historical

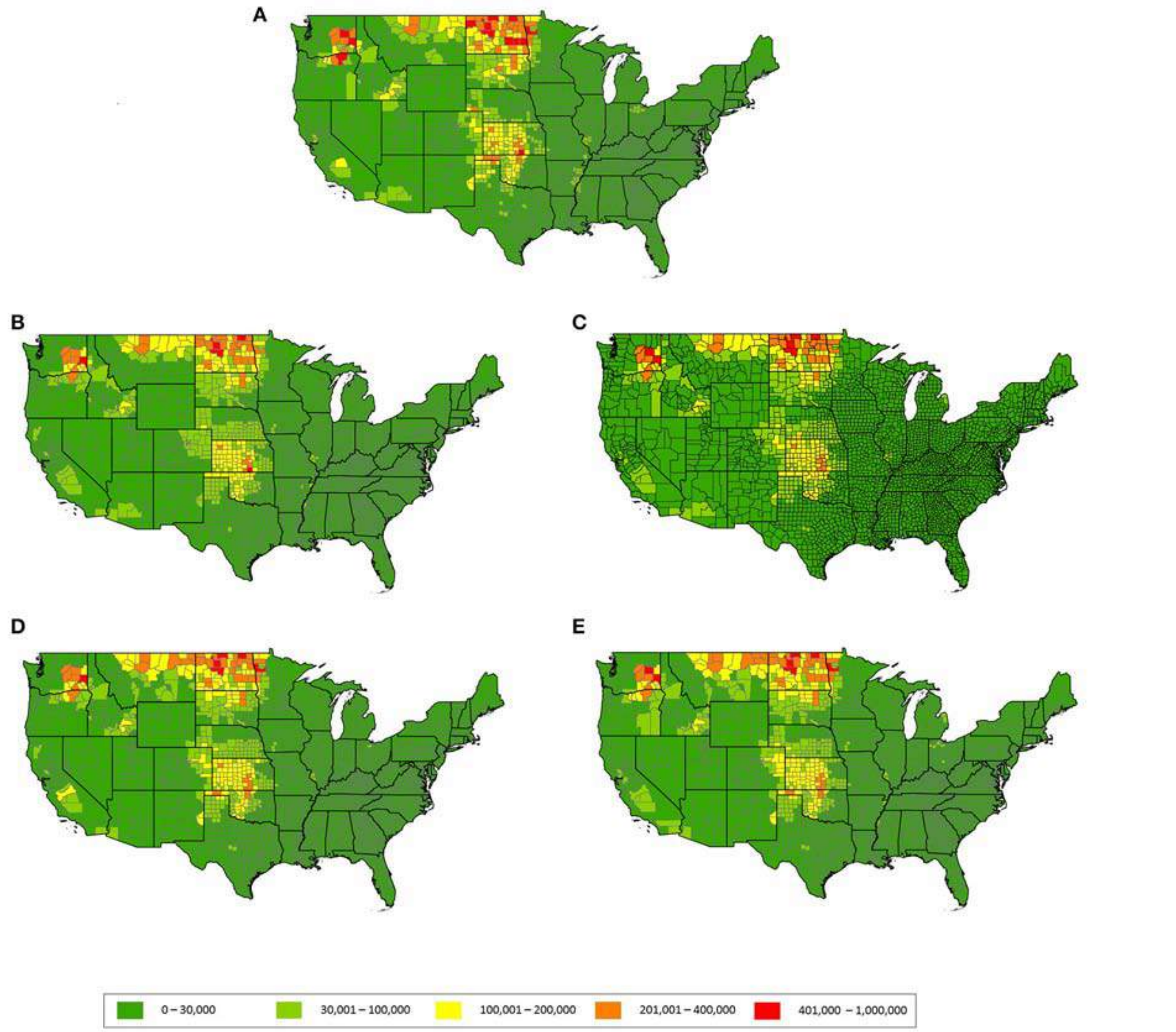

FIGURE 2 | Wheat harvest acres per county under **(A)** No climate change scenario, **(B)** IGSM policy scenario, **(C)** IGSM reference scenario, **(D)** MIROC policy scenario, and **(E)** MIROC reference scenario. Wheat harvested acres are the sum of acreage for hard red winter wheat, hard red spring wheat, soft red winter wheat, white wheat and durum wheat.

crop mix ratios blended with crop mixes for regions 200 miles south following Adams et al. (1999). For subregions on the southern border of the US (southern California, Arizona, New Mexico, the Gulf coast, southern Texas, and Florida), we allow the share of heat-tolerant crops currently produced in hot regions (such as oranges and grapefruit) to double. Adaptation behaviors are selected by maximizing total social welfare in ASM, and cannot be fully isolated. So in this study, the model chooses the optimal set of adaptation strategies and we only report overall effects of the scenarios plus narrow in on crop mix and land use adaptation.

ASM output yields national, subregional and foreign welfare estimates, prices, production and land use. For simplicity, Fisher price and production index numbers were used to capture the multi commodity price and production changes in the nation and the PNW states. We also downscaled the results to the county level for graphic displays utilizing the approach developed in Attwood et al. (2000) and Pattanayak et al. (2005).

RESULTS

Land Reallocation

Compared to the no climate change scenario, total cropland acreage in the United States shrank under the IGSM climate projections and increased under the MIROC climate projections. Total cropland used in the US is lower under aggressive mitigation and higher without it. Results showed land moving into pasture or idled under IGSM scenarios principally because of the relatively high yield increase rate and consequent low commodity prices. The higher cropped acreage under the

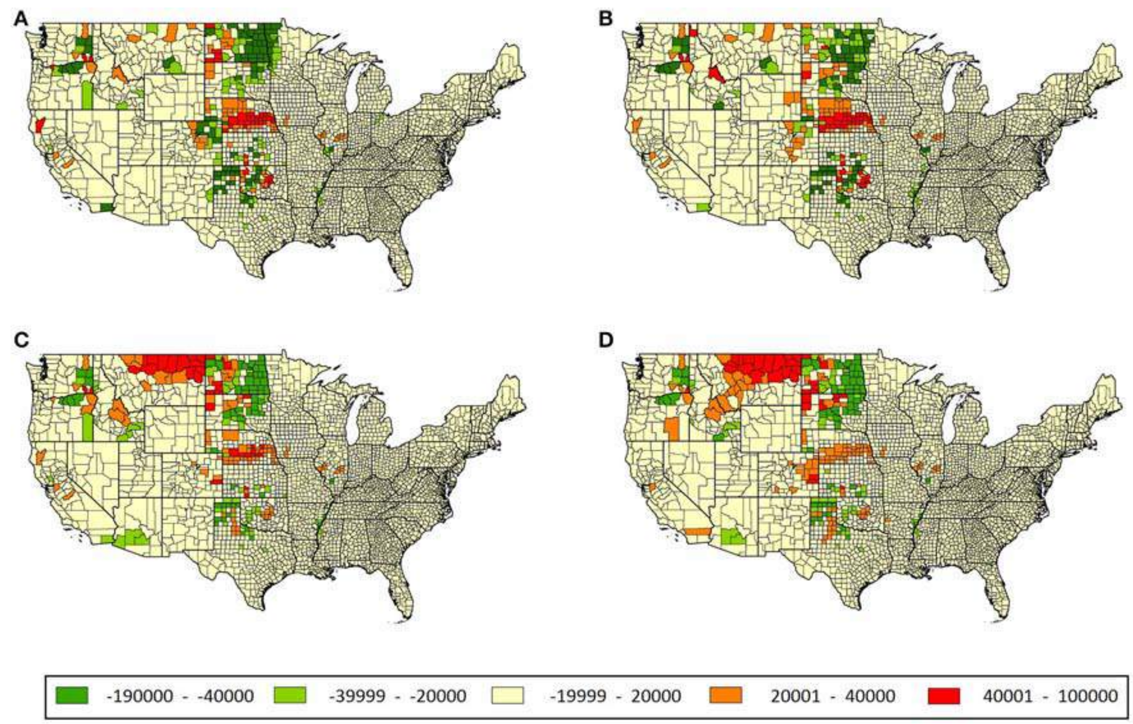

FIGURE 3 | The difference in wheat harvested acres by US county relative to the no climate change scenario under the **(A)** IGSM policy scenario, **(B)** IGSM Reference Scenario, **(C)** MIROC policy scenario, and **(D)** MIROC reference scenario. Wheat acres are the sum of acres in hard red winter wheat, hard red spring wheat, soft red winter wheat, white wheat and durum wheat.

MIROC scenarios is explained by the lower crop yields under that scenario. In the PNW, total wheat acreage declined under all the climate change and mitigation scenarios. Similarly, national wheat acreage declined under all climate/mitigation scenarios except for MIROC-Ref (no mitigation) (**Table 3**). Declining wheat acreage occurred again because of the increasing yields and resultant lower prices.

Total cropped land was smallest under the more optimistic IGSM climate projections with aggressive mitigation. This occurs because increased production causes decreased prices and net returns causing land to move out of cropping into pasture. Nationally, corn, soybeans, wheat, hay and cotton dominate land use (**Table 4**). The percentage of harvested acreage by crop was relatively stable across the climate and mitigation projections. Soybean acreage increased under all climate change scenarios. Since soybeans and corn partially compete for acreage, the land share of corn decreased. The price for soybeans was higher than its historical level, but the price of corn dropped, which in turn led to the shift between two crops. Wheat occupied slightly more land (as a percent of total acreage) under the IGSM scenarios, but its acreage share decreased under the MIROC scenarios. The land share of hay and cotton decreased under most scenarios, except for hay under MIROC-Ref.

Land use shares changed more in the PNW than occurred they did nationally. Wheat, hay, barley, potatoes and corn were the most important regional crops and occupied over 94% of the cropland (**Table 5**). Compared to a no climate change case, wheat and barley lost PNW land share under most scenarios, except for wheat under IGSM-Pol. Conversely, the land share occupied by hay and corn increased under all the scenarios. Regionally the crop shares were relatively stable under the IGSM scenarios, while the PNW land reallocations under the MIROC scenarios were slightly larger than the national ones, but still stable compared to the no climate change scenario.

Generally, the results showed adjustments in total area in crops with northward movements, especially at the national level. This is because while adaptation allows crop mix to change, the effects of market demand and natural resource endowments mediate the effects.

Wheat Acreage and Production

As shown in **Figures 2**, **3**, wheat harvested acreage exhibited some shifts within regions.

Under the IGSM-Pol scenario, there were a number of counties where wheat declined due to the substantial yield increases and resultant low market prices. In particular, the Beach et al. (2015) EPIC estimates show an increase in the national average wheat yield of 18% under dryland conditions. Yield changes for wheat and other crops coupled with relatively inelastic demand, led to a decline in prices and in turn in national and PNW wheat acreage as well as that of other crops. In the major production regions for hard red winter wheat (Southern Great Plain), a northward shift in harvested acreage from Texas and Colorado to Nebraska occurred. This is an adaptation

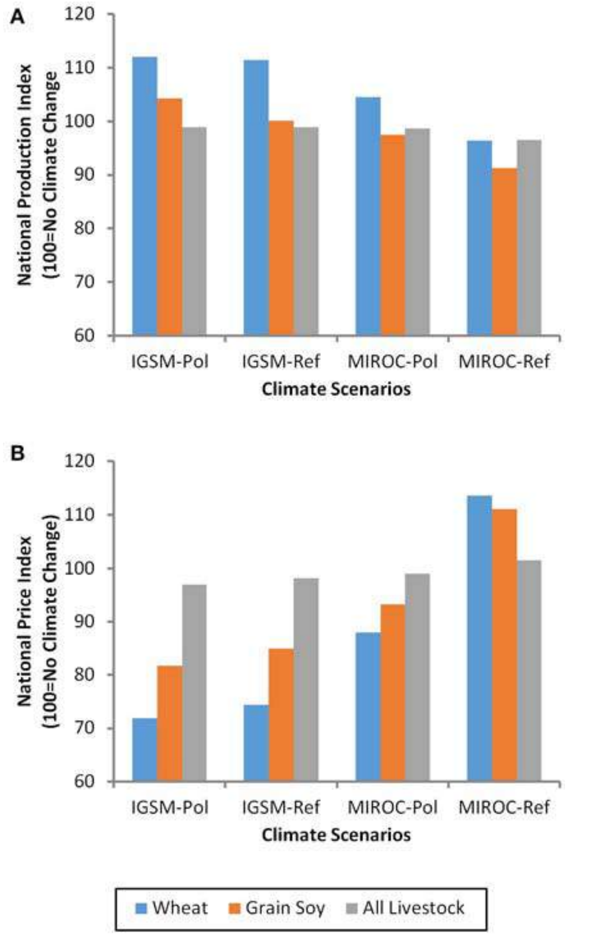

FIGURE 4 | Index numbers for US national agricultural production and prices across four GCM and mitigation extent cases. **(A)** Production indices for volume of US wheat harvested, cereal and soybean crops harvested, and livestock, **(B)** Price indices for US wheat harvested, cereal and soybean crops harvested, and livestock. Each panel shows production and price indices for the climate projections and mitigation extent scenarios IGSM Policy (IGSM-Pol), IGSM Reference (IGSM-Ref), MIROC-Policy (MIROC-Pol), and MIROC-Reference (MIROC-Ref). Index values are relative to a baseline with no climate change impacts.

response to move the wheat production to lower temperature regions. Also in the Northern Great Plains, hard red soft wheat shifted from east to west in South and North Dakota and marginally into Montana to take advantage of lower temperatures at higher elevations. Similarly, in the Mississippi River basin in Missouri and Arkansas wheat land shifted northward. In the PNW, the wheat production area moved eastward again to higher and cooler elevations.

Under the IGSM-Ref scenario, wheat acreage showed similar regional pattern shifts to those under the IGSM-Pol scenario but with smaller declines in harvested acreage. Hard red winter wheat in the Southern Great Plains moved northward to Nebraska and into higher elevation areas in Colorado and Wyoming. In North Dakota, wheat areas shifted from east to west and marginally into Montana with a decrease of total wheat harvested acres. Also, more than 1.5 million North Dakota acres switched from hard red spring wheat to hard red winter wheat and durum wheat as an adaptation to the higher temperatures. A northward shift in wheat acreage also occurred in the Mississippi River basin. In the PNW, we found more wheat was grown in the higher elevation regions in Idaho. Spring barley acreage in the PNW was generally stable across the climate projections. Coupled with the higher rate of yield increases than national average, the PNW gained in market share of barley under the climate change projections relative to the no climate change case.

The acreage and geographic distribution of wheat under the MIROC projections differed mainly due to smaller estimated yield changes. Under the MIROC-Pol scenario, national wheat acreage was the same as if no climate change occurred. The largest shift was observed from the east to the west in the Dakotas. Declines in hard red spring wheat production in North Dakota were offset by increases in hard red winter wheat in Montana. Also a shift in hard red winter wheat from the Texas High Plains to Nebraska was observed. Cooler temperatures in Nebraska and increased soil moisture made dryland production more viable. In the PNW, the wheat and barley acreage fell and shifted from irrigated to dryland production. Under this scenario, irrigated hay replaced irrigated wheat, because irrigated hay yields increased and the crops compete for land and water.

Nationally, the MIROC-Ref scenario showed harvested wheat acreage increased due to dramatic increases in cultivation in Montana which was driven by lower overall yields and a higher wheat price. In the dry MIROC-Ref scenario, we find: (a) Texas wheat moving northward, (b) more wheat grown in Nebraska, and (c) some of the PNW production shifting out of Washington and Oregon into Idaho. In general, the wheat cultivation areas shifted northward in the southern regions of the Great Plains and to higher elevation areas in the northern Great Plains. Moreover, the substitution out of spring wheat to winter wheat is another adaptation strategy to the higher temperatures under climate change.

