

## ***Dryland Cropping in the Western United States***

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### **OVERVIEW**

#### **Ia. Introduction**

The major regions for dryland cropping in the western United States are in the inland Pacific Northwest (PNW), situated contiguously in eastern and central Washington, eastern and north-central Oregon, the Idaho panhandle and the intermountain region of southeastern Idaho, northern Utah, and western Montana (Figure 1). Elsewhere, limited dryland crop production occurs in the foothills along the Central Valley in California and, except for small, scattered areas, is almost nonexistent in Nevada and Arizona.

We define dryland cropping as that practiced where average annual precipitation is 24 inches or less and no irrigation is used. Approximate land area devoted to dryland cropping in the western United States is 10,817,000 acres (Table 1). Of this, 8,271,000 acres are in the inland PNW, 2,124,000 acres in the intermountain region, and 422,000 acres in California. This chapter focuses on these dryland cropping regions (Figure 1, Table 1). Because of climatic variability, the inland PNW is subdivided into three average annual precipitation zones: low—less than 12 inches of precipitation; intermediate—12 to 18 inches of

precipitation; and, high—18 to 24 inches of precipitation.

#### **Ib. Climate**

*Inland Pacific Northwest.* The Mediterranean climate of the inland PNW is influenced by frontal weather systems carried on prevailing westerly winds off the Pacific Ocean. The Cascade Mountains to the west impose a rain shadow effect. The Rocky Mountains to the east provide some protection from the coldest arctic air masses moving down from the north. Elevation ranges from 1000 to 4500 feet above sea level. The driest part of the cropping region is in south-central Washington. It receives as little as 6 inches of average annual precipitation, among the lowest recorded for dryland wheat production in the world. Precipitation gradually increases from west to east (Figures 2a, 2b, 2c). The eastern part of the area receives 24 inches of precipitation annually. Between 60% and 70% of annual precipitation occurs from November through April, and about 20% of the total occurs as snow at higher elevations and latitudes (Papendick et al., 1995). Further details on climate and topographical influences appear in Horner et al. (1944) and Naffziger and Horner (1958).

Crop production heavily depends on stored winter precipitation as indicated by significant correlation coefficient of 0.77 between grain yield of adequately fertilized wheat and soil water stored at the end of the wet season (April 1) (Leggett, 1959). Winter weather is cool to cold, having mean daily temperature in December and January of 32° F but occasionally dipping to 15° F or lower. During extreme cold periods, soil that is not covered with snow may freeze to depths of 16 inches. Frozen soil can lead to heavy water runoff and soil erosion when ensuing weather changes to rain or causes snow to melt (Ramig et al., 1983). During summer, high pressure systems dominate the weather, leading to warm, dry conditions and low relative humidity. Average afternoon

temperatures in summer range between 78<sup>0</sup> F and 95<sup>0</sup> F.

*Intermountain.* The climate is transitional between the maritime climate of the Pacific Coast and continental climate of the Great Plains, depending on the prevailing winds and temperatures. Average annual precipitation ranges between 11 and 20 inches, distributed nearly uniformly throughout the year (Figure 2d), showing a small peak in May and June caused by increased thunderstorm activity. Winter precipitation falls mostly as snow, and the soil is snow covered for most of the winter. Temperature extremes are common during winter. Summers are moderately warm to hot, but periodic rain showers help to elevate relative humidity.

*California.* Dryland cropping areas of California experience a typical Mediterranean climate, having wet and cool winters and dry and hot summers (Figure 2e). Frosts occur, but soils commonly do not freeze. As in the PNW, crop production highly depends on soil water stored during winter. Nonetheless, large water deficits exist during summer months when solar irradiance is high and precipitation is rare, falling in insignificant amounts. Average annual precipitation in the region varies from 12 to 20 inches.

### **Ic. Soils**

*Inland Pacific Northwest.* Most soils in the dryland cropping areas are formed from a thick deposit of windblown silt, called “loess,” which in some locations is 250 feet deep overlying basalt rock (Busacca, 1989). Deposits, along with natural soil erosion from wind and water, have formed a unique topography that is steeply sloping with dune-like hills in the high precipitation zone. Farming takes place on 8% to 30% slopes, where some slopes are as steep as 45%. Such steep slopes often present a severe water erosion hazard during the wet winter season. In lower precipitation areas, where topography is more gently rolling, wind erosion is a greater threat than water erosion. Loess and related sand dunes originated from wind reworking sediments that cataclysmic glacial outburst floods deposited

about 15,000 years ago (Busacca, 1991).

Pre-agricultural vegetation ranged from sagebrush-steppe in the driest areas to meadow steppe in areas of intermediate precipitation and to coniferous forest with increasing precipitation (Daubenmire, 1970). Soils under dryland crop production have developed mainly in postglacial loess under perennial bunchgrass vegetation. These are dark, organic-matter-rich prairie soils, i.e., Mollisols in the U.S. classification system (Soil Survey Staff, 1999). In areas receiving less than 9 inches annual precipitation, soils are low organic matter desert soils or Aridisols, with Entisols on active and recently stabilized dunes (Boling et al., 1998). In northern, eastern, and southeastern areas, soils formed in loess under conifers are Alfisols. Some forest soils have quantities of volcanic tephra from eruptions of volcanoes in the Cascade Range and are classified as Andisols. The pH of topsoil ranges from less than 6 to 6.5 in the high precipitation zone and becomes neutral to alkaline in lower precipitation zones where soils are more calcareous.

Soil texture is predominantly silt loam but has higher sand content in the lower precipitation zones. Following intensive cultivation grain farming for more than 100 years, many soils have lost 40% to 50% of their original content of organic matter from topsoil erosion and oxidation. Presently, organic matter content in the surface 4 inches of cultivated dryland soils ranges from in excess of 3% in the high precipitation zone to less than 1% in the low precipitation zone. Soils are generally permeable and in most areas are deep enough to adequately store winter precipitation and retain between 9 and 12 inches of plant available water (Papendick, 1996). Some soils in north-central Oregon and central Washington are shallow and have considerably less water storage capacity, but they still are sufficient for profitable crop production.

*Intermountain.* Mollisol soils predominate in the diverse intermountain crop production area (NRCS, 2001). There are also minor areas of Inceptisols and Alfisols. Most of the Mollisols fit into the Xerolls suborder, but in colder areas Cryolls are common. Soils are mostly derived

from Quaternary parent material of various origins, although older parent material formations occur widely. Soil texture ranges from silt loam to loam with organic matter content between 1% and 2%. Native vegetation on the dryland cropped area is grassland, mixed grassland-shrub, and some coniferous forest.

*California.* Soils in the undulating foothills along the Central Valley are medium to shallow in depth (<35 inches) and often stony. The majority of soils are Alfisols; the remaining are Mollisols or Entisols. Native vegetation is mainly grassland-oak. The pH is neutral to slightly alkaline. Soil organic matter (SOM) content can be low following prolonged cultivation. Approximately 50% of California dryland soils have a moderately fine texture, 25% medium to moderately coarse, and 25% moderately coarse. About 75% of the dryland crop production is on slopes greater than 5% (Luebs, 1983).