Effects on Agricultural Production and Prices

Index numbers were used to summarize production and price changes (**Figures 4**, **5**). They were computed for several classes of products. The cereal and soybean crop indices incorporate results for corn, soybeans, durum wheat, hard red spring wheat, hard red winter wheat, soft red winter wheat, soft white wheat, sorghum, rice, oats, spring barley, and winter barley define others briefly. The indices show smaller levels of PNW wheat production under all climate scenarios along with lower levels for PNW cereal and soybean production under all climate scenarios but MIROC-Ref scenario with the PNW exhibiting greater adjustments relative to the national results (**Figures 4**, **5**). PNW livestock production increased under the IGSM climate projections and were smaller under the MIROC projections. The IGSM projections stimulated more national wheat production than occurred under the MIROC projections. Conversely, wheat production in the PNW was lower under IGSM than MIROC as their US market share (**Table 6**). Under all climate scenarios

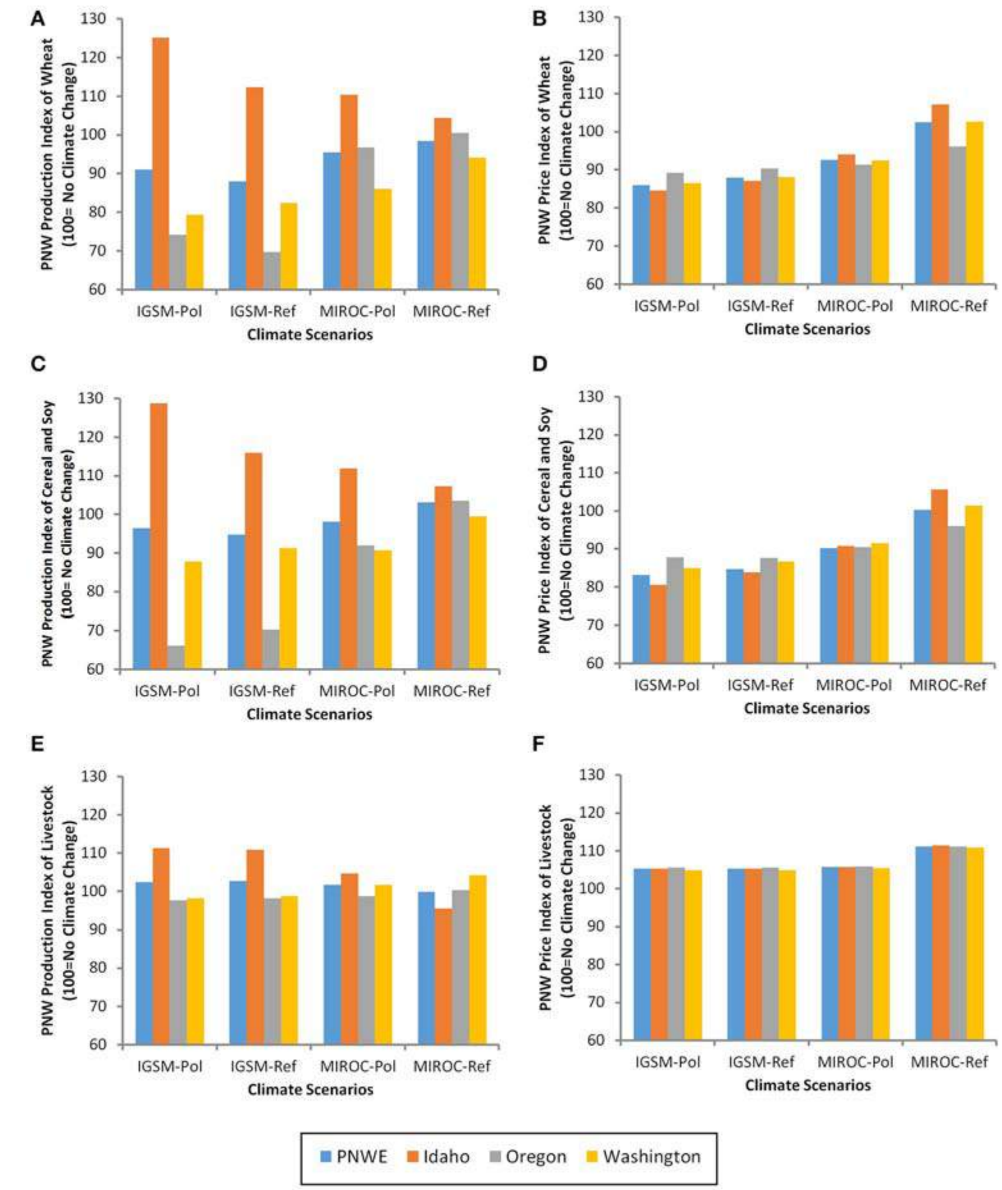

FIGURE 5 | Indices numbers for PNW agricultural production and prices across four GCM and mitigation extent cases. **(A)** Production indices for wheat, **(B)** Price indices for wheat, **(C)** Production indices for cereal and soybean crops, **(D)** Price indices for cereal and soybean crops, **(E)** Production indices for livestock, and **(F)** Price indices for livestock. Each panel shows the change in (or a comparison of) index numbers relative to the no climate change base vs. results under the climate/mitigation scenarios (IGSM Policy (IGSM-Pol), IGSM Reference (IGSM-Ref), MIROC-Policy (MIROC-Pol), and MIROC-Reference (MIROC-Ref) under the three PNW states (Idaho, Oregon, Washington) and the index for the region.

PNW wheat production is lower as it is in Washington and Oregon, but it is higher in cooler Idaho. This is consistent with the wheat in PNW shifting toward Idaho. Production in Idaho increases more under IGSM than under MIROC. It also increases under aggressive mitigation (policy scenario).

Similar results were found for cereal and soybean production. The national combined cereal and soybean production indices were highest under the IGSM-Pol scenario with lower results when mitigation is not pursued (IGSM-Ref). National production indices were even lower under the MIROC climate projection. The smallest level of national production was projected in the MIROC-Ref scenario where production declined the most. This is in response to the EPIC projections of national yields increasing under IGSM and decreasing under MIROC-Ref. As a consequence of the increased barley production and small wheat reductions in the PNW, aggregate cereal production achieved its highest values under MIROC-Ref. In the other three scenarios, the PNW showed less production than under

TABLE 6 | PNW market share as percentage of production (2010-2100).

Scenarios	Wheat (%)	Barley (%)	Hay (%)	Potatoes (%)	Corn (%)
No climate change	13.30	24.53	11.07	58.91	0.46
IGSM-Pol	10.58	29.65	19.15	63.91	0.53
IGSM-Ref	10.13	30.19	18.23	62.59	0.54
MIROC-Pol	11.91	24.50	22.37	63.63	0.61
MIROC-Ref	13.79	30.49	23.84	68.61	0.64

no climate change. Within the PNW, average cereal and soybean production indices under all climate scenarios were lower for Oregon and Washington than for Idaho which projects an increase in production compared to the no climate change case.

Generally, the change in wheat, cereal and soybean production levels in PNW is opposite of the changes found nationally. In the MIROC-Ref scenario, the PNW produced more than under the no climate change case, but the US total national production was lower. In the IGSM scenarios, national production increased, but PNW production decreased. This is consistent with the scenario dependent projected yields. Coupled with inelastic demand, drier and hotter conditions in eastern part of US projected by MIROC shifted production to the cooler west. Conversely, in the wetter IGSM scenarios, the east gains competitive advantage and, in turn, increases production.

The livestock production indices at the national and PNW level did not show large differences compared to the no climate change scenario, perhaps because we did not model climate change induced shifts in production. The livestock production index nationally and in the PNW showed a range of about 4%, caused by the feed cost and land use variation.

Price indices were also computed with the results shown for wheat, cereal and soybeans and all livestock in **Figures 4**, **5**. Free trade across regions and the law of one price force PNW prices to follow nationwide trends. Wheat and cereal prices were higher under the drier MIROC climate projections compared to the IGSM projections and comparatively lower when aggressive mitigation policies were pursued.

Nationally, wheat prices fell more than did the cereal and soybean price index for all climate projections relative excepting under MIROC-Ref. But in the PNW, the relative wheat price change is less than that for the cereal and soybean price index.

Similar to the production results, livestock prices at the national and regional level showed little change. Prices were 5% higher than under the no climate change case for the PNW across all climate projections. Nationally, prices were lower under the IGSM climate projections compared to results under the MIROC climate projections although total range across all four climate scenarios was small being approximately 5%.

Producer and Consumers' Welfare

Welfare change estimates for consumers', producers', international trade, and global society are shown in **Figure 6**. Consumers' welfare generally decreased with the smallest change occurring under the IGSM-Pol and the largest under MIROC-Ref. This is consistent with the changes of price and production index of final product production (**Figure 7**). Higher levels of consumers' welfare occurs when aggressive mitigation

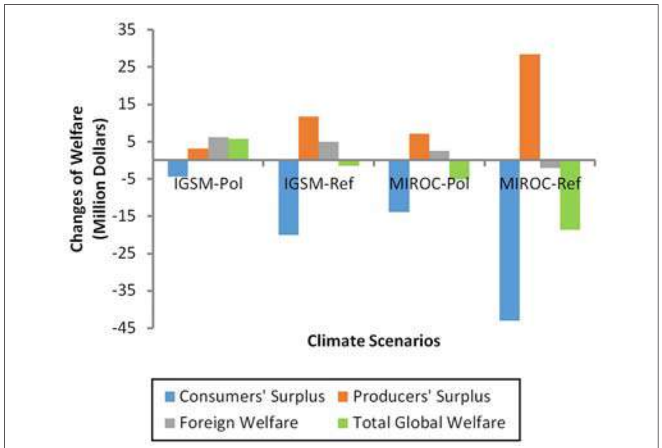

FIGURE 6 | Changes in consumers', producers', foreign and total social welfare relative to no climate change under four climate projections from GCM/ mitigation extent cases (IGSM-Pol, IGSM Policy; IGSM-Ref, IGSM Reference; MIROC-Pol, MIROC-Policy; and MIROC-Ref, MIROC-Reference).

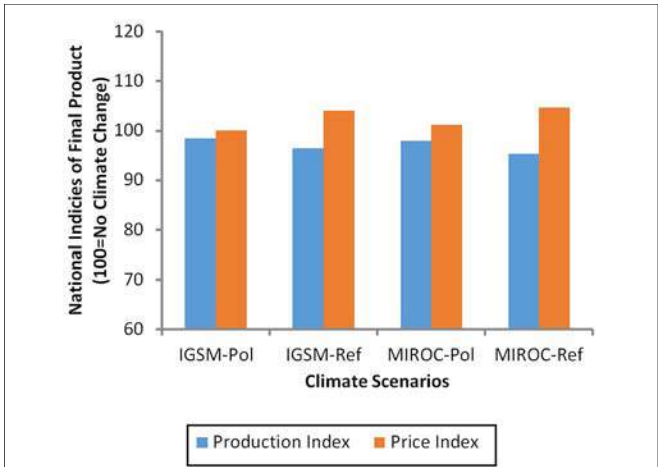

FIGURE 7 | Index numbers for US national agricultural final products production and prices across four GCM and mitigation extent cases (IGSM-Pol, IGSM Policy; IGSM-Ref, IGSM Reference; MIROC-Pol, MIROC-Policy; and MIROC-Ref, MIROC-Reference).

is pursued and lower when mitigation is minimal. Such a result was not unexpected as those scenarios had relatively higher production and lower prices at the national level which benefited consumers.

The results for producers' welfare or net income (measured as producers' surplus) are the opposite of the consumers' results. Average producers' welfare is larger the less is produced so with the more severe MIROC cases and under less aggressive mitigation. We also found that foreign welfare changes due to international trade, are greatest under the less severe IGSM climate projections compared to the more severe MIROC climate projections.

Across these results we found consumers' surplus loss was larger than the producers' surplus gain leading to lower total societal welfare for all climate projections except for IGSM-Pol. Smaller losses were shown under aggressive mitigation (policy scenario) compared to the reference scenario. Further, there was also income redistribution as seen by the opposite signs of producers' and consumers' welfare in each climate scenario.

DISCUSSION

In this study, we found that overall crop mix shares did not change much but total acres harvested did. Acres in wheat production shifted north and west to cooler conditions in the Great Plains and east out of Oregon and Washington to higher altitudes and cooler temperatures in Idaho as also projected in the econometric based analysis of Cho and McCarl (2017). More winter wheat is planted along the northern border of the US, instead of spring wheat as an adaptation to higher temperatures under climate change. Overall this study showed, the PNW showed declining production of wheat in the PNW, mainly in Washington and Oregon but with increasing production in Idaho. Under all but the MIROC-Ref climate projection, the PNW lost wheat market share. Our results show increases in market share for the PNW for barley, hay, and potatoes.

Wheat production and prices were found to be sensitive to the climate projection and the extent of mitigation which illustrated that climate change severity and adaptations greatly impact vulnerability. Predicted wheat yield changes generally lead to national wheat production increases in all scenarios but the MIROC-Ref case. Similarly, national cereal and soybean production was higher under the wetter IGSM projection compared to the drier MIROC projection. Consequently, national wheat, and combined cereal and soybean crop prices were lower in the IGSM climate projection than under the MIROC climate projections.

This study showed total social welfare is projected to be higher under the wetter IGSM climate projection relative to the drier MIROC climate projection. Total social welfare is relatively higher if aggressive mitigation is pursued compared to less aggressive action. Nationally, an inverse relationship was found both between price and production, and between consumers' and producers' welfare when comparing the results of the four climate/mitigation projections. This was present across the results with the relationship generally being production reductions relatively benefited producers and disadvantaged consumers with the converse happening when production increased. Similarly, the relatively lower production changes under no mitigation benefitted producers and disadvantaged consumers relative to aggressive mitigation. This reflects the importance of considering demand curves and price adjustments rather than solely looking at yield and total production impacts.

These findings are potentially contradictory to Lobell and Field (2007) which asserted declining global wheat production, although they had a caveat about the United States. Here, the findings suggest increasing US wheat production under all climate situations except for the MIROC climate projection coupled with limited mitigation effort.

LIMITATIONS AND FUTURE STUDY

As in all other studies, this research has limitations and areas where it could be extended. First, as discussed above, the future economic and market structure is hard to predict so we imposed the projected climate change on the current, 2015, economy. This allows for an analysis of just the climate change effects. However, this arguably could influence the results as the economic and market conditions will change in the next 100 years. An alternative base year could be used in future work.

Second, ASM fails to account for all the transactions cost that would occur with switching land use, such as building altered commodity movement and processing infrastructure, or carrying out education programs to teach farmers new production techniques. Estimates could be gathered for these transaction costs and built into the model.

Third, the analysis did not account for climate change induced alterations in the supply and demand conditions within the rest of world and only focused on changes in the United States. Incorporation of information on global market effects would be a significant addition.

Fourth, the underlying EPIC data on climate projection effect on yields were only available for 9 crops in the United States and only for the climate model and mitigation cases used herein. EPIC also assumed unconstrained water use for irrigated crops. Although ASM took water reductions into account, further work could be done to improve these projections. Adding simulations for more minor crops and climate/mitigation cases across an ensemble of climate models would be a useful extension.

Despite the above limitations, we believe this study clearly demonstrates that climate change will impact wheat production in the United States nationally plus have different impacts across regions. This study suggested that PNW wheat distribution and total acreage is likely to change with shifts in comparative advantage. Finally, climate change is projected to cause an income distribution alteration between producers and consumers with total societal welfare higher if aggressive mitigation is pursued.

AUTHOR CONTRIBUTIONS

AT and CF led the analysis and constructed the initial paper draft. BM conceptualized the scenarios to be used and guided the others thorough ASM use plus did editing on the paper draft.

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Design and Use of Representative Agricultural Pathways for Integrated Assessment of Climate Change in U.S. Pacific Northwest Cereal-Based Systems

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This paper presents the design and use of Representative Agricultural Pathways (RAPs) in regional integrated assessment of climate impacts. In the first part of the paper, we describe the role of pathways and scenarios in regional integrated assessment as well as the three RAPs developed for a study of dryland wheat-based systems in the U.S. Pacific Northwest. We use this example to illustrate the challenges associated with the development and implementation of RAPs, including the engagement of research team and stakeholders, the dimensionality problem in integrated assessment, incorporation of economic data, and quantification of uncertainties. In the second part, we illustrate the use of RAPs in the study of climate impacts on dryland wheat-based systems. Results show that the direct impacts of future climate projections through crop yields provide the largest source of uncertainty in the climate impact and vulnerability analysis, but the indirect impacts of climate change through price projections embedded in RAPs also play an important role in the analysis. We conclude that in addition to being an essential element in designing an integrated assessment at the regional level, the RAPs development process can facilitate stakeholder engagement and improve communication of climate impact assessments.

Keywords: representative agricultural pathways, regional integrated assessment, climate change, wheat production, U.S. Pacific Northwest

Abbreviations: AgMIP, Agricultural Model Inter-comparison and Improvement Project; GCM, Global Climate Model; RAP, Representative Agricultural Pathway; RCP, Representative Concentration Pathway; SSP, Shared Socio-economic Pathway; REACCH, Regional Approaches to Climate Change – Pacific Northwest Agriculture; RIA, Regional Integrated Assessment; TOA-MD, Tradeoff Analysis Model for Multi-dimensional Impact Assessment; WWA, Annual Rotation of Winter Wheat and Spring Wheat with Summer Crops; WWF, Winter Wheat-fallow System; WWT, Transitional Wheat System.

INTRODUCTION

Future scenarios play a key role in climate impact assessments based on computer simulation. In the current research methods widely in use, these scenarios (defined as a complete characterization of the model inputs and outputs to represent a future state of the world) are constructed using "pathways" that provide narrative descriptions and quantification of variables for the disciplinary components of an integrated assessment. At the global scale, Representative Concentration Pathways (RCPs; Van Vuuren et al., 2011) and Shared Socio-economic Pathways (SSPs; O'Neill et al., 2014) are now being used to construct scenarios for simulation studies.[1] In addition to its use for global integrated assessment modeling, an aim of the SSP framework is to provide the basis for more detailed sector and regional (national or sub-national) analysis. The Agricultural Model Inter-comparison and Improvement Project (AgMIP) developed the concept of Representative Agricultural Pathways (RAPs) to provide the additional agricultural detail needed to implement global and regional agricultural assessments (Rosenzweig et al., 2013; Rosenzweig and Hillel, 2015; Antle et al., 2017a). RAPs are projections of plausible future biophysical and socioeconomic conditions used to carry out climate impact assessments for agriculture (Claessens et al., 2012; Valdivia et al., 2015).

A coordinated agricultural project funded by the United States Department of Agriculture, named Regional Approaches to Climate Change—Pacific Northwest Agriculture (REACCH), was initiated in 2011 to investigate climate change impacts, adaptation, and mitigation in a contiguous region including northern Idaho, central Washington, and northern Oregon (see REACCHpna.org). The goal of the modeling team in the REACCH project was to assess climate impacts, adaptation, mitigation, and vulnerability of dryland wheat systems for the mid-twenty first century in the U.S. Pacific Northwest region. The REACCH project adopted the AgMIP methods for regional integrated assessment, including the development of RAPs (**Figure 1**) (Antle et al., 2015). The REACCH project utilized results from global modeling studies represented in the upper part of **Figure 1** to generate projections of future prices and crop productivity to be used as inputs into the regional analysis, represented in the lower part of **Figure 1**.

To implement the regional assessments, REACCH researchers carried out climate downscaling, crop model simulations, and economic modeling. Climate data included 14 global climate models (GCMs)[2] of the Coupled Model Inter-Comparison Project 5 that were evaluated for simulating credible climate characteristics across the region (Rupp et al., 2013) for two RCPs, RCP 4.5 and 8.5. The Multivariate Adaptive Constructed Analogs statistical downscaling approach was used to translate climate model outputs from their native coarse resolution to finer spatial resolution required for impact modeling (Abatzoglou and Brown, 2012)[3]. These data were combined with soil, crop, and management data to implement the cropping systems simulation model (CropSyst) developed at Washington State University. CropSyst was used to simulate crop yields for the principal cropping systems in the region (described further below), under projected climate conditions (Stöckle et al., 2003, 2017). Outputs from CropSyst were combined with data from the U.S. Census of Agriculture in the region, and used to parameterize an economic impact assessment model (Tradeoff Analysis Model for Multi-dimensional Impact Assessment, TOA-MD) (Antle et al., 2014). In particular, crop yields were simulated at each grid cell with a 4-km spatial resolution, and linked to individual farms through zip-code. This economic model was used to simulate economic impact, adaptation, and vulnerability of farm households to climate change under current and possible future conditions defined by climate and socio-economic scenarios.[4]

In implementing RAPs, the REACCH team addressed several key elements in developing and using RAPs: the process used to create RAPs, including the engagement of the research team and stakeholders; how to deal with the "dimensionality" problem (i.e., the large number of possible scenarios) that occurs in experimental designs with multi-disciplinary and multi-scale analysis; how to incorporate available economic data, including price and productivity projections from global models and regional projections of production costs, into regional scenarios; and how to quantify model and scenario uncertainties and incorporate them in the analysis and communication of results.

This article discusses how the REACCH team addressed these elements of pathway design and use, and illustrates them with climate impact and vulnerability analysis carried out in the REACCH project for wheat-based agricultural systems in the U.S. Pacific Northwest. To illustrate the development and use of RAPs we focus on climate impact and vulnerability, but note that RAPs are equally relevant to adaptation and mitigation analysis. In the next section, we discuss how the RAPs methodology described in Valdivia et al. (2015) was implemented and elaborated to address various methodological challenges in RAPs design and implementation. We then describe the RAPs developed for

[1]The Representative Concentration Pathways (RCPs) describe four possible climate futures using radiative forcing values in the year 2100 relative to pre-industrial values, depending on how much greenhouse gases are emitted in the future. These values are used to initiate climate model simulations. The Shared Socioeconomic Pathways (SSPs) describe five possible socio-economic futures using a set of variables describing socio-economic conditions, including demographic and economic trends. The RCPs and SSPs are used together in integrated assessments of future climate impact, vulnerability, adaptation, and mitigation.

[2]The names of these 14 global climate models are bcc-csm1-1, BNU-ESM, CanESM2, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2G, GFDL-ESM2M, inmcm4, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MRI-CGCM3, HadGEM2-CC, HadGEM2-ES.

[3]The Multivariate Adaptive Constructed Analogs (MACA) method is a statistical downscaling approach that translates the coarse resolution of daily output from global climate models into local weather data at the time and spatial scale needed for regional impact assessment. The MACA method is advantageous due to the use of constructed analogs to avoid interpolation from reanalysis and the use of multivariate approach that improves the physical relationships between weather variables (see the detailed discussion in Abatzoglou and Brown, 2012). The MACA method, as a statistical downscaling approach, requires a long-term high-quality data that include a representative sample of observations.

[4]A variety of farm-level characteristics can be taken into account in households to simulate the economic and social consequences of climate change and adaptation, but typically key factors, including farm size, agricultural production costs and revenues, non-farm income, and household size, are used to characterize farm households.

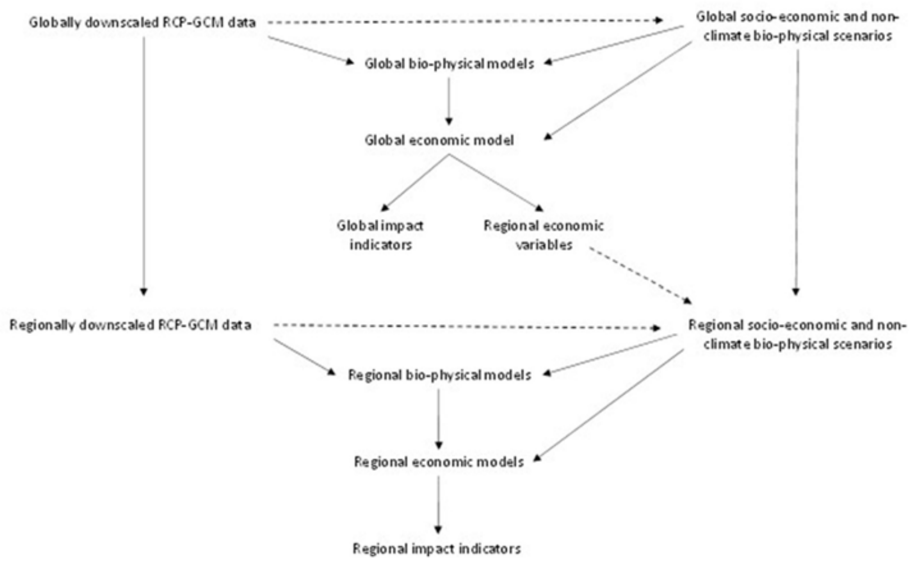

FIGURE 1 | Global and regional integrated assessment framework as implemented by the Agricultural Model Inter-comparison and Improvement Project (AgMIP). Solid arrows show linkages consistent with global pathways design in which global socio-economic scenarios are independent of global emission concentration pathways (RCPs). Dashed arrows indicate possible linkages from RCPs to global and regional socio-economic scenarios.

the REACCH project, and present results illustrating their use, including in an uncertainty analysis. In the concluding section, we reflect on implications of the analysis for further development and implementation of regional integrated assessment methods, including AgMIP's efforts to develop coordinated global and regional integrated assessments.

MATERIALS AND METHODS

Design and Development of RAPs

The RAPs Design Process in the REACCH Project

Following the logical structure of RCPs and SSPs for global assessments, RAPs are intended to provide a logically consistent set of bio-physical and socio-economic drivers to be used with the climate data generated by downscaling outputs from global climate models to the regional level (Valdivia et al., 2015). When the global models used to generate data of bio-physical and socio-economic drivers as inputs to regional analysis are implemented with the RCP and SSP framework, the RAPs are logically linked to these pathways, as illustrated in **Figure 1**. To implement RAPs, scientists and other experts with knowledge of agricultural systems, including extension specialists and experts from the agricultural industry, work together through a step-wise process to develop narratives describing plausible future world conditions and to then construct quantitative values for model parameters. An Excel spreadsheet tool called DevRAP is used to develop and document the RAPs (Valdivia et al., 2015). The DevRAP tool includes information related to global as well as regional pathways and scenarios being developed, the time horizon of the analysis, the title, and narrative description of the pathway, and a matrix to document the assumed direction and magnitude of changes in variables and the rationale for those changes. Elements of RAPs can include any factor considered relevant by the research team and stakeholders, but typically include bio-physical, institutional, policy, socio-economic, and technological factors.

The first part of the process is to define the basic elements of the analysis, including the time horizon, the number of RAPs, and linkages to global pathways and scenarios. Following the AgMIP regional integrated assessment method, the REACCH project selected a set of global socio-economic pathways that were used by global modeling teams, and linked their regional RAPs and economic data to these global pathways. The REACCH project utilized prices and crop productivity trends from global models, together with regional projections of production costs (discussed below) as inputs for the regional economic analysis. In the study below we chose the time horizon of medium future, i.e., 2050, because prices and crop productivity trends from global models are only available in 2050. More importantly, stakeholders, especially farmers, show great interests in the next 30 years, rather than distant future.

The second part of the process involves the identification of the specific variables to be included in the RAPs, and a process for quantification of their changes over the time horizon of the analysis. AgMIP devised a series of steps for this purpose involving members of the research team, and possibly other experts and stakeholders who have expertise relevant to the variables included in the RAPs. Within the REACCH project, a team of researchers was identified with expertise in the relevant disciplines required for a comprehensive RAP assessment. The team first met for an all-day workshop to learn about the RAPs concepts and process, and started with a "Business as Usual" RAP and a short narrative description consistent with the global pathways that had been identified. The team members identified key parameters and drafted short narratives for them. Team members were assigned variables for further research and quantification using a template for documentation. At a second meeting, team members reported findings and discussed storylines for each variable and reached consensus on quantification, including direction, relative magnitude, and the percent change, a short narrative explaining the rationale for the change, references to literature used, and an assessment of confidence in the quantitative values. The team also reviewed variables for internal consistency. Next, additional RAPs were identified, and the development process was repeated. The RAPs were presented to the entire research project team and stakeholders at project meetings and through reports. The RAPs were revised based on feedback from these meetings and reports.

REACCH RAP Narratives

The REACCH RAPs development team evaluated the number of RAPs that would be feasible to use in the modeling studies and concluded that three would be adequate to capture the range of plausible conditions relevant to the wheat systems in the Pacific Northwest region. In addition to the Business as Usual case, the team identified a relatively optimistic Sustainable Development pathway and a more pessimistic Dysfunctional World pathway.

RAP 1: Sustainable development

This RAP is linked to SSP1 (Sustainable Development). Under this pathway, rural development continues with moderate increases in population in regional centers, with larger and more diversified regional economies having a positive impact on community and social well-being. Traditional commodity subsidies are replaced by a carbon tax and an expansion of conservation and environmental programs, which slow the consolidation of land into larger farms and support some expansion of mid- and small-scale farms. Recent trends in mechanical, chemical, and biological technology continue, but in response to the carbon tax, there is more innovation in technology that helps reduce fossil fuel intensity. Global commodity prices rise moderately along with the increases in fossil fuel prices due to the carbon tax.

RAP 2: Business as usual

This RAP is linked to SSP2 (Middle of the Road) and SSP5 (Conventional Development). Under this pathway, rural development continues with moderate increases in population in regional centers, larger, and more diversified regional economies, and trends toward mechanical, chemical, and biological technology continue. Trends toward environmental regulation to protect air and water quality continue, but fiscal pressures lead to real reductions in traditional commodity subsidies and other agriculture-specific conservation programs making conservation more individualized. Agricultural prices increase in real terms due to continued growth in demand, especially for feed grains and for politically mandated production of biofuels. Some rural farm-based communities continue to sustain infrastructure and social cohesion, while others continue to experience net out-migration.

RAP 3: Dysfunctional world

This RAP is linked to SSP3 (Fragmented World) and SSP4 (Inequality World). Under this pathway, an unbalanced rural development occurs, with the continued loss of "agriculture in the middle" and consolidation of most commodity production into large corporate entities with contract arrangements for farm management and related impacts on rural farm-based communities. Suburban development continues largely unregulated in peri-urban areas and rural areas. Traditional farm subsidy programs are largely eliminated, and conservation and environmental programs are limited due to budget constraints. Advances in large-scale mechanical, chemical, and biological technology continue, but disruptions to global agricultural research and development and agricultural trade result in substantially higher and volatile agricultural commodity prices.

Our pathway narrative descriptions are consistent with global RAPs. In both RAP 1 (sustainable development) and RAP 2 (business as usual), trends toward environmental regulation continue, with a major difference in carbon tax.

RAP Variables, Trends, and Ranges

Each RAP includes a set of variables to represent plausible future bio-physical, institutional, policy, socio-economic, and technological conditions. The focus is on variables in the simulation models that will be used, but the RAPs can also include other variables to provide context for interpretation of results. As shown in **Table 1**, likely trends are drawn for each key variable under each RAP based on global or regional economic model projections, historical data and/or experts' opinions. In **Table 1**, rising arrows indicate increasing trends and falling arrows indicate declining trends. Angles of arrows represent magnitudes of relative changes. **Table 2** shows the range of each trend. The crop simulation and economic modeling teams use these trends to assign values to model parameters. The range of each trend was used to design sensitivity and uncertainty analysis.

There are both similarities and differences between the variables in each RAP. Generally, likely trends for key variables in RAP3 differ in direction and magnitude from those in RAP1 and RAP2, while likely trends of key variables in RAP1 and RAP2 have similar direction but differ in magnitude. A key difference between RAP3 and the other two is the assumption of trade barriers and disruptions to global agricultural research and development, limiting production, and leading to higher commodity prices projected by global economic models in RAP3. It is also notable that all three RAPs have commodity subsidies decreasing, but the rationales differ according to the RAP narratives. In RAP1, commodity subsidies decrease because they are replaced by conservation subsidies, whereas in RAP3 commodity subsidies decrease due to overall reduction in public support.

Incorporating Output Price and Production Cost Projections

In collaboration with AgMIP and the Inter-sectoral Impact Model Inter-comparison Project, a group of 9 major modeling teams completed the first global agricultural economic model inter-comparison of climate change impacts in which all of

TABLE 1 | Likely trends of variables for REACCH RAPs.

Category	Variable/Indicator	RAP1 (*Sustainable development*)	RAP2 (*Business as usual*)	RAP3 (*Dysfunctional world*)
Bio-physical conditions	Soil erosion reduction	↗	↗	↗
	Irrigation	↗	↘	↘
	Pests, weeds, and diseases control	↗	→	→
Institutional and policy conditions	Commodity subsidies	↘	↘	↘
	Crop insurance subsidies	↘	↗	↘
	Conservation and environment programs	↗	↗	↘
Socio-economic conditions	Commercial farm size	↗	↗	↗
	Gross domestic product	↗	↗	↗
	Population	↗	↗	↗
Technology conditions	Improvements in conservation technologies	↗	↗	→
	Pest management effectiveness	↗	↗	→
Prices from global/national models (relative to 2005 baseline, without climate change)	Wheat	↗	↗	↗
	Corn	↗	↗	↗
	Oilseed	↗	↗	↗
	Cattle	↗	↗	↗
	Chemicals	↗	↗	↗
	Fertilizer	↗	↗	↗
Prices from global/national models (relative to 2005 baseline, with climate change)	Wheat	↗	↗	↗
	Corn	↗	↗	↗

(Continued)

TABLE 1 | Continued

Category	Variable/Indicator	RAP1 (*Sustainable development*)	RAP2 (*Business as usual*)	RAP3 (*Dysfunctional world*)
	Oilseed	↗	↗	↗
	Cattle	↗	↗	↗
	Chemicals	↗	↗	↗
	Fertilizer	↗	↗	↗

Directions of arrows indicate an increasing or decreasing trend. Angles of arrows indicate relative magnitude of changes.

TABLE 2 | Ranges of variable changes for REACH RAPs (%).