## **II. CROPPING SYSTEMS**

### **Ila. Inland Pacific Northwest**

#### **-- Low Precipitation**

The low precipitation (<12 inches average annual) dryland cropping region in east-central Washington and north-central Oregon covers 3,846,000 acres (Figure 1, Table 1), and is by far the largest cropping zone in the western United States. About 1,013,000 acres currently are enrolled in the Conservation Reserve Program (USDA-FSA, 2000), where land is removed from crop production and growers are paid an average of \$50 per acre per year to grow perennial grasses and shrubs for environmental and soil conserving benefits. This land is under contract for 10 years, during which time neither tillage nor harvest is allowed.

Single families operate most farms, which average 3,000 acres in size. Family farms of 6,000 acres or larger are common, especially in areas that receive less than 10 inches of annual precipitation. Grain yield and profit per acre are lower than in the higher precipitation areas. Since land was broken out of native grassland and sage in the 1880s, farming has been almost exclusively a tillage-based wheat-fallow system, where only one crop is grown every 2 years. Today, growers practice winter

wheat-summer fallow on 90% of cropland. Average long-term winter wheat grain yield after summer fallow ranges from 15 to 50 bu/a.

The main purpose of summer fallow is to store a portion of winter precipitation to enable successful establishment of winter wheat planted into moist soil in late summer or early fall. Fallow also helps ensure economic crop yields and reduces risk of crop failure from drought. Between 60% and 75% of precipitation received during winter months after wheat harvest is stored in the soil up to April. However, precipitation that occurs after April, as well as a considerable quantity of water stored in the soil, is lost during late spring and summer (Leggett et al., 1974). By the end of the fallow cycle, an average of only 30% of precipitation received during the 13-month period is stored in the soil. The processes of water loss and seed zone water retention from summer fallow under PNW conditions have been described by Papendick et al. (1973) and Hammel et al. (1981).

Growers practice a 3-year winter wheat-spring cereal-fallow rotation on about 10% of the cropland. In general, growers will consider planting a spring cereal, primarily wheat or barley, if overwinter water recharge occurs to a soil depth of 3 feet, and at least 5 inches of plant available water is stored in the soil. Continuous annual cropping occurs on less than 1% of land. Average grain yield of spring wheat and spring barley after winter wheat range from 600 to 2200 lbs/acre. Winter wheat after summer fallow is the dominant rotation, as it provides relatively stable grain yields and is less risky when compared with spring wheat or barley. However, growers are increasingly interested in spring wheat due to recent release of high yielding cultivars. Many growers also want to increase intensity of cropping (i.e., decrease frequency of fallow) and reduce or eliminate tillage. Both practices help control wind and water erosion and, in the long term, improve quality of dryland soils (Kennedy, 1998). Reduction in price of some non-selective herbicides and recently introduced no-till drills that fertilize and plant in one pass through the field, leaving ample residue cover, have sparked interest in more intensive cropping systems. Experience of researchers and growers with a wide array of alternative crops such as peas, Canola, condiment

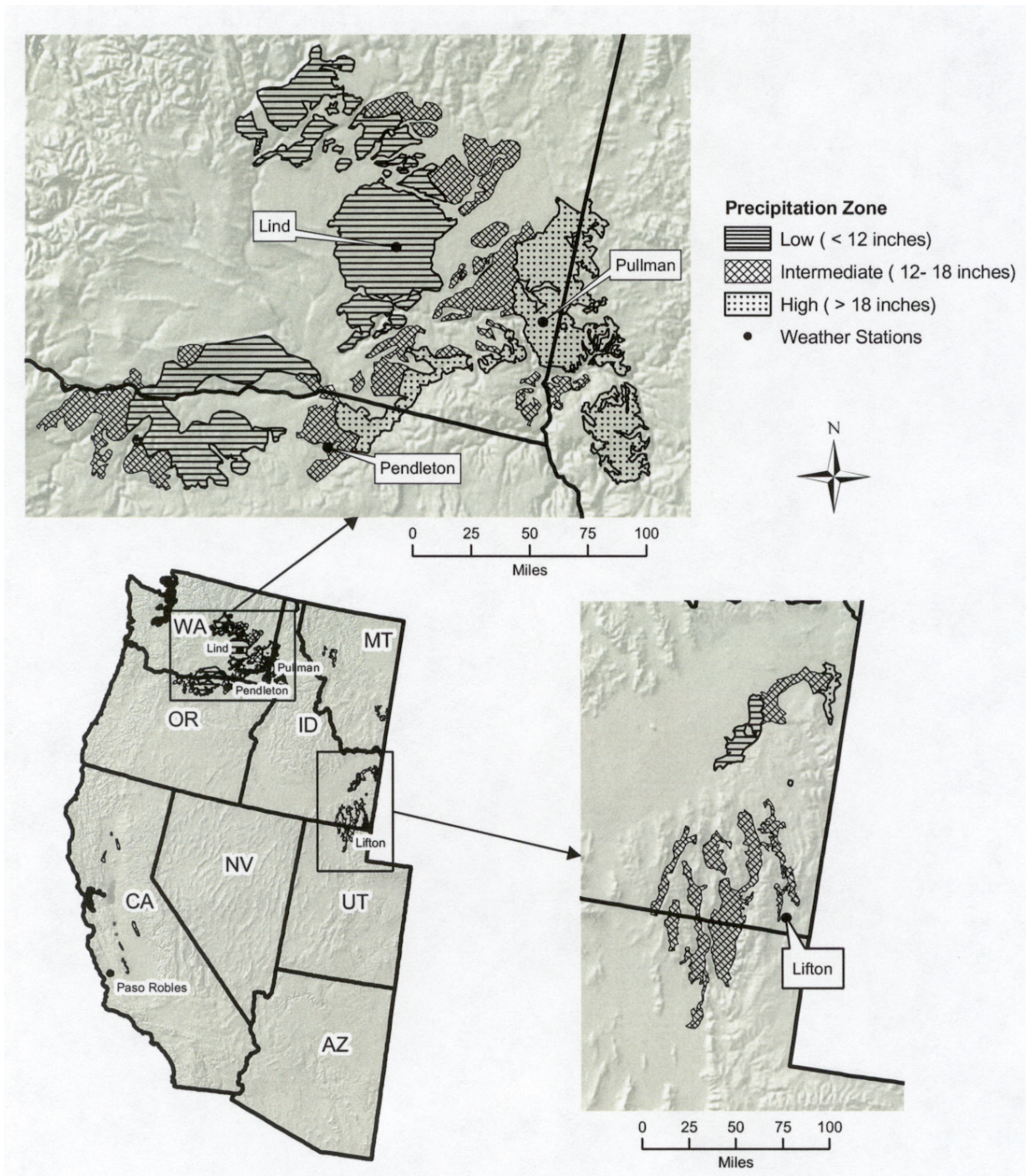


Figure 1. Dryland cropping regions in the western United States.

**Table 1. Land area devoted to dryland cropping in three regions of the western United States.**

<b>Region</b>	<b>State<sup>†</sup></b>	<b>Acres</b>
<b>1. Inland Pacific Northwest</b>		
Low (<12 inches) ‡	Washington	3, 021,000
	Oregon	825,000
Intermediate (12 to 18 inches)	Washington	1,534,000
	Oregon	798,000
	Idaho	62,000
High (18 to 24 inches)	Washington	944,000
	Idaho	924,000
	Oregon	163,000
<b>2. Intermountain</b>		
	Idaho	1,556,000
	Utah	348,000
	Montana	220,000
<b>3. California</b>		
	California	422,000

† Total dryland crop acres by state: Washington 5,499,000; Idaho 2,542,000; Oregon 1,786,000; California 422,000; Utah 348,000; western Montana 220,000.

‡ Numbers in parentheses are average annual precipitation.

mustard, safflower, sunflower, and flax has not yet revealed a crop that can compete agronomically or economically with cool-season cereals. Nonetheless, strong interest and support exist for research on new crops and for more diverse rotations in the low precipitation environment.

Growers raise soft white, hard red winter, and spring wheat cultivars. In general, available cultivars have excellent yield potential, disease resistance, winter hardiness, and end-use quality. However, growers in the low precipitation zone have not been able to take full advantage of the extensive progress in soft white winter wheat development because all but one cultivar released in the past 35 years are semidwarfs that carry dwarfing genes (Allan, 1980). Semidwarfs have short coleoptiles. Length of the coleoptile is correlated with ability of winter wheat to emerge from the soil when planted deep to moisture. Stand establishment of winter wheat on summer fallow is a crucial factor affecting grain yield (Bolton, 1983). Growers in this zone need cultivars that emerge rapidly (7-10 days) when moisture is limited and up to 6 inches of dry soil cover the seed (Schillinger et al., 1998). In response to the expressed needs of growers, breeding of standard height and tall soft white winter wheat lines with good emergence potential has recently been included in objectives for low precipitation areas.

### **I Ib. Inland Pacific Northwest -- Intermediate Precipitation**

The PNW intermediate (12- to 18-inch average annual) precipitation zone comprises about 2,400,000 acres in dryland crop production (Table 1, Figure 1). Much of the intermediate zone is traditionally farmed in a winter wheat-summer fallow rotation, changing to a more crop-intensive 3-year rotation of winter wheat-spring barley-fallow as precipitation increases. Historic reasons for winter wheat-fallow are more stable crop yields, improved weed control, and restrictive requirements of past federal farm programs on cereal grain allotments. Since the elimination of farm program provisions in 1995, fallow acreage has been reduced due to the advent of more intensive cropping systems such as winter wheat-spring cereal-fallow rotation or annual cropping. An important benefit of rotation

and more intensive cropping is reduction of soil erosion.

The 2-year winter wheat-fallow rotation has a greater risk of diseases and winter-annual grass weed infestation than a 3-year rotation because of its higher frequency of winter wheat. Spring barley provides somewhat better root disease control for winter wheat than spring wheat in a 3-year rotation. Researchers and growers have tested the agronomic and economic feasibility of alternative crops having drought tolerance, such as narrow-leaf lupine, Canola, and mustard for inclusion in cereal-based systems. For example, spring canola or condiment mustard is adapted and can substitute for a spring cereal.

The more intensive winter wheat-spring broadleaf and winter wheat-spring cereal rotations are practiced in areas having higher and more dependable precipitation. Some successive cropping of spring cereals, either barley or wheat, occurs in areas with shallow soils (<3 ft deep) where the soil profile fills to capacity with water during winter, or where erosion potential is high.

Soft white winter wheat is the highest yielding crop in all rotations and, historically, provides the best economic return. Average grain yields range from 45 to 80 bu/a having a straw yield of 1.75 to 3.5 tons/a (Papendick, 1996). Growers plant both soft white and hard red spring wheat. Spring barley yields following winter wheat range from 1.5 to 3.0 tons/a in more productive areas and produce half the residue that winter wheat produces. Spring legumes include dry pea, processing pea, lentil, and chickpea. Some growers have experimented with warm season crops such as corn, safflower, sunflower, and proso millet. However, these crops are not popular because of high soil water use, frequent lack of adequate summer heat units, variable grain yield, and lack of accessible markets.

### **I Ic. Inland Pacific Northwest --High Precipitation**

This zone receives more than 18 inches of annual precipitation and comprises 2,025,000 acres of dry-farmed cropland. The territory includes the steeply sloping Palouse area of eastern Washington and northern Idaho,

recognized for world record grain yields of dryland winter wheat that average 90 to 100 bu/a and can exceed 135 bu/a. At these production levels, straw yields range from 3.5 to 5 tons/a. Precipitation is adequate for annual cropping. In most years, available soil water content to a soil depth of 6 feet reaches maximum in early spring. Healthy winter wheat efficiently extracts this soil water by harvest. Because of its consistent high yields, winter wheat is the major profit-making crop, grown in rotation with spring crops of barley, wheat, pea, lentil, chickpea, Canola, and condiment mustard. Fall-planted barley and Canola are occasional replacements for winter wheat. Of spring crops in rotation with winter wheat, typically 40% is barley or wheat, 40% pea or lentil, and 20% other crops, including grass seed or fallow (Papendick, 1996). Grain and residue yields from spring cereals are 50% to 70% of those for winter wheat. Lentil and dry pea grain yields average 1,350 to 1,800 lbs/a and produce an equal quantity of residue. A serious shortcoming of grain legumes is the low crop residue produced to carry into the following winter wheat crop.

A common 2-year rotation is winter wheat-pea or lentil, used because the legume crop improves yield of the succeeding wheat crop 10% to 20% when compared with yield following a spring cereal (Guy and Gareau, 1998). Continuous cropping of winter wheat has been practiced sometimes because the market for wheat was favorable, and at other times to maintain a high allotment for wheat acreage established for the USDA Farm Program. But yields of continuous winter wheat produce 30% to 50% less than wheat yields grown in rotation with spring crops because of heavier weed infestations, increased diseases, and poorly understood soil and unweathered residue inhibitory factors (Wuest et al., 2000).

Due to elimination of cropland base in the USDA Farm Program, and an increased emphasis on resource conservation and environmental protection, 3-year rotations of winter wheat-spring barley or spring wheat-grain legume, or a cereal-only rotation of winter wheat-spring barley-spring wheat are common. Alternative spring crops, Canola or mustard, are adapted and yield well. Longer rotations and higher crop diversity

improve pest control by breaking up weed, insect, and disease cycles and facilitate use of reduced- and no-till practices. Advancements in spring wheat breeding, including new cultivars producing grain yields of 60 to 90 bu/a have enhanced the 3-year rotation.

In past years, enrollment of cropland in CRP was limited for economic reasons. The maximum payment offered considerably less than profit from producing a crop. However, following recent sign-ups, payments to growers have been as high as \$90 per acre per year. Enrollments are increasing, boosted by low wheat prices, uncertainty about government subsidy support, and soaring fertilizer, fuel, machinery, and other operational costs. Still, only 185,000 acres, less than 10% of cropped area, currently is enrolled.

#### **IId. Idaho-Utah-Montana Intermountain area**

The dryland intermountain cropping area covers 2,025,000 acres (Figure 1, Table 1). Dry cropland often is interspersed with irrigated areas. Cropland is 2000 to 6500 feet in elevation above sea level, usually surrounded by mountains.

A cool climate (Figure 2d) and short growing season dictate production of mostly cool season crops. Winter and spring wheat, spring barley, and hay are major crops (Idaho Agricultural Statistics Service, 2000; Montana Agricultural Statistics Service, 2000; Utah Agricultural Statistics Service, 2000). Cool season grain legumes and *Brassica* oilseeds are minor crops sometimes grown in rotation with small grains. Alfalfa and grass hay often are grown in rotation with small grains but also are cropped in monoculture.