Category	Variable/Indicator	RAP1 (*Sustainable development*)	RAP2 (*Business-as-usual*)	RAP3 (*Dysfunctional world*)
Bio-physical conditions	Soil erosion reduction	−10 to 0	−10 to 0	−10 to 0
	Irrigation	+10 to 20	−5 to 0	−10 to −5
	Pests, weeds, and diseases control	20 to 40	−10 to +10	−10 to +10
Institutional/policy conditions	Commodity subsidies	−100 to −80	−30 to −50	−80 to −50
	Crop insurance subsidies	−100 to −80	+50 to 100	−80 to −50
	Conservation and environment programs	+50 to 100	+20 to 40	−80 to −40
Socio-economic conditions	Gross domestic product	+100 to 130	+130 to 150	+50 to 80
	Population	+20 to 40	+20 to 40	+20 to 40
	Commercial farm size	+10 to 30	+40 to 60	+60 to 80
Technology conditions	Improvements in conservation technologies	+60 to 100	+20 to 40	No change
	Pest management effectiveness	+60 to 100	+20 to 40	No change
Prices from global/national models (change relative to 2005 baseline, without climate change)	Wheat	−10 to +20	−5 to +35	+10 to +50
	Corn	−15 to +15	−5 to +30	+10 to +40
	Oilseed	−5 to +20	0 to +35	0 to +60
	Cattle	−15 to +15	−5 to +30	+10 to +40
	Chemicals	+10 to +40	−5 to +30	0 to +40
	Fertilizer	+10 to +40	−5 to +30	0 to +40
Prices from global/national models (change relative to 2005 baseline, with climate change)	Wheat	−5 to +25	0 to +50	+30 to +100
	Corn	−5 to +25	0 to +40	+30 to +90
	Oilseed	+5 to +35	+10 to +50	+10 to +100
	Cattle	−5 to +25	0 to +40	+30 to +90
	Chemicals	+20 to +70	+0 to +40	+10 to +70
	Fertilizers	+20 to +70	+0 to +40	+10 to +70

the models used a standard set of scenarios linked to one emissions scenario and two socio-economic scenarios (Nelson et al., 2014; von Lampe et al., 2014). These scenarios did not embody effects of increasing carbon dioxide concentrations on crop yields so in this sense they can be viewed as relatively pessimistic. However, these scenarios did incorporate a relatively optimistic set of projected crop yield growth rates to represent the impacts of ongoing productivity improvements, ranging from 1 to 2.5 percent annually for major crops (wheat, coarse grains, rice, sugar, and oilseed) across the major regions of the world (von Lampe et al., 2014), so in this respect the scenarios can be viewed as somewhat optimistic.

These global economic model projections show that, without climate change, price changes to 2050 could range from −30 to +40 percent relative to 2005 baseline values, due to factors such as income growth, population growth, and increases in agricultural productivity. In contrast, the effects of climate change on prices in 2050, all else held constant, range from 0 to 60 percent increases relative to 2005 baseline values. Thus, combining the economic model uncertainty and climate uncertainty, there is a wide range of uncertainty in future price projections. We know that historically, agricultural commodity prices have declined in "real" terms for the past century or more, reflecting the fact that global agricultural production has increased at a faster rate than global demand, despite population growth (USDA, 2016). A major question for the twenty-first century is whether this long-term trend in prices is being reversed by the combined effects of demand growth, environmental degradation, reductions in productivity growth, and climate change. These model projections show that the continuation of this trend is very uncertain, but it is also not apparent that there will be substantially higher prices—the result will depend on the relative importance of factors shifting supply and demand.

Projected crop yields are generally lower in most parts of the world in response to climate change, particularly in the latter half of this century, in the tropics, and under high emissions scenarios (Porter et al., 2014). The 9 global economic models in the AgMIP inter-comparison study show lower yields on average, ranging from –40 to +10 percent in yield changes averaged across major commodities. Most models project some increases in land area under production, but little impact on trade or consumption.

As discussed above, socio-economic variables in RAPs such as population, gross domestic product (GDP), commodity prices, and input prices can be derived from the global economic models or from extrapolations of historical price trends. All of the economic models discussed above project prices for wheat and oilseed crops with or without climate change for the U.S. (Nelson et al., 2014). Since the wheat and oilseed markets are global and the REACCH region produces and exports these crops, the global prices will largely determine prices received by farmers in this region. Some production input prices (e.g., cost of diesel fuels and fertilizers) are also determined to a large degree by global fossil fuel prices, but other input prices such as electricity and labor wages are region-specific and can be estimated based on historical trends and other factors, such as national policy, incorporated in the RAPs.

To represent plausible future trends of input and output prices for the REACCH region, we observe that farm net returns are calculated as the difference between revenue and cost. For farms to earn a positive real rate of return, this difference must be positive, or the ratio of cost to revenue must be less than one. Following this idea, we use the assumption of a stable long-term relationship between revenue and cost to project future cost by projecting the cost-over-revenue ratio (CRR), which is defined as the ratio of production costs over production sales.[5] The CRR is useful because it allows us to predict the future production costs using the future revenues that are predicted by the global and regional economic models. Using historical county-level panel data, we estimate an econometric model of CRR and use it to predict future values. Variables used in the CRR model include crop yields and price indexes for livestock products, crops, energy, fertilizer, and chemicals.

To address the dimensionality problem caused by the combination of a large number of scenario elements, we assume three plausible future input and output prices under each RAP: low, "L," medium, "M," and high "H" input and output prices. Each RAP has output price projections with or without climate change from global and regional economic models, giving a total of 18 scenarios. **Table 3** shows details of the three price scenarios and the CRR under each RAP. All of the estimates for potential yields, prices, costs, and predicted CRR were also used to parameterize the regional economic simulation model.

Stakeholders Engagement

A stakeholder advisory committee (38 members) was formed since the initial of the REACCH project. Relevant stakeholders were identified and invited to join the stakeholder advisory committee, which includes representatives of growers, agricultural industry, commodities, citizen groups as well as state and federal agencies. The REACCH project prioritized engaging stakeholders to integrate local and scientific knowledge in research, education, and extension. The level of engagement and associated participatory approach and method were dependent on specific research teams and objectives within the REACCH project.

The RAPs team engaged stakeholders in the design process after the preliminary business-as-usual RAP short narrative description was formed. Stakeholders in the advisory committee participated in the designing process of the RAPs through workshops held by the RAPs team at annual project meetings. There are three major steps in engaging stakeholders. First, the RAPs team trained stakeholders with researchers and other experts on the concepts and process. Second, the RAPs team divided all participants including stakeholders into small groups and facilitated their discussion on additional RAPs and scenarios and elements that should be included in the business-as-usual RAP. In the REACCH project, the stakeholder advisory committee was only formally consulted after the initial RAPs development had been completed. Third, the RAPs team

[5]We assume that production costs are proportional to revenues that are the product of prices and yields. When predicting the future cost-over-revenue ratio, we use projected prices and yields according to the RAPs and crop simulations. Also, the assumption of a stable cost-over-revenue ratio in the long term is plausible, given the fact that farming business is competitive. If there was a decoupling due to price shocks, the cost-over-revenue ratio would vary in the short term (e.g., a year) but eventually stabilize in the long term, which is appropriate for climate change impact assessment. Moreover, our observed county-level data shows that the cost-over-revenue ratio is stable from 1974 to 2004.

TABLE 3 | Assumptions of changes in yield potentials and input and output prices for cost-over-revenue ratio (CRR) prediction and economic impact simulation (%).

CC	RAP	Price scenario	Yield potentials	Crop price		Chemical price	Fertilizer price	Fossil fuel price	Predicted CRR
				Wheat	Oilseed				
N	1	L	30	–10	–5	10	10	20	12.7
		M	30	5	7.5	25	25	35	–5.3
		H	30	20	20	40	40	50	–17.6
	2	L	30	–5	0	–5	–5	0	–2.9
		M	30	15	17.5	13	13	15	–12.7
		H	30	35	35	30	30	30	–14.2
	3	L	10	10	0	0	0	10	–6.9
		M	10	30	30	20	20	30	–10.2
		H	10	50	60	40	40	50	–11.1
Y	1	L	30	–5	5	20	20	50	0.3
		M	30	10	20	45	45	70	–19.5
		H	30	25	15	70	70	90	–37.6
	2	L	30	0	10	0	0	30	–3.6
		M	30	25	30	20	20	45	–16.9
		H	30	50	50	40	40	60	–19.0
	3	L	10	30	10	10	10	40	–6.8
		M	10	65	55	40	40	65	11.2
		H	10	100	100	70	70	90	53.8

CC, climate conditions; N, without climate change; Y, with climate change; L, low input and output prices; M, medium input and output prices; H, high input and output prices.

presented the finalized RAPs to stakeholders at project meetings and through reports. The REACCH project held six annual project meetings, which enabled the RAPs team to engage stakeholders in this three-step approach.

This process of stakeholder engagement was used due to the features of the REACCH project, including a stakeholder advisory committee and several project meetings. Also, within the REACCH project, two survey teams collected social and economic information on farmers. The team member could already have interactions with farmers based on their research for the REACCH project. In addition, the majority of the design and implementation of RAPs involves quantifying parameters in the future, so researchers rather than stakeholders are appropriate to be fully engaged in the process. It would be more useful to fully engage stakeholders in the process when considering the implementation of adaptation strategies.

Issues and Challenges in RAP Development

The REACCH modeling team identified several practical and methodological challenges in designing and implementing RAPs, including training participants, engaging stakeholders, and linking global and regional pathways and scenarios.

Training Participants

A first challenge is to train all of the participants, including research team members, outside experts, and stakeholders, about the scenario design framework and the RAPs methodology. Research team members as well as outside experts and stakeholders often find it difficult to quantify key variables and may feel that values used are subjective. For example, government policies on crop insurance and conservation vary periodically and have effects on federal subsidies, and conservation technology to protect the environment depends on future technology innovation with substantial uncertainty. Also, the RAPs can contain many elements that do not enter into the models being used. This raises several issues. One is that researchers and stakeholders may expend substantial time on features that are not used in the modeling (e.g., variables included in **Tables 1, 2** but not in **Table 3**), and some of the REACCH stakeholders questioned the usefulness of developing elements that could not be quantified in the models, even though they were justified by the research team as providing context to interpret model results. To address these issues, the developers and facilitators of RAPs development explained that the goal is to produce a consistent plausible future, not a prediction of the future. It is important for the participants to understand the overall assessment framework (**Figure 1**) and the role of pathways and scenarios in the experimental design aspect of simulation modeling. As for elements representing aspects of a future world that stakeholders consider and are relevant to research questions, we need to include additional researchers and experts with knowledge of these specific questions of interest and capacities to quantify parameters used for modeling. This may involve additional literature review, survey of expert opinions, collection of data, and improvement of existing models.

Engaging Stakeholders

A second challenge in RAPs development is when and how to engage stakeholders. Engaging stakeholders is now widely promoted in research community and has partly been driven by increasing demand from decision-makers in the private and public sectors for an action-oriented interdisciplinary approach to solving complex economic, environmental, and social issues. A growing body of literature in engaging stakeholders focuses on how to improve the performance of stakeholder engagement and prescribed best practices to engage them (see a detailed review by Reed, 2008). While it is recommended to participate as early as possible, however, the time of participation is dependent on the objective, knowledge, and skills of researchers as well as capacities of stakeholders.

In the REACCH project, the stakeholder advisory committee was only formally consulted after the initial RAPs development had been completed. In contrast, some AgMIP teams incorporated stakeholders from the beginning of the process (Valdivia et al., 2015). It is not yet clear whether either of these approaches performs better. An AgMIP team in Southern Africa used a process similar to REACCH that did not include stakeholders in the initial RAPs development. In that case, the stakeholders found the RAPs to be too conservative, and encouraged the research team to develop new RAPs with more aggressive assumptions about possible technological and policy changes. For the REACCH project, however, this approach proved to be effective, in part because stakeholders participated in a project meeting where the preliminary RAPs were presented and recommendations from the project team members and stakeholders could be incorporated. Also, the role of stakeholders engagement depends on specific research, knowledge of research team, and capabilities of stakeholders. The design and development of RAPs requires scientific knowledge of modeling agricultural systems; thus, our approach of engaging stakeholders is appropriate for the study region to design and implement the RAPs and performs better for scientists rather than stakeholders to improve knowledge on climate change impacts. If it is action related, e.g., implementing adaptations to reduce negative or increase positive impacts from climate change, additional stakeholder engagement would be appropriate.

RAP Scope and Differentiation

A related issue that was identified through stakeholder engagement is the appropriate scope of RAPs. There is a tendency among stakeholder participants to feel the need to address many aspects of a future world that they may consider relevant, but these aspects may not correspond to the variables in the models being used. An example that arose in the context of the REACCH project is the type of contractual arrangements used between producers and grain marketing intermediaries. While this consideration is relevant in actual farm operations, there are no data available to allow this level of financial detail to be incorporated into the simulation analyses that were carried out by the project. In this type of situation, the result can be the use of a large amount of time discussing variables that are not used in models.

Another related issue is how different the RAPs are in terms of key variables impacting the analysis. As we will see in the discussion below, the quantitative analysis shows a similarity between RAP1 and RAP2 which reflects the range of feasible expectations held by the research team. For a number of variables, similar trends in the "Business as Usual" and "Sustainable Development" world were considered plausible. As noted above, one of the AgMIP teams developed RAPs that were considered by their stakeholders to be too similar to current world conditions. One of the qualitative judgments that RAPs developers must make is how distinct "plausible" scenarios can be from "expected" or "Business as Usual" scenarios. Many scenario design experts encourage researchers to consider future scenarios that are "wildcard" or that contain substantial "surprises" not considered likely under current conditions. But it has to be acknowledged that there is no "scientific" basis for such assumptions—there will always be a subjective element in the "art" in pathway and scenario development.

Linking Global and Regional Pathways and Scenarios

A third methodological challenge is to link global and regional pathways and scenarios, an important element in the design illustrated in **Figure 1**. **Figure 1** shows that the regional RAPs are linked to and depend on outputs from global models that in turn depend on global emissions pathways (i.e., RCPs) and global socio-economic pathways (i.e., SSPs). The REACCH team encountered several methodological issues in making these linkages, as discussed below in more detail. Two aspects of the linkage from global to regional pathways and scenarios were addressed in the REACCH project, building on the AgMIP methods discussed in Valdivia et al. (2015).

A first aspect of linkage is to do so consistently across global and regional scales. SSPs are intended to represent elements of the future that are not climate-dependent, thus allowing them to be combined with more than one RCP in the design of global integrated assessment scenarios in a "matrix" that represents the possible combinations of RCPs and SSPs (O'Neill et al., 2014). Thus, as **Figure 1** shows, the RCPs are inputs into global climate models, but do not directly affect elements of SSPs (as indicated by the solid arrows in **Figure 1**). However, this "matrix" design does not work logically for some elements of management that enter into bio-physical models (e.g., water management) and that cannot be defined independently of climate (represented in **Figure 1** by the dashed line from RCPs to global socio-economic scenarios). In addition, agricultural commodity prices are outcomes from global economic models and are also inputs or drivers on the regional or local scale (**Figure 1**). Thus, at the regional scale a RAP that includes global prices from a particular global economic model run is necessarily linked to the particular combination of RCP and SSP that was used to generate the global analysis.

The second aspect of linkage concerns the uncertainty associated with global models, including AgMIP global economic modeling and price uncertainty and methods to incorporate price uncertainty into regional RAPs. **Figure 1** and **Tables 1, 2** show that prices from global economic models are important components of regional RAPs. **Tables 1, 2** also show that these values span a wide range. In principle, this model uncertainty could be incorporated through Monte Carlo simulation, but distributions for most parameters are unknown and there are too many parameters to make this approach practicable. Therefore, as we discuss in the next section, a simpler sensitivity analysis approach is taken in which selected key parameters are varied, although the number of parameters still creates dimensionality challenges.

Wheat-Based Systems in the REACCH Study Region

Winter wheat is a major crop in the Pacific Northwest region, occupying 3.11 million acres as of 2014 (USDA, 2015). Most of this crop is grown across the Columbia Plateau between the Cascades and Northern Rocky Mountains. Using data from the U.S. Census of Agriculture and the National Land Cover Database, we characterized three rain-fed cereal-cropping systems in the region that are the focus of this study presented here, based on Huggins et al. (2015): the annual rotation of winter wheat and spring wheat with summer crops (WWA); the winter wheat-fallow system (WWF); and the transitional wheat system (WWT) that combines winter and spring wheat in a fallow rotation. In the eastern region with an average of 580 mm precipitation per year, farms use the WWA system in which winter wheat is rotated with spring wheat and summer crops over a 3–4 year cycle and fallow is typically not used. In areas with lower rainfall, farmers use the WWT system that includes winter and spring wheat in a 3-year rotation with fallow every third year. In the lowest rainfall areas (average 310 mm), the WWF system is used with winter wheat grown every other year with fallow used to restore soil moisture.

Table 4 summarizes the socio-economic characteristics of small (below the median cropped acres) and large (above the median cropped acres) farms within each dryland system using 2007 Census of Agriculture data. The census data were used in the analysis because they provide detailed information about virtually every farm in the region, and thus provide the best available data to characterize the farm population in terms of yields and economic variables that are the foundation of the economic modeling approach described below. The data show that WWF farms are the largest and have the lowest yields, but yields are similar between small and large farms of each system. The data also show that large commercial WWA farm sales of wheat are about 78 percent of total crop sales, whereas the WWF

TABLE 4 | Summary statistics from 2007 U.S.