Variability in elevation, temperature, precipitation, and soils dictates different cropping systems throughout in the region. Nearly 40% of dry cropland, or 800,000 acres, is currently enrolled in CRP. Where annual precipitation is below 14 inches, winter wheat-summer fallow is the dominant cropping system. Winter wheat grain yields after fallow range from 20 to 50 bu/a, depending on water availability. Winter wheat planting occurs in September or early October, and harvest starts in August but can extend into September. Due to cool temperatures, precipitation storage efficiency during fallow may be somewhat

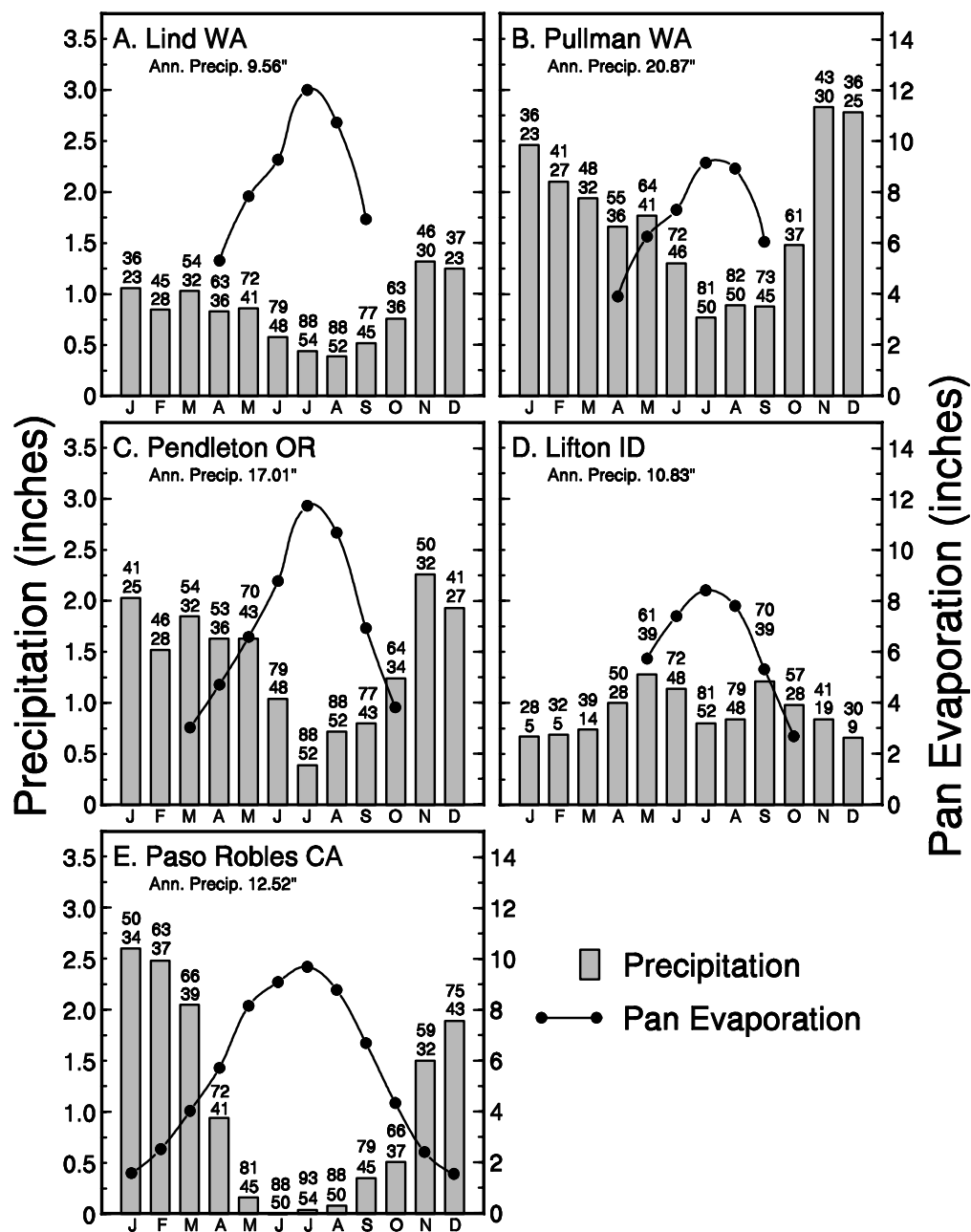


Figure 2. Mean monthly precipitation (30 yr) and pan evaporation (15 yr) from five dryland cropping areas in the western United States. Numbers above individual bars are mean monthly maximum and minimum air temperature.

**Table 2. Field operations for three fallow tillage management methods in a winter wheat-summer fallow cropping system. Long-term research at Lind, Washington, showed that with judicious use of herbicides, tillage operations can effectively be reduced from eight or more (conventional tillage) to as few as three (delayed minimum tillage), resulting in significant erosion control benefits and no adverse agronomic effects (modified from Schillinger, 2001).**

Date	Conventional tillage	Minimum tillage	Delayed minimum tillage
Aug †	V-shape sweep – 12-inch shank spacing, 14-inch-wide sweep to kill Russian thistle after wheat harvest	Nonselective herbicide for postharvest control of Russian thistle.	Nonselective herbicide for postharvest control of Russian thistle.
Nov	Chisel – 2-ft shank spacing, straight point, 10-inch depth.	Chisel – 4-ft shank spacing, straight point, 12-inch depth.	
Feb		Nonselective herbicide to control winter grass weeds.	Nonselective herbicide to control winter grass weeds.
Mar ‡	Primary tillage – cultivator, overlapping 7-inch-wide sweeps, 5-inch depth + 5-bar spring-tooth harrow (2 passes). Or, tandem disk, 5-inch depth (1 pass).	Primary tillage and application of aqua NH <sub>3</sub> with undercutter implement with overlapping 32-inch-wide V-blades, 5-inch depth + rolling harrow.	
Apr	Aqua NH <sub>3</sub> -N injection at 6-inch depth with shanks spaced 12 inches apart.		
May	First rodweeding, 4-inch depth	First rodweeding, 4-inch depth	Primary tillage and application of aqua NH <sub>3</sub> with undercutter implement with overlapping 32-inch-wide V-blades, 5-inch depth + rolling harrow.
June	Second rodweeding, 4-inch depth	Second rodweeding, 4-inch depth	First rodweeding, 4-inch depth
July	Third rodweeding, 4-inch depth	Third rodweeding, 4-inch depth	Second rodweeding, 4-inch depth
Sept §	Sow winter wheat with deep furrow drill, 16-inch row spacing	Sow winter wheat with deep furrow drill, 16-inch row spacing	Sow winter wheat with deep furrow drill, 16-inch row spacing

† Postharvest control of Russian thistle is generally not necessary when good stands of winter wheat are achieved.

‡ Attached rolling harrow is to break up large clods and fill air voids. Should not be used on soils lacking in clod structure.

§ Surface residue may exceed 2,000 lbs/a at the end of fallow when minimum tillage or delayed minimum tillage practices are used. If so, tillage to cut, align, or otherwise bury straw may be needed to allow effective grain drill operation.

higher in the intermountain area than in the inland PNW. As in the PNW, summer rainfall does not appreciably affect soil water content in the fall. (Massee and Siddoway, 1970). Massee and McKay (1979) showed that standing stubble increased soil water storage by trapping snow and that wheat yield increased 5 bu/a for each 12 inches of snow trapped.

January and February average minimum air temperature of 5<sup>0</sup> F (Figure 2d) demonstrates the critical need for insulating snow cover for winter wheat survival. But prolonged snow cover increases snow mold of winter wheat (see disease section), a common problem of the region. Small seedlings are affected less by snow mold than are larger wheat plants (Massee and McKay, 1979). The recommended September planting date for winter wheat is a compromise, balancing large seedling size from early planting for best yield potential against smaller seedlings from later planting for reduced snow mold exposure.

Some growers practice flexible cropping in areas that receive 14 to 16 inches annual precipitation but most still use winter wheat-summer fallow. The most common flexible cropping system is a 3-year winter wheat-spring cereal-fallow rotation. Growers practice annual cropping of continuous cereals, hay, or a combination in some areas where annual precipitation exceeds 16 inches. Continuous annual cereal cropping consists of winter wheat in rotation with spring barley or spring wheat.

Growers plant spring crops as early in spring as possible and harvest in August or September. Winter wheat grain yield in the annual crop areas ranges from 45 to 90 bu/a, and spring wheat and barley grain yield 1 to 2 tons/a. Grass hay produces a single cutting in early summer. Alfalfa grown in monoculture or mixed with grass usually produces two to three cuttings per season. The first cutting occurs in May in warmer areas and the final cutting in September. Hay dry matter yields range from 1.75 to 3.5 tons per acre per growing season.

## **Ile. California**

California leads the United States in number of crops grown and in overall crop production, but

dryland cropping is a minor component of the state total. Wheat and barley are produced on a continuous annual basis on about 200,000 acres, having grain yield ranging from 1,500 to 3,500 lbs/acre. Growers plant dryland cereal crops in late fall and harvest in May or June. Grass, alfalfa, or cereals produced for hay are grown on another 220,000 acres (Table 1).

Summer fallow is practiced only when fall precipitation is below average, which lowers the grain yield potential and increases the risk of producing annual-cropped cereals. When growers choose summer fallow, cattle typically graze stubble until February, then the soil is disked and harrowed. Growers generally use a combination of cultivation and herbicides to control weeds.

Scattered dryland crop production occurs along the western (coastal mountains) or eastern (Sierra Nevada) foothills of the Central Valley (Figure 1). In the late 1970s an estimated 2,000,000 acres were under dryland production (Hatfield, 1983; Luebs, 1983). Area has rapidly declined (USDA, 1999) due to leveling land to make irrigation possible, construction of buildings, government incentives for taking land out of production, and conversion of land into vineyards. Generally, land that remains in dryland production is not suitable for irrigation because of undulating or hummocky topography.

## **III. CULTURAL PRACTICES**

### **IIIa. Tillage and Planting**

#### **Winter Wheat-Summer Fallow Rotation**

Growers in the winter wheat-summer fallow production areas typically conduct eight or more tillage operations during fallow. Timing and extent of tillage vary depending on quantity of surface residue, weed infestations, soil type, potential for water runoff on frozen soils, and individual preference.

A typical sequence of conventional tillage practices during fallow appears in Table 2. Beginning just after wheat harvest, growers use a V-shaped sweep implement to kill weeds such as Russian thistle, if present, by severing the taproot. After fall rains have moistened the surface soil, growers generally chisel fields at higher elevations and latitudes in November to a depth of 10 inches or more to create channels open to the subsoil to aid

infiltration of runoff when soils are frozen (Pikul et al., 1992). In late winter a nonselective herbicide may or may not be used to control winter grass weeds. Initial spring tillage takes place from mid-March through April and commonly consists of one or two operations with a duck-foot cultivator plus attached harrow or a single operation with a tandem disk. Spring tillage disrupts soil capillary continuity to create a dry surface-tillage mulch that retards evaporation of stored water during dry summer months (McCall, 1925). Aqua or anhydrous  $\text{NH}_3\text{-N}$  is injected into soil with shanks in April or May. To control Russian thistle and other weeds, and to set the seed zone moisture line (break between disturbed soil on top and nontilled soil below), growers carry out three to five secondary tillage operations with rodweeder (a 1-in. square rotating rod operated up to 4 inches below the soil surface) in spring and summer.

Intensive tillage operations during fallow often bury surface crop residue, pulverize soil clods, and reduce surface roughness (Schillinger and Papendick, 1997). Blowing dust from excessively tilled fields leads to major soil losses and reduces air quality. Therefore, many growers are converting to minimum and delayed conservation tillage methods, using herbicides instead of tillage whenever feasible to reduce tillage to as few as three operations during fallow (Table 2). Long-term research at Lind, Washington, showed that minimum and delayed conservation tillage significantly increased surface residue and clod retention for controlling erosion with no adverse agronomic (Schillinger, 2001) or economic (Janosky et al., 2002) effects when compared with conventional tillage. Water content in the seed zone at the end of fallow was not affected by tillage treatment, suggesting that finely divided soil particles in tillage mulch are not as important for retarding evaporative water loss during the summer as previously thought. Rather, creating an abrupt break between the tilled and non-tilled layer with initial spring tillage, which severs capillary channels from the subsoil to the surface, appears to be the dominant factor regulating over-summer evaporative water loss. Also, initial spring tillage could be delayed until mid-May because late winter application of a nonselective herbicide provided

excellent weed control for several months.

If conservation tillage practices, as outlined in Table 2, were widely practiced in winter wheat-summer fallow production zones, a sharp reduction in wind erosion and suspended dust emissions could be expected, leading to improved air quality with no hardship to the livelihood of growers. However, no-till summer fallow (chemical fallow) shows limited potential in low precipitation areas because it increases evaporative loss of seed-zone soil water during dry summer months when compared with tillage (Lindstrom et al., 1974; Schillinger and Bolton, 1993).

Winter wheat is planted starting in late August in 14- to 18-inch wide rows using deep furrow split-packer drills. These drills are specifically designed to place seed as deep as 8 inches below the pre-planting soil surface into moist soil. Highest winter wheat grain yields generally are achieved with early planting (Donaldson, 1996; Donaldson et al., 2001) despite certain fungal diseases associated with this practice (see disease section). In dry years when seed zone water is inadequate for seed germination and emergence, growers plant shallow (1 to 1.5 inches deep) into dry soil using either hoe or disk type drills with 6-to 12-inch row spacing, delay planting until the arrival of fall rains, or postpone planting until spring.

### **Intermediate and High Precipitation Zones**

Tillage practices vary widely in intermediate and high precipitation areas where water erosion, rather than wind erosion, is the major soil conservation problem. Implements found on most farms include a moldboard or chisel plow, tandem disk, field cultivator, harrow or rotary hoe, rodweeder or cultiweeder, and either hoe or double-disk drills. Conventional tillage and planting operations and soil conservation practices in these regions have been described in detail by Papendick et al. (1983), Papendick et al. (1995), and Ramig et al. (1983).