Variables	Unit	WWA		WWF		WWT	
		Large farms	Small farms	Large farms	Small farms	Large farms	Small farms
Winter wheat yield	bushel/acre	66	62	51	53	55	62
		(19.2)	(21.1)	(15.5)	(18.3)	(19.3)	(18.9)
Spring wheat yield	bushel/acre	45	45	33	33	36	43
		(14.7)	(16.3)	(17.3)	(13.7)	(15.6)	(15.9)
Winter wheat revenue	$/acre	379	363	290	296	324	361
		(148.6)	(162.6)	(114.5)	(144.7)	(108.6)	(116.7)
Spring wheat revenue	$/acre	260	271	187	206	215	249
		(141.9)	(127.3)	(114.2)	(144.6)	(108.6)	(116.7)
Winter wheat revenue (% of total crop revenue)	%	62	63	91	79	78	58
		(24.9)	(34.6)	(17.6)	(35.5)	(22.5)	(31.9)
Spring wheat revenue (% of total crop revenue)	%	16	18	5	6	11	12
		(22.2)	(30.6)	(12.7)	(19.2)	(15.2)	(21.1)
Non-farming income (% of total household income)	%	71	42	71	37	69	49
		(30.1)	(32.7)	(30.4)	(34.1)	(29.2)	(34.5)
Total crop sales	$/acre	265	273	128	86	148	172
		(126.0)	(141.6)	(63.6)	(85.7)	(91.6)	(115.5)
Total production cost	$/acre	163	164	68	73	86	112
		(87.6)	(117.9)	(37.4)	(63.5)	(55.9)	(67.2)
Total farmnet return	$/acre	85	89	53	9	53	54
		(98.3)	(129.8)	(55.5)	(83.7)	(66.7)	(95.7)
Total government payment	$/acre	18	22	14	17	18	19
		(12.3)	(29.1)	(10.0)	(23.5)	(10.7)	(18.3)
Farm size	acre	2,654	486	4169	717	3,936	852
		(1422.4)	(334.8)	(2400.1)	(497.4)	(2331.6)	(533.1)
Fallow (% of cropland acreage)	%	0.8	0.3	50	65	27	25
		(2.2)	(1.4)	(9.9)	(22.9)	(8.2)	(8.3)
Number of farms		449	442	335	326	333	340

Census of Agriculture data for REACCH wheat systems Standard deviations are in parentheses. Data are for farms with more than 50 acres. WWF, winter wheat-fallow system; WWT, winter wheat transitional system; WWA, winter wheat annual cropping system. Small and large farms within each dryland system are defined as farms with farm land acreage below the median cropped acres and above the median cropped acres farms, respectively.

earn almost all of their income from wheat production and WWT farms are somewhat less specialized. These yields and sales data are the basis for the economic analysis reported below.

RESULTS AND DISCUSSION: USING RAPS IN THE REACCH PROJECT

In this section, we illustrate the use of RAPs in regional integrated assessment as implemented in the REACCH project. The study incorporated RAPs into climate impact analysis to investigate the impacts of climate change on current production systems under current socio-economic conditions relative to the current no-climate baseline, as well as impacts of climate change on future production systems under future socio-economic conditions related to the future no-climate baseline. In addition, the REACCH analysis investigated the contribution of each source of uncertainty in the climate impact assessment.

Impacts of Climate Change on Dryland Wheat-Based Systems

Here we present results using climate projections based on RCP 4.5 for the 14 global climate models used in this study. **Figure 2** shows the distributions of changes in simulated crop yields for winter wheat, spring wheat and spring peas, averaged over the study region for each of the 14 climate model projections for 2050 relative to baseline values from 1981 to 2010. Despite these differences across climate models and locations, the average yield changes are generally positive for wheat, but are negative in some cases for spring peas. These results reflect the fact that the climate models generally project warmer and wetter winters, but hotter and drier summer weather. The wheat and pea yield changes also incorporate the effects of higher CO_2 concentrations that are predicted to have a positive effect on yields according to the CropSyst model.

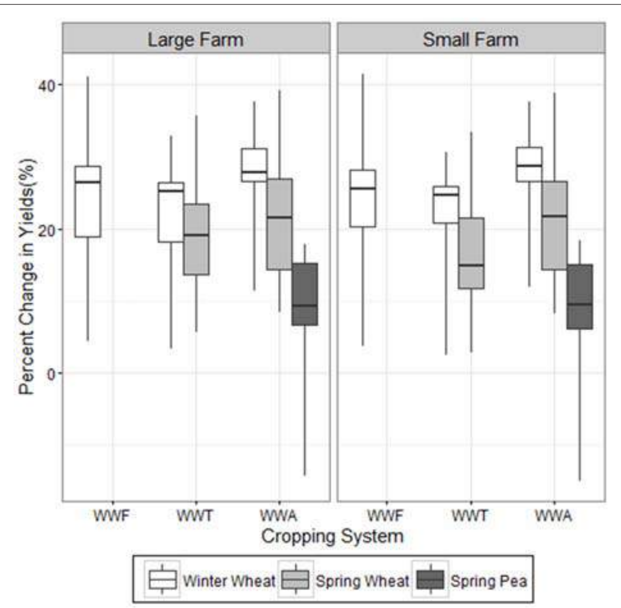

FIGURE 2 | Percent change in simulated yields in 2050 due to climate change, averaged over the REACCH study area, based on downscaled CMIP5 data from 14 global climate models under RCP 4.5. WWF, winter wheat-fallow system; WWT, winter wheat transitional system; WWA, winter wheat annual cropping system.

For each climate model projection, yields are simulated at each gridded cell and linked to individual farms through zip codes.[6] **Figure 3** shows one of the resulting distributions of simulated *relative yields* for one climate projection, where the variation is across gridded cells. A relative yield is defined as the average simulated yield under future climate at a site divided by the average simulated yield under current climate at the same site (thus a relative yield of 1 indicates no yield change due to climate change).[7] This figure demonstrates that there is substantial heterogeneity in projected yield changes across farms in the region, with yield increases at many locations (relative yield greater than 1), but with yield decreases at some locations (relative yield less than 1) due to spatial variation in projected weather patterns.

Table 5 presents results from the economic impact analysis. These results are impacts of climate change using the current cropping systems without adaptations such as changes in crop varieties, fertilizer application rates, or types of crops. The economic model TOA-MD utilizes the simulated relative yields, together with the agricultural census data in **Table 4** to define current economic conditions, and the RAPs data to define future economic conditions, to simulate economic impacts of climate change. Each scenario represents the combined effects of a particular global climate model output to project future prices, and a socio-economic scenario which includes projected changes in production costs, changes in policy (i.e., crop and conservation subsidies) and other parameters in the TOA-MD model. Seven measures of economic impact were simulated: vulnerability to loss (percent of farms that could experience a loss in farm income); total average gains, total average losses, and total average net gains in farm returns; total average gains, total average losses, and total average net gains in household income (which includes both farm and non-farm income).

Table 5 shows that the average economic impact of climate change on current production systems under current conditions (indicated in the table as "No RAP") is positive, consistent with the crop model simulations that show a positive impact on crop productivity, on average (**Figure 2**). However, due to the fact that there are some individual farms projected to experience higher yields, and some farms projected to have negative yield changes (as illustrated in **Figure 3**), the economic analysis show that on average about one-third of farms are vulnerable to economic losses from climate change (indicated as percent vulnerable

[6]The agricultural census provides detailed information on individual farms such as farm size, observed yields, agricultural production costs and revenues, government payments, and non-farm income. However, the exact location of an individual farm is not available in the agricultural census due to confidentiality, and zip code is the finest geographical information that is available. Yields are simulated at each gridded cell with a 4-km spatial resolution.

[7]A relative yield was used to correct biases from crop simulation models, and in combination with observed yields, calculate projected yiel with climate change (see a detailed description in Antle et al., 2017b).

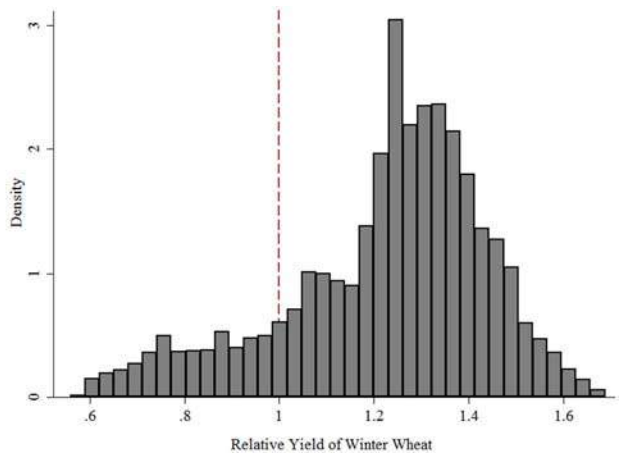

FIGURE 3 | Distribution of simulated relative yields of winter wheat for large farms in the REACCH study area using the annual cropping system in 2050, based on downscaled CMIP5 data from one global climate model and RCP4.5. Relative yield is defined as the yield simulated with future climate divided by the yield simulated with current climate at the same site for the same crop species.

in the table). These figures also show that small farms tend to be more vulnerable to loss than large farms under current world, presumably due to their different locations and economic conditions. The analysis also shows that impacts on small farms are less as a percentage of household income, due to the fact that small farms earn more of their income from non-farm sources.

Table 5 shows that when the analysis is carried out under the three RAPs, the impacts of climate change tend to be more positive, due to the fact that crop prices are projected to be higher in the future with climate change. Crop prices are the highest for RAP 3 which also shows the most positive impacts. However, it should be noted that the differences between the three RAPs is relatively small. This is due to two factors. First, as **Table 3** shows, the production cost is projected to be higher as crop prices and input prices increase, and the RAPs also embody the assumption that both output and input prices will increase in the future with climate change. Second, the other variables in the RAPs that affect economic returns, government subsidy payments, are assumed not to change with climate change. As a result, as the analysis presented in the next section will show more clearly, the interactions between climate and biophysical and socioeconomic factors in this analysis play a relatively small role in determining the outcomes.

Table 5 also shows some important differences in impact across the three cropping systems, with the WWF system generally showing higher vulnerability to climate change, with some notable differences across farm sizes. It is important to keep in mind that the WWF system is used in the driest area in the study region. Finally, we observe that the impacts measured relative to household income are generally smaller than when measured relative to farm income which is a component of household income. We emphasize here that our analysis focuses on climate change impacts without adaptation or mitigation. If adaptation or mitigation were included, farm household income would be likely to increase due to gains from adaptation and compensation for provision of mitigation services.

Quantifying Sources of Uncertainty

Uncertainty is associated with each component of integrated assessment, including the climate model projections of changes in temperature and precipitation, price projections from global economic models, crop model simulations, the regional economic impact assessment model, and the socio-economic conditions defined in the RAPs. In the REACCH study it was not feasible to utilize more than one crop model and one regional economic impact model, so the uncertainty analysis was constructed with respect to climate projections, global economic model projections of prices, regional projections of production costs, and other elements of the RAPs. For each uncertainty source, the variance-decomposition approach in Wallach et al. (2015) was used to construct the share of total variation associated with each factor as $S_i = \frac{\mathrm{var}[E(Y|X_i)]}{\mathrm{var}(Y)}$, where S_i is the contribution of the i th source of uncertainty (i.e., percent of total variation), Y is an outcome variable, X_i is the i th source of uncertainty, $E(\cdot)$ is the expectation operator, and $\mathrm{Var}(\cdot)$ is the total variance.[8]

Using this approach, the contribution of each uncertainty source to the variation in climate change impacts was quantified by using the first-order sensitivity coefficient to measure the share of total variation of outcome variables from 14 climate models through their direct impacts on crop yields, three RAPs, and the indirect impacts of climate change through three levels of future prices and associated production costs. Thus, in this analysis, we separate the effects of climate on future prices and production costs from the other variables contained in the RAPs.

Table 6 shows that the direct impacts of future climate projections through crop yields provide the largest source of uncertainty in the climate impact and vulnerability analysis, but the indirect impacts of climate change through price projections also play an important role in the analysis. Importantly, the analysis shows that the relative importance of direct climate impacts on yields varies substantially with the type of system. The results show that the WWA system outcomes are generally more sensitive to price changes in relative terms. The contribution of the RAPs, apart from price effects, is very small. These results demonstrate that both global climate and global economic model uncertainty may dominate the effects of other socio-ecomic variables contained in the RAPs. However, it is important to recognize that uncertainty in the crop model and the regional economic impact model are not incorporated here, and could also represent an important source of uncertainty.

[8]For simplicity, we assume no interactions between factors or uncertainty sources, i.e., second-order coefficients. If factors interact, the sum of shares across factors is not equal to one. Our results in **Table 6** show that the sum of first-order coefficients across variables is almost equal to one for each outcome. This indicates that interactions play a small role; otherwise, the sum of first-order coefficients would be much less than one.

TABLE 5 | Climate change impacts in 2050 without adaptation, REACCH study region.

				Impact on total farm net returns (%)			Impact on total household income (%)		
System	**Farm size**	**RAP**	**Vulnerability (%)**	**Gains**	**Losses**	**Net gains**	**Gains**	**Losses**	**Net gains**
WWF	Large	None	32.0 (7.19)	26.4 (5.05)	8.1 (2.63)	18.3 (7.65)	17.0 (3.63)	5.2 (1.53)	11.9 (5.13)
		1	25.6 (6.15)	30.6 (5.35)	5.8 (1.84)	24.8 (7.15)	22.9 (4.21)	4.3 (1.35)	18.6 (5.48)
		2	25.5 (6.17)	30.2 (5.29)	5.7 (1.82)	24.5 (7.07)	22.6 (4.18)	4.2 (1.34)	18.4 (5.44)
		3	24.6 (6.26)	32.8 (5.87)	5.7 (1.93)	27.1 (7.75)	23.9 (4.51)	4.2 (1.38)	19.8 (5.79)
	Small	None	35.2 (6.11)	25.0 (4.08)	9.6 (2.47)	15.4 (6.53)	12.1 (2.27)	4.6 (1.03)	7.5 (3.29)
		1	31.1 (7.10)	28.5 (5.15)	8.3 (2.78)	20.2 (7.85)	17.0 (3.11)	5.0 (1.78)	12.0 (4.64)
		2	30.9 (7.19)	28.1 (5.12)	8.1 (2.76)	20.1 (7.79)	16.8 (3.10)	4.9 (1.77)	12.0 (4.62)
		3	29.8 (7.59)	30.9 (5.94)	8.2 (3.04)	22.7 (8.88)	17.6 (3.38)	4.7 (1.88)	12.9 (4.95)
WWT	Large	None	32.7 (5.73)	24.8 (3.59)	8.1 (2.09)	16.7 (5.67)	16.6 (2.62)	5.4 (1.29)	11.3 (3.90)
		1	27.1 (5.39)	29.8 (4.25)	6.4 (1.76)	23.5 (5.99)	22.9 (3.20)	4.9 (1.38)	18.0 (4.52)
		2	26.4 (5.52)	28.2 (4.05)	5.7 (1.66)	22.4 (5.69)	21.8 (3.12)	4.4 (1.32)	17.4 (4.36)
		3	26.1 (5.59)	32.0 (4.79)	6.3 (1.87)	25.7 (6.61)	24.0 (3.46)	4.8 (1.44)	19.2 (4.83)
	Small	None	35.6 (5.00)	24.5 (3.16)	9.7 (2.06)	14.8 (5.21)	14.1 (2.02)	5.6 (1.06)	8.6 (3.08)
		1	30.3 (5.31)	28.5 (3.98)	7.8 (1.93)	20.7 (5.89)	19.6 (2.65)	5.4 (1.41)	14.2 (3.94)
		2	29.7 (5.45)	28.0 (3.97)	7.3 (1.91)	20.7 (5.86)	19.3 (2.66)	5.1 (1.40)	14.2 (3.92)
		3	29.3 (5.57)	30.5 (4.51)	7.7 (2.07)	22.8 (6.54)	20.3 (2.85)	5.2 (1.47)	15.2 (4.20)
WWA	Large	None	28.8 (4.48)	26.9 (3.22)	6.5 (1.44)	20.4 (4.64)	18.5 (2.44)	4.5 (0.91)	14.0 (3.34)
		1	22.5 (4.43)	32.3 (3.83)	4.8 (1.28)	27.5 (5.07)	25.4 (2.90)	3.8 (1.07)	21.7 (3.86)
		2	21.9 (4.51)	31.8 (3.79)	4.4 (1.26)	27.3 (5.01)	25.1 (2.90)	3.5 (1.05)	21.5 (3.83)
		3	21.4 (4.59)	34.2 (4.26)	4.6 (1.33)	29.6 (5.55)	26.5 (3.11)	3.6 (1.10)	22.9 (4.10)
	Small	None	35.1 (3.26)	26.0 (2.40)	10.0 (1.30)	16.1 (3.70)	10.4 (1.15)	4.0 (0.44)	6.5 (1.58)
		1	29.6 (4.35)	32.3 (3.15)	8.4 (1.97)	23.9 (5.01)	17.1 (1.73)	4.5 (1.29)	12.6 (2.45)
		2	29.3 (4.42)	31.9 (3.11)	8.1 (1.97)	23.8 (4.96)	17.0 (1.73)	4.4 (1.29)	12.6 (2.44)
		3	28.5 (4.67)	34.4 (3.58)	8.3 (2.14)	26.1 (5.61)	17.5 (1.83)	4.3 (1.37)	13.2 (2.56)

Standard deviations are in parentheses. Vulnerability = % of farms losing from climate change. Without RAPs, for each row there are 14 scenarios, including 1 RCP and 14 GCMs. With RAPs, for each row there are 1,134 scenarios, including 1 RCP, 14 GCMs, 3 price levels, and 27 policy levels (government payments, crop insurance payments, and conservation payments). WWF, winter wheat-fallow system; WWT, winter wheat transitional system; WWA, winter wheat annual cropping system.