Tillage and planting practices in the intermediate precipitation zone have similarities with practices employed in both low and high precipitation zones. Considerable use of summer fallow occurs in the intermediate precipitation zone, but potential for wind erosion is less because of finer-textured and better aggregated soils. The chisel plow and tandem

disk are common primary tillage implements, whereas the moldboard plow is rarely used or used only in certain regions. When using the 3-year winter wheat-spring barley-fallow rotation, secondary tillage prior to planting spring barley may consist of two or three cultivator and harrow operations followed by shank fertilizer application. Most drills used for spring-planted crops have rows spaced 6 to 12 inches apart and are equipped to deliver starter fertilizer with or near the seed (Wilkins, 1996). Fallow operations preceding the winter wheat crop mimic those used in the low precipitation zone (Table 2). Using strategies similar to those in the low precipitation zone, growers often employ deep fall chiseling of stubble to reduce runoff from rain or snowmelt on frozen soils.

In high precipitation annual crop areas, excessive residue from high yielding winter wheat, if left on the surface, commonly interferes with cultural operations. The moldboard plow has historically been used to completely invert the top 6 to 10 inches of soil to bury winter wheat stubble in the fall and to prepare a seedbed for the subsequent spring crop. Widespread use of the moldboard plow continues to contribute to severe water erosion on steep slopes in the Palouse region. Water erosion generally is not severe during the first winter after moldboard plowing, especially if the moldboard plow furrow is turned uphill. Major water erosion can occur in a 2-year rotation after the subsequent pea or lentil crop that produces little residue. In the more common 3-year winter wheat-spring cereal-grain legume rotation, spring cereal residue usually is chiseled rather than moldboard plowed. Cereal residue is long lived in this climate. If retained on the surface, enough residue will persist through the season of a legume crop and provide groundcover during establishment of the following winter wheat crop (Guy and Cox, 2002). Water erosion is less in 3-year rotations than in 2-year rotations, but still above acceptable levels.

Some growers dispose of wheat straw by burning fields either in the fall or spring and follow with reduced- or no-till planting of the next crop. Even without surface cover, soil erosion under burned reduced- and no-till plantings is considerably less than on moldboard plowed fields. But field burning

is increasingly criticized due to the negative impact of smoke on air quality. To conserve surface residue for erosion control and water conservation, many growers use chisel plows to create channels for water infiltration or use tandem disks that, when properly adjusted, chop crop residue to leave 60% or more of the cereal stubble on the soil surface. Reducing straw length and amount on the soil surface facilitates fertilizing and planting operations. Spring cereals produce considerably less residue than does winter wheat and are more manageable in tillage and planting operations. Factors related to crop residue retention, burial, and decomposition as affected by tillage and cropping system have been described by Douglas et al. (1999) and Elliott et al. (1999).

Interest continues to increase in all precipitation zones in development and implementation of no-till technology for dryland cropping systems. No-till is defined as planting directly into residue of the previous crop without tillage that mixes or stirs soil prior to planting. No-till opens the door in all production zones for energy savings, excellent control of wind and water erosion, and improved soil quality. Current estimates indicate that 5% of dry cropland in the western United States is planted using no-till (CTIC, 2001). Adoption is slow for reasons of transition costs, lack of experience and expert knowledge with no-till, grower resistance to change, and uncertainties over crop yields and risks of crop loss from unpredictable agronomic factors. However, potential long-term economic, resource conservation, and environmental benefits are all favored by no-till and provide incentives for a gradual continuing shift to this technology, which is viewed as the farming practice of the future.

### **IIIb. Fertility**

Value of fertilizer and organic residues for crop production on semiarid soils in dryland regions was recognized many years ago (Smith et al., 1946). Nitrogen is by far the nutrient most often deficient for ensuring optimum yield of all non-legume crops. Nitrogen application almost universally increases cereal yield in all precipitation zones on soils with low available soil N. Magnitude of nutrient response usually correlates with degree of deficiency, in the general order of N, S or P, K, followed by

micronutrients. Nutrient interactions can change this pattern, but only the interaction between N and S is routinely encountered in dryland cereal production. Nitrogen fertilizer application can intensify S deficiency and decrease yield under severe S deficiency (Rasmussen and Douglas, 1992).

Nitrogen response by cereal crops is influenced by amount of precipitation, soil depth, previous crop, and level of residual N in soil (Miller et al., 1988; Payne et al., 2000). The N rate for optimum grain yield of dryland wheat varies widely from year to year, mostly related to available soil water (Rasmussen, 1996). Nitrogen fertilization stimulates straw yield more than grain yield because vegetative growth is produced prior to onset of drought stress; increased straw production may lead to high water use by the crop, leaving less water remaining for grain production. Amount of precipitation during April, May, and June has a pronounced effect on grain yield, especially for spring-planted cereals.

Nitrogen use efficiency ranges from 23 lbs of grain per lbs N in wet years to 4 lbs of grain per lbs N in less favorable years. Soil testing for water and available N in the spring of the crop year provides a reasonable estimate of potential yield and N requirement (Leggett, 1959; Fiez et al., 1994). Synchronizing N supply with crop demand for N often increases N-use efficiency, but fertilizer often must be applied before growing-season precipitation is known. Thus, growers rely on weather trends and past experience to apply an "average" amount of fertilizer. The crop previously grown also has a pronounced effect on yield of the subsequent wheat crop, mainly due to its effect on soil water in drier areas (Rasmussen et al., 1989). Grain legume crops add to their value as a rotation crop by providing N to soil. A year of summer fallow mineralizes about 2.7 lbs of N/a per inch of average annual precipitation. Applied N for cereals ranges from 0 to 120 lbs/a. Soft white wheat (no protein requirement), hard red winter wheat (12% protein), and hard red spring wheat (14% protein) generally require 2.5, 3.0, and 3.5 lbs of available N, respectively, for each expected bushel of grain yield (Halvorson et al., 1986; Mahler and Guy, 1998).

Most fertilizer N is applied as anhydrous or aqua  $\text{NH}_3$  because it costs less than other sources. Nitrogen is shanked 4 to 6 inches deep using 12- to

16-inch shank spacing. In general, highest N use efficiency occurs when N is applied at planting. In a winter wheat-summer fallow system, N can be applied in mid-fallow (April-June) without loss through leaching or denitrification when annual precipitation is less than 14 inches. When annual precipitation is between 14 and 18 inches, N application just prior to planting is recommended. Above 18 inches of precipitation, improved N use efficiency for winter wheat is achieved by split application, applying N at planting, followed by a second application in the spring. Spring application can be limited in the high precipitation region due to wet soils, and aerial application of N in the spring is common. Spring-planted cereals benefit from placement of some fertilizer near the seed to enhance early growth (Klepper et al., 1983; Koehler et al., 1987). Most newer no-till drills can apply fertilizer with or near the seed during planting.

Sulfur is the second most deficient nutrient needed for crop growth. Sulfur deficiency occurs primarily in the intermediate and high precipitation zone of Oregon and Washington and on some soils in California. Cereals generally do not respond to S application when grown on soils with a calcareous horizon within 30 inches of the soil surface, since this layer contains significant available S (Rasmussen and Allmaras, 1986). Cereals occasionally exhibit S-deficiency symptoms during early stages of plant growth, but these will disappear after roots extend into the calcareous layer. Cereal crops require about 2.2 lbs of S for every 35 lbs of N, and application of 11 to 18 lbs S/a is common. *Brassica* crops require 3 to 10 times as much S as do cereals at equal yield. Sulfur is applied most commonly as ammonium thiosulfate or ammonium polysulfide combined with N application.

Phosphorus is the third most limiting nutrient. Application of P can increase retention of tillers and hasten maturity. Phosphorus deficiency in cereals is affected little by tillage and frequency of cropping, but becomes more prevalent with higher crop yield potential. Phosphorus deficiency occurs more often on upper slope positions where much of the topsoil has been lost through erosion (Pan and Hopkins, 1991). Band placement of P fertilizer is more efficient than broadcasting P. Band placement of P plus N fertilizer with or near the seed in cool wet

environments often enhances plant development. Deficiencies of K, Zn, Mn, and B occur only rarely in dryland cropping, especially in low precipitation zones.

Fertilizer applications that increase crop residue production generally enhance SOM levels over unfertilized conditions (Smith and Elliott, 1990). Nitrogen has the greatest impact, primarily because it has the greatest effect on dry matter production. Stubble mulching and other forms of conservation tillage conserve more SOM than does incorporating residue. Higher SOM increases microbial biomass, which in turn improves aggregate stability, aeration, water infiltration, and water movement through soil. Long-term N fertilization that has increased SOM also increases mineralizable N in soil (Rasmussen et al., 1998). Increased SOM content raises the amount of N that soil can supply and alters fertilizer N need.

Nitrogen fertilizer is decreasing soil pH because most fertilizer-N used in the western United States is ammonium-based and acid-forming (anhydrous and aqua NH<sub>3</sub>, urea, ammonium nitrate, ammonium sulfate). Increasing acidity in soil reduces biological activity, increases fungal populations, reduces availability of many important nutrients, and slows rate of N cycling in soil. Yield of most crops tends to decrease when pH goes below 5.3, although yields of lentil, pea, and alfalfa are reduced at pH 5.6 or less (Mahler and McDole, 1987). Soil acidity does not pose a problem where annual precipitation is less than 16 inches because soils have high pH and contain free lime below the 12- to 18-inch depth. Soil acidity can limit crop yields in regions having annual precipitation above 16 inches. Periodic liming may eventually be required to sustain crop yield.

### IIIc. Weeds

The most troublesome annual grass weeds for dryland cereal-based farming in the western United States are downy brome, wild oat, and jointed goatgrass. Russian thistle is a difficult annual broadleaf weed in low precipitation areas. Annual broadleaf weeds in cereals generally are less problematic than grass weeds because they can be selectively controlled using herbicides. Most legume and oilseed crops grown in rotation with cereals have good herbicide options for grass weed control. Effective weed management systems integrate

cultural, mechanical, and chemical control strategies as appropriate.

Downy brome, also called cheatgrass (Ogg, 1993), and jointed goatgrass (Donald and Ogg, 1991) are winter annuals having growth cycles similar to those of winter wheat. Although these weeds are problematic in all precipitation zones, the 2-year winter wheat-summer fallow rotation has the greatest risk for infestations because of high frequency of winter wheat. Early planted winter wheat on summer fallow can compete against downy brome and jointed goatgrass, particularly if precipitation for germination of weed seeds does not occur for several weeks after planting. In higher precipitation zones, where growers generally plant winter wheat only once in a 3-year rotation, the additional year out of winter wheat helps control these weeds. Some new herbicides offer effective in-crop control of downy brome, but herbicide resistance is expected to develop within a few years unless stringent herbicide-resistance management strategies are followed. Successive spring cropping is an effective control strategy for downy brome and jointed goatgrass because it reduces weed seed survival in soil.

Wild oat is a major problem in all crops. Great diversity occurs within the wild oat species. Prolific seed production, seed longevity, and wide adaptation, make this weed difficult to control. Herbicide resistance in wild oat is an increasingly important issue.

Russian thistle (Holm et al., 1997) presents a formidable obstacle to successful spring cereal production in low precipitation areas. Spring cereals have less early growth and slower canopy closure than does winter wheat. Russian thistle seeds germinate in repeated flushes during the spring after rainfall events of 0.10 inches or more. Heavy infestations may reduce grain yield of spring cereals by 50% (Young, 1988). Postharvest control of Russian thistle, either by means of a V-shaped sweep tillage implement or with herbicides, is an important management practice to prevent seed production and to halt its soil water use.

Other weeds of secondary importance, or those that are becoming increasingly problematic, include: kochia, Italian ryegrass, prickly lettuce, mayweed chamomile, prostrate knotweed, quackgrass, horseweed, common lambsquarter, redroot pigweed,

Canada thistle, and field bindweed. See Appleby and Morrow (1990) and Ogg et al. (1999) for comprehensive overview of integrated weed control in PNW dryland cropping systems.

### III.d. Diseases

Fungi that infect roots, crowns, and stems are the primary yield-limiting pathogens for dryland cereals in the western United States. Foliar diseases such as rust and smuts are not as damaging to cereals as in many other regions because of low humidity and winter-dominant precipitation combined with integrated genetic, chemical, and cultural management practices for their control (Smiley, 1996).

*Fusarium* foot rot, commonly called dryland foot rot, is prevalent in winter wheat in low precipitation wheat-summer fallow areas. *Fusarium* can survive for many years in soil (Inglis and Cook, 1986) and can even persist in soil that is too dry for other fungi (Cook and Papendick, 1972). Wheat becomes susceptible to *Fusarium* when under water stress, which typically occurs between anthesis and maturity. Diseased internodes have a chocolate brown color and damaged cells stop water flow in the xylem, impeding kernel development and causing heads to turn white. Fungicides and resistant cultivars to suppress *Fusarium* are not available, although varieties having the ability to tolerate or avoid plant water stress tend to be less susceptible to this disease (Cook, 1980). Growers can avoid planting too early (i.e., not before 20 August) and limit N fertilizer to evade early water stress and disease expression.

Snow molds are important on winter wheat in the intermountain region and at higher elevations and northern latitudes in the PNW. This group of diseases is caused by at least three genera of fungi, but the most important are *Typhula* species responsible for speckled snow molds. Snow molds are caused by both soil-borne and residue-borne pathogens that infect leaves under the snow and then grow into crowns. Wheat dies if covered with snow for more than 120 consecutive days. Some growers have flown on coal dust to hasten snow melt, but control of the disease is mostly accomplished by rotation to spring cereals, which escape infection, or by growing the few cultivars of winter wheat that can survive snow mold even with 100% destruction of leaves.

*Cephalosporium* stripe and strawbreaker foot rot are residue-borne pathogens of winter wheat. *Cephalosporium* stripe develops when the pathogen invades the xylem. Early stages of symptom development, i.e., while plants are still in the tillering or stem extension stages, can be recognized as yellow stripes running the full length of leaves and down leaf sheaths. As the disease continues to develop, plants typically are stunted and die shortly after heading and before grain fill. The pathogen then grows into surrounding parenchyma tissue of dead culms where it can survive for 2 years or more in buried straw (Bruehl, 1968). Root infection occurs from spores produced on undecomposed infested straw in soil, apparently through wounds produced on roots through soil heaving or other mechanical damage. Spores produced in infected roots are then carried upward in the transpiration stream, ultimately plugging the vascular system (Wiese, 1987). Plugging of the vascular system results in shriveled or no kernels, white heads, and reduced grain yield. Harvest and tillage operations return host debris and inoculum to soil. Sources of genetic resistance exist, and attempts are being made to incorporate *Cephalosporium* stripe resistance into winter wheat cultivars (Cai et al., 1998).