Strengths and Limitations

The experience with the RAPs for the REACCH project demonstrated the value of pathway and scenario development to the creation of a trans-disciplinary research effort, by facilitating communication within the research team and between the research team and stakeholders. As we discussed in this paper, RAPs implementation poses a number of challenges, including the engagement of research team and stakeholders, the dimensionality problem in integrated assessment, incorporation of economic data and quantification of uncertainties. Further systematic research on pathway and scenario development will be needed to evaluate alternative methods to address these challenges.

While systematic development of pathways and scenarios is essential for climate impact research, it is essential to recognize the limitations and areas for further improvement in methods. First, the design and implementation of RAPs assumes that both input and output prices will move in the same direction regardless of climate change. As a result, the projected cost of production offsets the effect of climate change on revenues and reduces the differences between the dysfunctional world pathway and the other two. Second, some variables in the RAPs that affect economic returns are assumed unaffected by climate change, e.g., government subsidy payments. Moreover, a lack of climate-related conservation policies in the RAPs diminishes the difference between sustainable development and business-as-usual pathways. Third, some important elements in the RAPs are not included in our analysis, e.g., crop pests and diseases. This is due to the fact that existing crop simulation models are incapable to handle these elements. Our analysis can include these elements in the future when crop simulation models are improved, and thus increase the accuracy of assessment results.

CONCLUSIONS

This paper presents the design and use of RAPs to construct plausible future agriculture-related pathways and scenarios for regional integrated assessment (RIA) of climate change impacts. We describe how the REACCH team uses the AgMIP RIA methodology to design three regional RAPs and discusses challenges associated with RAPs development and implementation, including the engagement of research team and stakeholders, the dimensionality problem in integrated

TABLE 6 | Decomposition of sources of uncertainty in climate vulnerability and impact (%).

Economic outcome	Cropping system	Farm size	Direct climate impact through crop yields	RAPs	
				Climate impacts on prices and cost of production	Non-price factors
Vulnerability (% of farms losing from climate change)	WWF	Large	86.3	12.7	0.5
		Small	52.5	46.5	0.6
	WWT	Large	70.7	28.3	0.6
		Small	61.0	38.1	0.6
	WWA	Large	49.5	49.1	1.0
		Small	27.6	70.9	1.0
Impact on total farm net return (%)	WWF	Large	84.4	12.7	2.4
		Small	57.0	40.1	2.2
	WWT	Large	66.8	27.7	4.6
		Small	60.6	36.4	2.5
	WWA	Large	54.5	41.0	3.9
		Small	37.6	57.4	4.1
Impact on total farm income (%)	WWF	Large	91.4	7.0	1.2
		Small	68.7	30.1	0.7
	WWT	Large	77.1	19.6	2.8
		Small	72.0	26.4	1.2
	WWA	Large	67.8	29.3	2.5
		Small	58.4	39.7	1.3

For each row, there are 126 scenarios including 14 GCMs, 3 RAPs, 1 RCP, 3 output and input price levels, and 27 policy level (i.e., commodity, conservation, and crop insurance payments). WWF, winter wheat-fallow system; WWT, winter wheat transitional system; WWA, winter wheat annual cropping system.

assessment, incorporation of economic data, and quantification of uncertainties. We illustrate the use of the three RAPs in a study of climate change impacts on dryland wheat-based systems in the U.S. Pacific Northwest region.

We find that under future socio-economic conditions characterized in RAPs the average economic impact of climate change without adaptation is more positive than no RAP scenarios, although the differences between the three RAPs are relatively small. Results show some important differences in impact across the three cropping systems, with the winter wheat-fallow system generally showing higher vulnerability to climate change compared to the annually cropped system. These findings imply that without accounting for changes in socio-economic conditions represented in RAPs, the economic impact of climate change on dryland wheat-based production systems would be over-estimated in the study region. The economic analysis also shows heterogeneous climate impacts among wheat farms due to the fact that, with climate change, some farms are likely to gain whereas other are vulnerable to loss.

To further evaluate the relative importance of climate modeling uncertainty and RAPs uncertainty, we evaluated the contributions of uncertainty sources to the variation in climate change impacts. Results show that the direct impacts of future climate projections through crop yields provide the largest source of uncertainty in the climate impact and vulnerability analysis, but the indirect impacts of climate change through price projections embedded in RAPs also play an important role in the analysis. These results demonstrate that the use of RAPs is an essential element in an integrated assessment of climate change impacts at the regional level.

Finally, we emphasize the critical role that a transparent, protocol-based approach to pathway and scenario development plays in improving the science base for integrated assessment. A protocol-based approach is needed to facilitate the ongoing improvement of climate impact assessment through coordinated global and regional assessments (Rosenzweig et al., 2013; Antle et al., 2017a).

AUTHOR CONTRIBUTIONS

JA: Led research team, lead contribution to design, and implementation of research, conceived and drafted paper, led revisions. JM and HZ: assisted design of research, contributed to research implementation, drafted some sections of paper, assisted in revisions. SC: assisted design of research, contributed to research implementation, assisted in revisions. PD, SE, CK, CS, JD, and JAb: contributed to research implementation, assisted in revisions.

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Confronting Climate Change Challenges to Dryland Cereal Production: A Call for Collaborative, Transdisciplinary Research, and Producer Engagement

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Semi-arid cereal systems face challenges worldwide that are driven by ongoing and projected climate change. These challenges include ensuring cropping system resilience and productivity under changing water and temperature regimes while reversing soil degradation, reducing crop susceptibility to pests, pathogens and weed competition, and exploiting genetic resources to develop cultivars with resilience to climate stresses and improved compatibility with cropping system innovations. Meeting these interdependent challenges requires transdisciplinary efforts that integrate knowledge across many scientific domains. The USDA-NIFA-funded coordinated agricultural project, "Regional Approaches to Climate Change for Pacific Northwest Agriculture" (REACCH), employed this transdisciplinary approach to address climate change and sustainability challenges for rain-fed cereal-based systems in the semi-arid intermountain Pacific Northwest. To engage with and contribute to similar efforts globally, REACCH sponsored a workshop "Transitioning Cereal Systems to Adapt to Climate Change" (TCSACC) in November 2015. Participants from 17 countries and five continents with expertise in agronomy, crop physiology, crop modeling, crop protection, breeding and genetics, sociology and economics shared their perspectives, successes, and challenges to achieving transdisciplinary research integration for semi-arid cereal systems under changing climates. Conference goals were to: (1) strengthen the global network of researchers addressing climate change effects on semi-arid cereal-based systems, (2) share the approaches to achieving transdisciplinary collaboration to advance climate change resilience in cereal systems, and (3) identify the elements of a collaborative research agenda that are needed to advance global food security in the twenty-first century. This paper distills the conference themes and summarizes the calls to action that were discussed: Establish coordinated, large scale, transdisciplinary efforts; Consider Genetic × Environment × Management × Social system (G × E × M × S) interactions; Integrate social, economic, and biophysical science, and engineering; Improve integration among knowledge communities; Consider global context of production systems; Develop more inclusive cropping system models; Enable comprehensive data management and data sharing; Include landscape and ecosystem services perspectives; Establish and support existing global collaboration networks.

Keywords: climate, resilient, cereals, transdisciplinary, research, collaboration, farmers, agroecology

INTRODUCTION

The challenges to achieving sustainable food security in the coming decades are daunting. The convergence of a rapidly growing global population, increasing consumption behaviors, and turbulent social, economic and geopolitical issues will impose difficult conditions for farmers everywhere. Additionally, increasing global land and ocean temperatures and increased frequency of extreme weather events are contributing to changing agroclimatic conditions throughout the world (Fuhrer, 2003; Kalra et al., 2007; FAO, 2011; Walthall et al., 2012; Collins et al., 2013; Mayer, 2013; Lobell and Tebaldi, 2014). The severity of these challenges has troubling implications for health and prosperity at household, community, regional, national and global scales.

Among the most vulnerable systems are cereal systems in semi-arid regions, which account for much of global food production. These include regions dominated by large scale industrial agriculture and others where small-holder production predominates (Lowder et al., 2016). These regions share vulnerability to fluctuations in precipitation and periods of elevated temperature that will present increasing challenges under climate change (Asseng et al., 2014; Challinor et al., 2014; Wilcox and Makowski, 2014). Some of the challenges are common to all systems, inviting collaboration to address them, while others are specific to regions, farming systems, and the social, economic, and ecological systems that support them. Identifying the common and unique challenges and finding solutions for local and regional conditions is a high priority to ensure global food security.

Cereal systems in semi-arid regions, like all food production systems, are social-ecological systems (SES), as such it is widely recognized that they can be productively studied within a broad framework that encompasses genetics, environment, management and social dimensions and their interactions ($G \times E \times M \times S$) (**Figure 1**; Hatfield and Walthall, 2015; Tonnang et al., 2017). Hence, efforts to improve them must be transdisciplinary [Wickson et al., 2006; Francis et al., 2008; National Science Foundation (USA), 2015; Wigboldus et al., 2016], bridging traditional agricultural and related ecological, biogeochemical, hydrological, meteorological, social, and economic disciplines (Howden et al., 2007; Francis et al., 2008; Hatt et al., 2016). In addition, these efforts must engage food system stakeholders to incorporate their understanding of the opportunities, constraints, and risks involved in implementing adaptive farming practices. Stakeholder participation helps research arrive at tenable "best management practices" (BMP's), including "climate friendly BMPs" (cfBMP's) (Pan et al., 2017) that are more readily adopted (Schaap et al., 2013). These collaborations must encompass the temporal and spatial scales relevant to agricultural landscapes undergoing climate change to encompass the extent of these systems and the processes that affect them. Efforts to do so are underway in different parts of the world and their effectiveness could be improved by cross-project communication or coordination.

"*Regional Approaches to Climate Change for Pacific Northwest Agriculture*" (REACCH), was a seven-year collaborative effort by the University of Idaho, Washington State University, Oregon State University, and the United States Department of Agriculture (USDA) Agricultural Research Service, funded by the USDA National Institute of Food and Agriculture (NIFA). The project conducted trans-disciplinary research, education, and outreach focused on the cereal based systems of the inland Pacific Northwest (iPNW) under projected climate change. It aimed to improve knowledge of the production systems, identify opportunities to improve their efficiency and sustainability, promote farmer participation, provide decision support tools, educate producers and citizens at all levels. The conceptual framework, outputs and outcomes of the REACCH project can be accessed through its web site: https://www.reacchpna.org, and in publications, including some appearing in this special issue of Frontiers in Ecology and Evolution: (1) Develop a theoretical framework integrating cropping system, economic and climate modeling (Abatzoglou et al., 2014; Antle et al., 2017; Stöckle et al., 2017), (2) Monitor greenhouse gas (GHG) emissions and nitrogen and carbon dynamics in the production systems (Chi et al., 2016, 2017; Waldo et al., 2016; Kostyanovsky et al., 2017), (3) Compare current and aspirational production systems for productivity and GHG emission potential under current and projected climate (Pan et al., 2016, 2017; Brown et al., 2017; Maaz T. et al., 2017; Maaz T. M. et al., 2017; Stöckle et al., 2017), (4) Address the environmental, social, and economic factors influencing agriculture and technology adoption (Antle et al., 2017; Karimi et al., 2017; Kaur et al., 2017), (5) Anticipate climate change related changes in crop protection requirements (Davis et al., 2015a,b, 2017; Eigenbrode et al., 2015; Foote et al., 2017), (6) Work closely with producers to develop and guide project activities (Kruger and Yorgey, 2017; Yorgey et al., 2017), (7) Educate students from elementary through graduate levels to prepare coming generations for challenges related to climate change in agriculture (White et al., 2014), (8) Ensure data from the project and related projects are managed to facilitate detecting trends and interdisciplinary collaboration (Flathers et al., 2017), and (9) Coordinate all these activities under an integrated, transdisciplinary framework (Eigenbrode et al., 2014, 2017; Morton et al., 2015).

REACCH is a regional effort, but it is part of the global response to climate change effects on semi-arid cereal

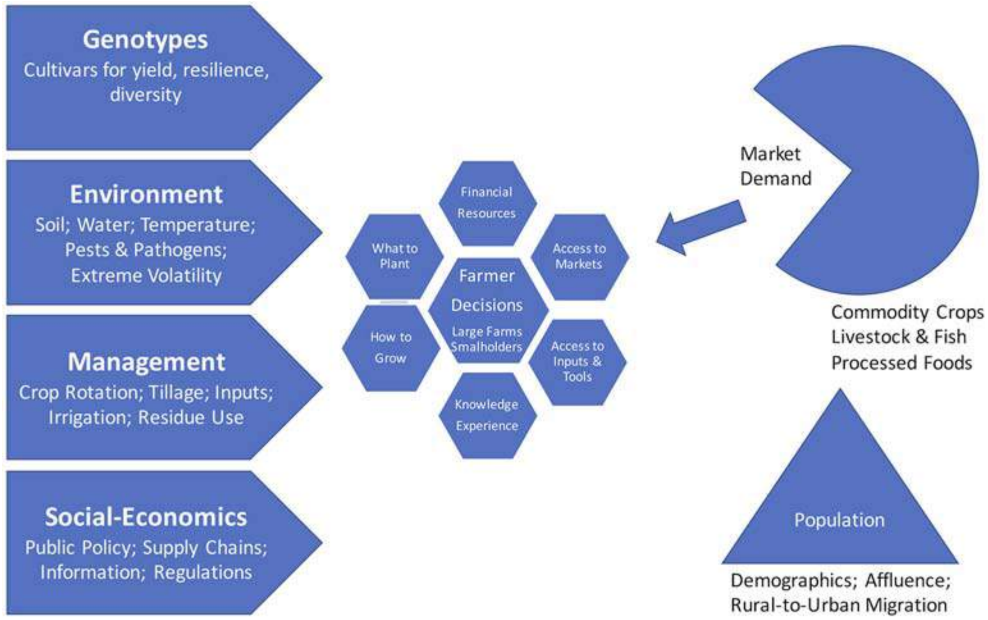

FIGURE 1 | Schematic representation of cereal production as a social-ecological system. The domains of ***environmental conditions*** of soil quality, precipitation, fresh water access, temperatures, pest pressures, and extreme weather events; ***genotype*** properties of cultivars, annuals, perennials, root structure; biological N fixing; stress tolerance; ***agronomic management*** of crop diversity, tillage, input use, livestock integration, residue retention, and ***social-economic*** factors that affect market demand, price signals, capital investment, public incentives, regulations, research; and cultural customs and attitudes all interact to establish the context, motivation, and resources that influence farmers' decisions concerning how to adapt to changing climate regimes.

production systems. Similar coordinated efforts are under way or needed everywhere and could benefit from communication, coordination, and collaboration. To help address this need, REACCH sponsored a workshop-style international conference, *"Transitioning Cereal Systems to Adapt to Climate Change"* (TCSACC), which preceded the 2015 combined annual meetings of the USA Tri-Societies (American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America) and Entomological Society of America (Minneapolis, MN, Nov. 13–15). TCSACC convened 120 scientists from 17 countries on five continents, representing the major semi-arid regions where cereals are produced. Participants included scientists from major universities and national research entities (CSIRO and Department of Environmental and Primary Industries, Australia, USDA-ARS, and NIFA, USA), CGIAR centers including CIMYYT, ICARDA, ICRISAT, ICIPE, and scientists within the CGIAR Climate Change, Agriculture and Food Security Research Program, the Chinese Academy of Sciences, and others. Conference goals were to: (1) strengthen the global network of researchers addressing climate change effects on semi-arid cereal-based systems, (2) share the approaches to achieving transdisciplinary collaboration to advance climate change resilience in cereal systems, and (3) identify the elements of a collaborative research agenda that is needed to advance global food security in the twenty-first century. Keynote addresses reviewed conditions and research efforts in semi-arid systems in North America, South America, Australia, Africa, India, and China. Concurrent breakout sessions addressed specific themes: *Water resources and crop production, Cropping system improvements and innovation, Crop protection: pests, weeds, and pathogens, Genetic improvement and integration, Identifying and assessing adaptation strategies, Greenhouse gases: Monitoring and approaches to mitigation, Cropping system models as platforms for integration, Collaborative translational science to address climate change in semiarid systems,* and *Data management to enable regional and global efforts*. Closing discussions sought to identify needs or continuing effort and opportunities for collaboration. Slide presentations, videos of keynotes, and notes from discussions, and short bios of all conference attendees can be accessed on the conference web site: https://aridcereals.nkn.uidaho.edu. This paper provides highlights of the conference and summarizes its conclusions and suggested action steps.

RESEARCH THEMES TO ADDRESS CLIMATE CHANGE EFFECTS ON CEREAL SYSTEMS

Cropping System Improvements and Innovation to Address Water Scarcity

Cereal production systems in semi-arid habitats are limited primarily by available water, which is projected to be exacerbated by climate change in many of regions where these systems occur (Hijmans et al., 2005; Fraser et al., 2013; IPCC, 2014). Agronomic adaptations to cope with water scarcity and drought have been utilized for millennia (e.g., Sandor et al., 1990). In some regions, alternating years of fallow allows cropping on limited precipitation. This has been the predominant practice, for example, for much of iPNW wheat-based dryland farming where nearly 25% of cereal systems are in annual fallow (NASS, 2015). However, reliance on annual fallow has significant limitations. If the fallow cycle does not provide adequate ground cover protection by residue mulch or standing stubble, it leaves the topsoil vulnerable to wind and water erosion (Singh et al., 2012), also annual fallow is extremely inefficient with respect to water conservation and results in poor overall water use efficiency (Hatfield et al., 2001). Another limitation of alternating fallow is that it is effectively a monoculture that restricts the use of non-cereal crops (e.g., legumes, "green manure" cover crops, oil seeds) and limits cropping system diversification and intensification important for breaking disease and pest cycles, improving soil properties, enhancing weed management, and helping with nutrient management through introduction of biological nitrogen-fixing species (Tilman, 1999; Kirkegaard et al., 2008; Maaz T. et al., 2017).

Contemporary practices such as prudent use of tillage and residue management (Kirkegaard et al., 2014), novel rotations (Whitbread et al., 2015), or "response farming" (Stewart and Faught, 1984) can help conserve water and increase water use efficiency on farms to help with current and anticipated chronic and episodic water limitation. In the REACCH project, for example, experimentation and modeling have examined viability of winter canola, winter legumes, and triticale as rotational crops in the lower rainfall regions of the iPNW (Maaz T. M. et al., 2017; Pan et al., 2017; Stöckle et al., 2017). Water conserving technologies examined have included use of alternative wheat harvesting equipment (e.g., stripper headers) that maximize post-harvest residue height, thereby trapping additional winter moisture, have also been included in this modeling analysis. In some settings, *in situ* or *ex situ* rainwater catchment during wet seasons may be improved to help bridge over dry periods (Kumar et al., 2016). Additionally, flex or opportunity cropping systems are in development as fallow replacement options when pre-plant precipitation and soil water storage are sufficient (Kaur et al., 2017).

Achieving sustainability will require farming methods that efficiently utilize non-renewable resources and leverage and contribute to ecosystem services that impart greater crop adaptive capacity and resilience to changing climates and environmental stress including water limitations (Reynolds and Langridge, 2016). Additional research is needed everywhere to identify and evaluate additional alternative rotational crops and agronomic practices to improve the efficiency of water use. Mid-term climate projections or forecasts are notoriously difficult, but if these are reliable, they can be used to allow farmers to make decisions about which crops to plant depending upon anticipated available water (Meinke and Stone, 2005; Doblas-Reyes et al., 2013). Availability of more economically viable crops or methods will enable this sort of adaptive management, or "flex cropping" (e.g., Kaur et al., 2017).

Genetic Improvement and Integration

Genetic resources are a foundation of successful production systems (**Figure 1**). Advances in breeding and genetics coupled with greatly increased application of chemical inputs (primarily synthetic nitrogen fertilizer), have significantly forestalled the global food security crises that had been envisioned in the late twentieth century. Ongoing population growth will require continued progress in increasing yields, but yield improvements must be coupled with improved tolerance to the abiotic and biotic stresses- related to climate change (e.g., Kole et al., 2015). New genomic tools for better understanding the physiological bases of plant responses to stress, responsiveness to CO_2 fertilization, greater water and nitrogen use efficiencies, and especially heat and drought stress will enable this. In wheat, the USDA NIFA-sponsored Triticeae Coordinated Agriculture Project (T-CAP) has organized and funded 56 participants in 28 institutions and 21 states and includes efforts to adapt wheat and barley for improved water use efficiency (WUE), nutrient use efficiency (NUE), and drought resistance. International efforts include the USAID Climate Change Resilient Development program-funded Climate Resilient Wheat (CRW) projects in Kazakhstan and India, the latter partnering with the Indian Council of Agricultural Research (ICAR)-Directorate of Wheat. These are multi-million-dollar efforts that promise rapid improvements in cereal grain adaptation to climate related stress.

In addition to these approaches to improving yield potential, there is wide recognition that improved global coordination and broader integration involving breeders, crop modelers and agronomists is needed to promote progress. Yield and quality performance results from the interactions of genetics, environment, and management (G×E×M; Hatfield and Walthall, 2015), while approaches that are based on a single technological innovation in one of these areas can only provide partial success (Anderson et al., 2016). Since both breeding and agronomy were instrumental in the achievements of the green revolution, continued innovation will be required to meet these ongoing challenges (summarized in Anderson et al., 2005; in their review of ongoing work on yield gaps in Australia). Furthermore, ongoing yield advances must be accompanied by improved sustainability of the yield over many years and the ability to deliver multiple ecosystem services. For example, the CRW project in Kazakhstan adopted this integrating approach by investigating experimental plantings of drought resilient crops; alternative crop rotations; shifting from monoculture to diversified planting strategies; use of low-till and no-till farming methods; and accessing information from new weather forecasting technology.

Research gaps and needs identified in discussions at TCSACC and outcomes of the 2013 workshop sponsored by USAID and the Bill & Melinda Gates Foundation (Reynolds and Langridge, 2016) include improved technology to enable genomic and high-throughput phenomic selection, emphasizing yield stability, and quality to complement yield targets, including more defined environmental effects in experimental designs, universal data sharing between projects, access to knowledge repositories including those from private companies, improving utilization of cropping system models in impact assessments and cultivar selection decision-making. Such cooperation would advance the accurate identification and focus on phenotypical traits that are most compatible with current and alternative production systems and crop rotations.

Cropping System Models: Platforms for Integration and Data Harmonization

Progress in developing cereal cultivars and designing and implementing cropping systems adapted to climate variability and extreme events will require integration of empirical and modeling approaches. This is because of the impracticality of conducting sufficient numbers of extensive empirical studies replicated across production landscapes that are variable in space and in time. Instead, improved approaches to develop virtual cropping system models coupled with more accurate and affordable sensors and field data acquisition systems to parameterize them is required, and it is achievable (Jones et al., 2016). The primary effort to compare and improve cropping systems modeling has been through the Agricultural Model Intercomparison and Improvement Project (AgMIP) (http://www.agmip.org). Building on foundations laid by Heady (1957), Duncan et al. (1967), and Dent and Blackie (1979), the CERES crop models in the mid-1980's eventually were incorporated into widely used DSSAT (Hoogenboom et al., 2012) and APSIM (Holzworth et al., 2014). The cropping system model, CropSyst (Stöckle et al., 2003), also had its genesis in the early 1990's. With AgMIP's influence, continued improvement of cropping models has involved many disciplines to incorporate more factors and their variability with time and location. Cross-disciplinary improvements to agricultural modeling would greatly contribute to reducing the degree of uncertainty that confronts decision makers at all levels of the food production sector (Asseng et al., 2013). Significant gaps remain to be resolved (Jones et al., 2016), including incorporating pests, weeds, diseases, rotational effects, soil and nutrient variables, genetic variability, and episodic abiotic stresses. To enable this, support is needed for archiving research data and model outputs, with attention to interoperability, and common meta-tagging conventions for cross-validation, sharing, and creatively synthesizing modeling outputs, and supporting next generation modeling efforts (see www.agmip.org).

Data Management to Enable Regional and Global Efforts

Achieving the potential of crop modeling and collaborations that draw upon results of research underway globally will require improved access to data, including results from agronomic trials, effects of biotic and abiotic stresses, gridded output from simulation models, and data from social and economic surveys. Efforts to address cereal production systems worldwide are currently diminished by the inadequate capacity and capability of existing data repositories to host and support enhanced accessibility to these diverse data sets. In other words, the capacity for mobilizing "Big Data" for agriculture is sorely needed.

Work at the forefront to meet this need includes efforts by AgMIP, the USDA's Greenhouse Gas Reduction through Agricultural Carbon Enhancement network (GRACEnet, https://www.ars.usda.gov/anrds/gracenet/gracenet-home/; Jawson et al., 2005), the Global Research Alliance on Agricultural Greenhouse Gases (GRA) (with 46 participating countries; http://globalresearchalliance.org), the CGIAR, through its Data Management System within its Open Access Open Data initiative (http://www.cgiar.org/resources/open-access/), and the Global Wheat Initiative (http://www.wheatinitiative.org/). The consensus of TCSACC participants was that approaches are needed to acquire and manage diverse sorts of data pertinent to entire production systems and to share and compare these across semiarid systems and regions.

Crop Protection: Pests, Weeds, and Pathogens

Projections for cereal production systems under climate change typically are constructed without considering associated changes in pressure from insect pests, weeds and diseases (Coakley et al., 1999; Garrett et al., 2006, 2014; Juroszek and Von Tiedemann, 2013; Eigenbrode and Macfadyen, 2017). Attempts to incorporate disease and insect effects into model projections presents challenges because responses by individual pests, weeds, and diseases can arise from direct effects on agent physiology, behavior, and phenology that influence geographic range, reproduction and mortality impacts (Juroszek and Von Tiedemann, 2015). Drivers include seasonal warming and increasing atmospheric [CO_2] on pest fecundity and population dynamics (Dyer et al., 2013), shifts in geographic or elevational ranges of pests (Bebber et al., 2013; Bebber, 2015), expression of plant resistance factors affecting pests (Tyler and Hatchett, 1983; Currie et al., 2014), acceleration of pest resistance to pesticides and Bt (*Bacillus thuringiensis*) genetically engineered crops (Venugopal and Dively, 2017), changes to feeding behavior, phenology, and voltinism (Ziter et al., 2012), and alterations to trophic interactions and biological control mechanisms (Gillespie et al., 2013; Romo and Tylianakis, 2013; Eigenbrode et al., 2015).

A review of worldwide research on insect pests of wheat and climate change (Eigenbrode and Macfadyen, 2017) found research addressing only a dozen species, most of which had only been studied using a particular approach such as niche modeling, chamber studies, empirical study, and population modeling. For pathogens, the incidence, effectiveness of resistance genes and multispecies interactions are all liable to change in response to climate induced stress. The cumulative impact of these factors can affect disease severity (Garrett et al., 2006, 2014). For weeds, which are less well-studied (Juroszek and Von Tiedemann, 2013), drivers include accelerated C_3 weed invasiveness and competition under higher atmospheric [CO_2] (Ziska, 2016), and increased incidence of weed resistance to herbicides (Peters et al., 2014; Ramesh et al., 2017).

Needs for research and action to address knowledge gaps concerning pests and climate change in cereal systems include obtaining additional long-term records of pest abundance or pest injury and coupling these with historical climate records, incorporating pests and natural enemies into niche overlap and phenological models, and focusing on mechanisms that employ complementary, comprehensive approaches for understanding the aggregate impact of individual pest, weed, and disease species on future crop productivity (Eigenbrode and Macfadyen, 2017). Although the importance of incorporating plant protection into whole system management is evident, achieving increased integration remains a significant challenge. Often agronomic goals take priority, with pest management issues considered as an afterthought. Agronomic practices such as alternative tillage or more diverse rotational or nutrient management schemes are anticipated to influence pests, weeds, and disease risks. Monitoring insect community responses to various adaptive cropping practices should be studied at experimental field scale in order to avoid unintended consequences and to understand and capitalize on the most effective opportunities to improve pest, weed, and disease management.

Greenhouse Gases: Monitoring and Approaches to Mitigation

Along with the needs for adaptation to changing climates, it will be important to minimize the negative impacts of agriculture on the climate system. The agricultural sector produces slightly <10% of GHG emissions (CO_2eq.) in the USA (Snyder et al., 2009) and about 11% worldwide (FAO, 2014). Approximately 65% of this total in CO_2eq. is N_2O emissions from agricultural soils (FAO, 2014); on a per gram basis N_2O has a Global Warming Potential that is 310 times greater than CO_2 (United Nations Framework Convention on Climate Change). Poorly performing agricultural practices contribute to increased GHG emissions associated with deforestation and grassland land use conversion. The magnitude of N_2O soil emissions, and related emissions from agricultural nitrate runoff in surface waters (e.g., Turner et al., 2015) presents opportunities for innovative agricultural practices (e.g., fertilizers with nitrification inhibitors and precision application of fertilizers) to reduce GHG emissions and benefit producers in the short term. Although the mitigation of agricultural GHG emissions generally does not provide a monetized return to farmers and is not currently encouraged by direct public policy incentives or regulations (Brown et al., 2017); effective adaptation practices could achieve "win-win" benefits in which cropping system profitability is increased through more efficient use of applied nitrogen, resulting in both improved farm productivity and reduced N_2O emissions (Millar et al., 2010). Roughly 1% of the nitrogen applied results in N_2O production, but emissions are variable, influenced by climate, soil organic carbon (SOC), soil texture, soil drainage, soil pH, crop management practices, soil nutrient conditions, and soil O_2 status (IFA/FAO, 2001; McSwiney and Robertson, 2005; Del Grosso et al., 2010; Lehuger et al., 2011; Chi et al., 2016, 2017; Waldo et al., 2016).

Improved monitoring of GHG emissions under different cereal production and nutrient management practices is needed for ascertaining the effects of various cropping strategies on GHG emissions and to identify how these emissions could be minimized (e.g., Chirinda et al., 2010; Liebig et al., 2010; Millar et al., 2010; Dendooven et al., 2012; Kostyanovsky et al., 2017). Increased technical accuracy and more extensive field monitoring of these emissions can be combined with modeling to improve the evidence-base for public policy decisions that affect agricultural productivity and sustainability (Moore et al., 2014; Officer et al., 2015).

Needs are evident for increased GHG monitoring as a component of efforts to improve cereal system resilience to climate change. Data are lacking, particularly fine temporal and spatial scale flux data, on GHG emissions from production systems. This situation should be improved through development of better, less expensive sensors. Accompanying this are needs to understand soil microbial processes and the effects of environmental conditions on their emissions. Precision fertilization practices in large mechanized farming systems and, where appropriate, in small-holder systems, can increase returns to farmers by more efficiently using fertilizer; and also contribute to reduced emissions, thus resulting in so-called win-win scenarios.

Social and Economic Dimensions

This G × E × M × S framework (CGIAR, 2012; **Figure 1**) incorporates the understanding that agricultural systems are social-ecological systems. Adaptation to climate change depends upon technological capabilities, market economic costs and returns of adopting new production practices, and the sociological factors and public policies that govern producer behavior. For example, vulnerability to drought in wheat producing regions varies not only with projected impacts of drought on production, but also with the levels and types of inputs, crop residue retention practice, and other agricultural investments that are made to impart resilience (Challinor et al., 2010; Simelton et al., 2012; Fraser et al., 2013). In addition, actions taken by farmers are influenced by perceptions of climate and climate change patterns, which can differ from measured trends (Kibue et al., 2016) and by other factors (e.g., cultural and individual attitudes) that influence openness to change versus inclination to maintain traditions (e.g., Kok et al., 2009).

In many parts of the world, particularly in north temperate regions, farmers have often been reluctant to accept the validity of climate change, and this perspective reduces their likelihood of adopting new practices (Arbuckle et al., 2013; Jorgensen and Termansen, 2016). Their perceptions of risk, which are essential to motivate adoption (Nigg and Mileti, 2002) can significantly vary, and are influenced by farmers' levels of indebtedness, awareness of alternative practices, age, and other attributes. Farmers' willingness to extend and diversify their crop rotation strategies can also be significantly affected by public and private crop insurance policies that encourage and cover the adoption of new crops and inter-cropping acreages. Thus, integrated research responses to climate change in agriculture should strive to understand these sociological forces and incorporate them into transdisciplinary assessment and strategy recommendation efforts (Maaz T. et al., 2017).

The socio-economic challenges facing small-holder farmers in developing nations are significantly shaped by the constraints and opportunities associated with farming on small parcels of land, fragmented landscapes, and limited access to water, inputs and productivity technologies. It must also be recognized that women led small-holder households are a significant segment of the developing world's farming sector; and are often subject to gender discrimination and lack of support from agricultural public institutions and private sector supply chains (Chan, 2010; Doss, 2017). These challenges are compounded by the limited health and education infrastructures and services that are characteristic of poor, rural small-holder communities (Lowder et al., 2016). Small-holders often have more vulnerability to warming environments, particularly in tropical and sub-tropical areas where cereal crops are already cultivated under conditions that are close to their temperature tolerance thresholds (Hossain et al., 2016). This vulnerability is exacerbated by extreme weather events (e.g., droughts, flooding, hurricanes, etc.) that can overwhelm small-holder household resources and the capacities of domestic and international social and public support and disaster recovery institutions and organizations (Hallegatte et al., 2016; Adiku et al., 2017).

Adaptation solutions must be relevant to the local conditions facing the farmer. For example, the "Push-Pull" farming system in East Africa is proving to be a promising integrated crop and livestock strategy for small-holders (Pickett et al., 2014). This practice is suited for the scale of their farm operations and employs traditional elements including intercropping of maize and a fodder to maximize benefits to farmers through suppression of weeds and cereal stem borer pests, providing nitrogen fixation and forage for cattle. This farming practice shows great promise to improve small-holders' total farm productivity and revenues, and reduce their exposure to risks. Whether and how the principles working in east African push-pull systems can be adopted for larger scale systems remains to be examined.

Regardless of a farm's scale, the socioeconomic environment of private sector supply chains and market access, public taxation and regulation policies, agricultural research and extension outreach efforts, and other factors will establish the context within which each farmer operates. Identification of "actionable" agricultural adaptation strategies will require an assessment of both agronomic and socioeconomic forces to determine which practices and technologies would be most effective for farmers in specific circumstances and locations. Development of cfBPM's should include local farmer engagement in the planning and conduct of field research trials that leverage farmer knowledge and experience. Inclusive producer involvement can help identify implementation issues that must be resolved in order to encourage farmers' adoption of innovative practices (Sayre and Govaerts, 2011; Hellin et al., 2014). For example, farming system groups or Communities of Practice, comprised of farmers who work with agricultural industry, ensure that research better serves the needs of farmers in Western Australia (Anil et al., 2015). In the iPNW, proactive farming organizations like Shepherds Grain (https://www.shepherdsgrain.com) and the Pacific Northwest Direct Seed Association (http://www.directseed.org) help inform and research directions to promote sustainable production in the region.

Decision support tools based on agrometeorological models have been developed or are in development for various semi-arid regions to serve large-scale mechanized agriculture or small-holder systems (Sadras et al., 2003; Hochman et al., 2009; McCown et al., 2009; Chen, 2017; Prokopy et al., 2017; http://climateengine.org, https://www.agbizlogic.com). The increasing accessibility of data, continuing innovation, and improvement of user interfaces, and improvement of climate models is certain to accelerate development and deployment of these tools into the future. There is a great need to support the community of private and public entities working to deliver and improve these tools. Success requires appropriately downscaled climate models, coupled with next generation, regionally relevant cropping system models, presented through interfaces that based on economic and social contexts of their intended user populations (Kibue et al., 2016; Marshall et al., 2016; Nguyen et al., 2016; Panda, 2016).

Ecosystem Services Issues: Landscape Scale and Watershed Management for Sustainability

Most efforts to improve the productivity, resilience and sustainability of cereal cropping systems primarily focus on practices that impact farm-level yields and their economic viability across a range of operational scales and degrees of technological mechanization (Robertson and Swinton, 2005; Lobell et al., 2009). However, the quality and quantity of agricultural products and their associated financial returns to farmers are not the only outcomes of significance to humanity. The additional challenges of coping with the disruptive forces of climate change and minimizing environmental degradation require that society's strategies for agricultural innovation and development must also address the long-term impacts of farming practices on local and regional ecosystem services (Elbehri et al., 2017).

When impacts of individual on-farm practices are aggregated at a landscape scale to encompass local watershed and regional river basin geographies, the cumulative benefits, and costs of "ecosystem services" can begin to be recognized and valued (Daily, 1997). Ecosystem services are dynamic and complex natural processes that significantly determine water quality, surface water flows, groundwater replenishment, soil formation, soil fertility, and erosion control, habitats for pollinators, pests and pest predator biodiversity, and other environmental conditions (Daily, 1997, 1999; Kremen, 2005; Palmer et al., 2005). Identifying and measuring how agricultural practices impact ecosystem services is challenging because farm operations tend to generate "non-point source" changes to the environment that are often subtle and only discernable over longer time frames than that of seasonal crop harvests and annual returns on investment (Pradhan et al., 2015).

Ecosystem services have an immediate impact locally, by effecting production performance on the individual farm. These services also propagate across landscapes and geographies beyond the "farm gate" (Schellhorn et al., 2008). The beneficial effects of ecosystem services at the farm level, in terms of improved soil structure and organic matter, and moisture retention can be recognized and valued for their contributions to building and conserving healthy soils (Lal, 2014). These outcomes enhance the future productivity of the land, one of the fundamental "natural capital" assets of farmers (Pearce and Turner, 1990; Voora and Venema, 2008). The economic returns on farmer investments and practices that promote and contribute to local ecosystem services may be realized over longer periods of time (e.g., from several years to the next generation). Farmers, especially those that own their land, can privately capture some of these benefits in terms of reduced expenses for agrochemical inputs, increased water use efficiencies, biological pest control, and other operational cost savings. They may also benefit from future appreciation of land values due to improved soil tilth and fertility.

Determining the value of agriculture's impact on ecosystem services beyond farm property boundaries is challenging because cumulative "downstream" benefits or adverse effects are determined by combined effects of decisions made by many farmers concerning their cropping system practices (Herrero et al., 2013; Lindborg et al., 2017). These impacts can result in positive outcomes such as cleaner and more abundant fresh water supplies, biological nitrogen fixation nutrient inputs, or improved biodiversity habitats (Dale and Polasky, 2007; Scherr and McNeely, 2008; Power, 2010). They can also result in negative outcomes such as nitrate and phosphorus water pollution or sedimentation of waterways, all accumulating and accruing in the public domain (Rabotyagov et al., 2014; Garnache et al., 2015).

It is difficult and costly to monitor, measure and quantify the extended impacts of ecosystem services on other private parties; economic sectors (e.g., fisheries); and the broader public (e.g., "public health, goods and services"; Jacobs et al., 2016). Accurately attributing water quality conditions to local and regional agricultural practices is challenging. An example of such difficulties can be seen in the USDA's multi-year Conservation Effects Assessment Project (CEAP) that studied several watersheds for water quality impacts of minimum tillage and cover cropping practices. To date, CEAP's field studies have not yet been able to determine how river basin water quality variations can be attributed to specific conservation farming practices within the studied watersheds (Tomer and Locke, 2011). On the other hand, CEAP projects have made significant progress in understanding and demonstrating how agricultural practices could be managed to reduce nitrate and phosphorus water pollution in environmentally sensitive rivers and estuaries (e.g., Mississippi River Basin and Chesapeake Bay; Lund et al., 2011; Osmond et al., 2015). The USDA's continued support of CEAP's field research, farmer education and encouragement of innovation (e.g., the NRCS Environmental Quality Incentives Program assistance to farmer investments in improved practices) is needed to build a better, more accurate knowledge base of how watershed ecosystem services function; and how they could be better protected, managed and valued.

An improved ability to understand and measure regionally scaled ecosystem service impacts is critically needed to inform federal and state regulatory frameworks that guide and govern fertilizer and other agrichemical input application intensities, timing, and cropping system integration. Success in stabilizing and restoring the health of major watersheds and aquatic fisheries will significantly depend on identifying and promoting improved agricultural practices management. An excellent resource that discusses leading efforts and decision support models for assessing ecosystem services valuations and their utility in determining values within a specific regional river basin can be found in a "Case Study of the San Pedro River Watershed, Arizona" published in 2012 by the USGS with cooperation of the Bureau of Land Management (Bagstad et al., 2012).

Semi-arid cereal cultivation significantly benefits from well-functioning ecosystem services, and depending upon adopted practices can either positively or adversely impact the continued performance of these natural processes. As an example of these interrelationships, crop residue and ground cover management strategies that reduce soil erosion and weed establishment and return organic nutrients and carbon to the soil are important contributing factors for healthy soil biomes and enhanced water use efficiencies across multiple crop rotations. When individual farmer's best management practices are replicated at landscape scales, local water resources are both qualitatively and quantitatively improved. Similarly, maintenance of riparian buffers, contoured terrain, and natural vegetation habitats can reduce agrichemical runoff to surface waters; and supports biological pest control and pollination services. Leveraging these environmental services are especially significant for non-cereal rotation crops that benefit from insect pollination (e.g., canola). A comprehensive discussion of the opportunities, constraints, and challenges of semi-arid crop production is provided by (Wani et al., 2009).

Inattention to the need to balance these mutually interdependent relationships between cropping systems and their local and extended environment can lead to unintended consequences that impair the productivity of ecosystems that are distant from agricultural areas. An example of the disruptive effect of poorly managed farming practices can be seen in the large hypoxic zone that has formed in the Gulf of Mexico. The excessive levels of nutrients that have leached or runoff from the Upper Midwest agricultural regions are a significant contributing factor to the adverse impacts of the Mississippi River's discharges into the Gulf (García et al., 2016).

Integration

Agricultural production systems are dynamic, involving interacting technical, social, and ecological factors (**Figure 1**). A premise of REACCH and TCSACC, which it sponsored, is that correctly addressing the multifaceted challenges to cereal system sustainability requires that these various factors and their interrelationships are considered together, rather than piecemeal. Transdisciplinary efforts that involve scientists and the direct participation of farmers to facilitate field trials are able to benefit from local farmer knowledge and may also catalyze farmers' willingness to collaborate in testing and implementing adaptive, more resilient cropping system practices that are relevant to their local area (Tress et al., 2004).

GOING FORWARD

Based on discussions within TCSACC and this perspective paper, progress to achieving more integrated and effective approaches for addressing the challenges of climate change in semi-arid systems will be accelerated by improved interdisciplinary and inter-sectoral integration that can address production at a comprehensive systems level. This is necessary to remediate the typical "siloed" efforts within individual disciplines that can fail to generate actionable knowledge that is urgently needed to improve agriculture systems.

Establish Coordinated, Large-Scale, Transdisciplinary Efforts

There is a growing body of literature concerned with interdisciplinarity and transdisciplinarity (e.g., Frodeman et al., 2017), but the challenges pertaining to comprehensively addressing large scale production system sustainability are unique (Morton et al., 2015). Participants in REACCH and TCSACC were committed to this view and to identifying the needed linkages across disciplines and sectors. Successfully responding to these challenges will require resources. The term "transdisciplinary" as used here refers to integration across sectors, including scientists and other stakeholders. There is a need for more projects structured like REACCH to support this type of integration across disciplines, geographies, and temporal scales; and to complement such research with outreach and education components.

The REACCH project facilitated a cross-fertilization of ideas and integrated research approaches and results produced by diverse disciplinary teams. Although the REACCH project has concluded, further development and application of multidisciplinary "platforms" will continue in the recently established USDA Long Term Agroecological Research network (LTAR). LTAR is comprised of 18 agricultural research sites managed by selected US land grant universities; and is building collaborative research and data sharing capabilities that address entire production systems and that are supported by field data acquired over lengthy periods of time (http://www.tucson.ars.ag.gov/ltar/). Future success of such large-scale, long term projects will depend upon initiatives that:

Consider G × E × M × S Interactions

Genetic improvement and farming systems were historically developed separately. Currently and more so in the future, synergies must be studied so that traits can be developed for compatibility with agronomic systems to maximize potential yield and sustainability. Conceptual, structural, cultural, and statistical and institutional innovation are needed to coordinate the agronomic and genetic efforts. This entails at minimum considering not only the Genotype × Environment interactions that are requisite for improving crop varieties, but in addition the role of management in achieving the greatest potential on the ground, leading to the G × E × M concepts (Hatfield and Walthall, 2015). Discussion at TCSACC embraced the recognized need to extend these efforts to include socioeconomic aspects; deliberately integrating social, scientific, and engineering disciplines to consider the holistic food sector, and to adopt the integrating principles of agroecology (Francis et al., 2008; Hatt et al., 2016) (**Figure 1**) .

Improve Integration among Knowledge Communities

Knowledge assets, including archived data relevant to sustainable use of resources, modeling and scenario building, must be accessible to deliver high-quality, relevant information to support decisions about landscape management (Cash et al., 2003), and to facilitate knowledge communication across boundaries (Tàbara and Chabay, 2013). This is related to a participatory research paradigm. Facilitating scientific, evidence-based data that informs and supports decision makers' promulgation of public policies that motivate and assist farmer implementation of Best Management Practices (BMP's) for successfully adapting to climate change challenges. Some advocate for the "upside down" or network focused extension models rather than the traditional model in which scientists provide knowledge to farmers.

Consider Global Context of Production Systems

In a globalizing world, many production systems are as strongly influenced by extra-regional factors such as global markets and trade, movements of pests and diseases and the quarantines that attempt to mitigate them, as they are by local biophysical and social conditions. The CGIAR's Research Program on "Climate Change and Food Security" (CCAFS) is an important internationally supported effort to develop and promote increased awareness and implementation of "climate smart" agricultural practices throughout the world and to inform decision makers in national and global forums and multi-lateral initiatives. CCAFS has particularly focused on identifying and advocating best practices that could be adopted by small-holder farmers throughout the developing world (Campbell and Dinesh, 2017).

It will also be important to understand how adaptive cropping system strategies can enable the agriculture sector to achieve improved productivity levels with reduced GHG emissions. International efforts to identify, verify, and encourage farming practices that reduce GHG emissions are making gradual progress in gaining inclusion in many countries' "nationally determined contributions" to reduce emissions (i.e., UNFCCC: COP21 Paris Agreement; Richards et al., 2015). In addition, a related initiative by the French Ministry of Agriculture and civil society NGO's seeks to promote farming practices that sequester organic carbon in soils: www.4p1000.org (Minasny et al., 2017), effectively drawing down atmospheric CO_2 levels while simultaneously improving soil health at landscape scales (FAO, 2017).

Develop More Inclusive Cropping System Models

With the leadership of AGMIP, cropping system model development seeks to involve more disciplines to inform models that incorporate more of the suite of factors that influence cropping system performance. Gaps remain, notably the need to incorporate pests, weeds, diseases, rotational effects, soil and nutrient variables, and episodic abiotic stresses into these models.

Pursuit of this goal supports large projects and the community of large projects seeking to conduct research that integrates these multiple factors. Crop models can support systems thinking and provide system modeling and linked models that can be used by scientists and by policy makers. For example, cropping system models can be components in regional hydrological modeling approaches that include cropping system models, such as BioEarth at Washington State University (http://bioearth.wsu.edu).

Enable Comprehensive Data Management and Data Sharing

Large, integrated projects require systems to store, access, manipulate and visualize data. Global modeling efforts, like AGMIP, depend upon agronomic and other data from multiple systems that can be accessed for model improvement and system comparisons. The existing systems for achieving this must be maintained. Comparative and collaborative efforts for innovation in the rapidly changing field of data management for large projects and regional collaborations will be essential.

Include Landscape and Ecosystem Services Perspectives

Cropping systems exist within landscapes that include diverse other land uses. Pests and the natural enemies potentially move among land uses influencing if not ensuring the sustained performance of the production elements. Hydrological resources are also shared within these landscapes. Thus, successful agriculture requires attention to sustaining these services while minimizing the disservices that can occur at the landscape level from inappropriate, intensive production technology (Schellhorn et al., 2008; Power, 2010; Veres et al., 2013).

Establish and Support Existing Global Networks

TCSACC participants endorsed the importance of nurturing existing networks of scientists working to help cereal systems in semi-arid regions transition in response to changing climates and other global and local challenges. Momentum from the conference has contributed to two activities: (1) The International Wheat Initiative's Expert Working Group on Wheat Agronomy (Agronomy EWG), which is premised on the requirement for interdisciplinary approaches to improving cereal-based cropping systems, was established in 2016 (http://www.wheatinitiative.org/activities/expert-working-groups/wheat-agronomy); (2) in support of this, a "Wheat Initiative Agronomists Community" (WIAC) within the Agronomy Society of America has been formed to facilitate a global community of researchers dedicated to reducing yield gaps by considering these systems holistically (https://www.agronomy.org/membership/communities/wheat-initiative-agronomists-community). The WIAC is undertaking an international inventory of research underway to address wheat system agronomy with a longer term aim to identify research priorities within and among countries and regions.

CONCLUSION

TCSACC, the Agronomy EWG, and other gatherings and initiatives have recognized the importance of coordinated, collaborative efforts to support adaptation of vitally important cereal production systems of the world, especially those located in the already vulnerable semi-arid regions that are critical for food security. As the TCSACC title indicates, many of these systems must *transition* to new agronomic practices to achieve sustainability. Inherently, this entails efforts that must consider these systems in their entirety from crop genetics; to agronomic practices that conserve water and soil resources; and innovative responses to changing pest, disease and weed pressures. These efforts will require better tools and models to more clearly anticipate specific climate-change related challenges in the near, middle, and long term. All of this must occur through partnerships that consider the social and economic constraints and opportunities available at the local, regional, continental, and global scale. The need is acute. Going forward, resource allocation to research and policy to support successful transitions for semi-arid cereal systems should be guided by this inclusive perspective. One successful model for doing so is provided by the REACCH project in which a large team of scientists and educators is funded and charged with achieving the requisite transdisciplinary integration at regional and, ideally decadal scales. We urge the adoption of this and similar models without delay.

AUTHOR CONTRIBUTIONS

SE: convened the TCSACC conference that provides the basis and impetus for this article, organized the author team and writing process, conducted research, and composed and edited the text; WB: participated in the TCSACC conference and author team meetings, conducted research, and composed and edited the text; DH: participated in the TCSACC conference and author team meetings, conducted research, and composed and edited the text.

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The REACCH project is designed to enhance the sustainability of cereal production systems in the inland Pacific Northwest under ongoing and projected climate change, while contributing to climate change mitigation by reducing emissions of greenhouse gases.

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