Strawbreaker foot rot (eyespot) develops as a consequence of infection at the base of tillers and the mainstem just above or at the soil surface (Bruehl et al., 1968). These infections develop as elliptically shaped lesions, also known as eyespots, that progress through successive layers of leaf sheaths and finally into the culm. Severely infected tillers and stems break over, hence the name “strawbreaker.” The fungus responsible for strawbreaker foot rot overwinters on infected stubble. Conidia disperse by raindrop splash to young winter wheat plants when temperatures are cool (below 50° F). Resistant cultivars, crop rotations, and chemical control can limit yield losses due to disease.

*Rhizoctonia* root rot is the most important disease of spring wheat and barley planted directly into cereal stubble (Weller et al., 1986). *Rhizoctonia* is a minor disease of wheat and barley grown with conventional tillage but can be devastating for these crops under no-till. Practices that limit severity of this disease in no-till cropping systems are i) elimination of volunteer and other grass weeds that

serve as hosts for the pathogen during the “green bridge” period 2 to 3 weeks and preferably 2 to 3 months prior to planting barley or wheat (Smiley et al., 1992), and ii) soil disturbance in the seed row 2 to 2.5 inches below the seed at time of planting (Roget et al., 1996). At present, no cereal cultivars are resistant to *Rhizoctonia*. In addition, as most broadleaf crops are susceptible to *Rhizoctonia*, crop rotation is of little or no benefit (Cook et al., 2002).

For broadleaf crops, fusarium wilt and *Aphanomyces* root rot reduce yield of pea (Hagedorn, 1984). Both pathogens survive for long periods as resistant spores in soil. Fusarium wilt resistant cultivars are widely grown, but no pea cultivars are resistant to *Aphanomyces* root rot. Residue-borne *Ascochyta* spp. can cause leaf blight of pea, lentil, and chickpea, but most devastating losses have been with chickpea. In the 1980s, *Ascochyta* blight destroyed chickpea production in northern Idaho, resulting in a moratorium on production. In 1993 *Ascochyta* blight resistant cultivars of chickpea were released, and production has returned.

#### **IV. CONSERVATION CHALLENGES**

##### **IVa. Wind Erosion**

Wind erosion in many dryland farming regions is a major cause of soil loss. It also degrades off-site urban air quality by small particulate emissions. Soil particles less than 840 microns (.033 inches) in diameter often are described as the “erodible fraction” (Chepil, 1941). Many soils in the western United States have significant quantities of these particle sizes because of both their loessial and volcanic origin and low organic matter content reduced by more than a century of farming.

Saxton et al. (2000) showed that several soil types in the Columbia Plateau of the inland PNW are dominated by particles less than 75 microns (.003 inches) diameter readily suspended and transported for long distances during dust storms (suspension erosion). Soil loss as high as 50 tons/a from suspension erosion has been measured from newly planted winter wheat after summer fallow in a single one-day wind erosion event in Washington (K.E. Saxton, unpublished data). Little opportunity remains for erosion control once particles become airborne, thus control strategies focus on reducing wind

velocity at the soil surface by crop and residue cover or aggregation if moisture and soil structure provide this capability. These soils also contain many small particulates less than 10 microns (.0004 inches) in diameter (PM-10) that are considered a health concern when inhaled into lung tissue. Communities in California, Arizona, Washington, and elsewhere are developing control strategies for this environmental and health concern in cooperation with regional growers.

In addition to suspension erosion, larger soil particles and aggregates (>75 microns) are eroded by movement at the soil surface (creep) or short duration suspensions (saltation). Thus, plant material on the surface, soil clods, and rough soil surfaces provide protection and particle trapping (Fryrear, 1984; Horning et al., 1998). Best management practices for controlling wind erosion in dryland farming areas have been outlined by Papendick (1998).

##### **IVb. Water Erosion**

Water erosion is most severe during winter when residue cover is lacking, as with newly planted winter wheat after summer fallow or grain legumes. The heaviest erosion typically takes place on slopes when rapid snowmelt or rain occurs on thawed soil overlying a subsurface frozen layer (McCool, 1990). In many areas of the inland PNW and intermountain region soil freezing may occur to depths of 4 inches several times during winter with occasional freezing to 16 inches (Papendick and McCool, 1994). Partial or complete soil thawing frequently occurs between freezing events.

Few dryland crop regions in the western United States have erosion rates less than 2 tons/a, and most have rates greater than 4 tons/a (NRCS, 2001). Annual water erosion rates for conventional till winter wheat-spring barley-summer fallow rotation in the intermediate precipitation zone range from 8 to 20 tons/a. In the high precipitation Palouse Basin in southeast Washington and northern Idaho, water erosion rates following conventional moldboard plow tillage used in past years averaged 20 tons/a per year, but rates above 25 tons/a were common and could reach 200 tons/a on some steep slopes (USDA, 1978). Presently, more than 40% of Palouse Basin cropland is under conservation tillage, and water

erosion rates have been reduced by 3 tons/a per year from previous (USDA, 1978) levels. Soil erosion from dry farmed cropland in all regions of the western United States still exceeds tolerable rates (NRCS, 2001). Further adoption of conservation tillage and a continued move toward no-till is needed to reduce soil erosion.

## V. ECONOMIC CONSIDERATIONS

During the last decade of the twentieth century, three primary factors dominated economics of dryland crop production, and wheat in particular, in the western United States. These factors are i) robust technical progress, ii) erratic world grain market prices, and iii) unwavering income support to growers from the federal government. New technologies such as improved cultivars that have greater disease resistance and higher yield potential, more effective and affordable herbicides, a wide range of fertilizers and delivery systems, and marked improvements in reduced- and no-till farming methods have increased grain yields and favored more intensive cropping.

The most obvious consequence of these technological improvements has been a reduction in summer fallow and commensurate increase in cropping intensity in the western states (Smith and Young, 2000). But winter wheat-summer fallow has remained more profitable than more intensive cropping systems in low precipitation regions (Young et al., 2001). Foreign producers have vigorously adopted new technologies and since 1998, given favorable weather, world wheat markets often have been glutted. By 1998-2001, prices for soft white wheat slumped to historic lows in real terms of \$2.50/bu. The problem of excess supply was further exacerbated by recession in east Asia, where most wheat produced in the western United States is sold.

Growers' loss of income in the market place has been cushioned by government subsidies. Before 1996, the U.S. government relied on crop acreage restrictions to control production levels and provided safety net programs to protect growers' incomes by increasing payments to growers when prices were low. In 1996, the "Freedom to Farm Act" eliminated crop acreage restrictions and substituted a declining schedule of fixed payments to be phased out by 2003. Due to low prices starting in 1998, the U.S.

Congress reversed the declining schedule of payments by adding large annual supplemental payments. Total payments to wheat and other cereal grain growers reached record levels by 2001. For many growers these payments accounted for more income than grain sales.

In response to low market prices, the 2002 Farm Bill returned to subsidy payments that varied with production levels and were higher when grain prices declined. Over time, most analysts agree that subsidies for grains in the United States and Europe increase surpluses and perpetuate low prices. Farmland prices also increase in areas where subsidies are provided.

## VI. ADVANCES IN DRYLAND FARMING

Potential for economic and environmental benefits is a major driving force in the ongoing gradual shift by dryland growers to adopt reduced- and no-till farming methods. Ironically, economics is probably the main factor limiting rapid adoption of conservation practices. Transition costs and uncertainty about crop yields often are cited as main obstacles to change, along with lack of experience by individual growers, limited research for answers when problems occur, and general lack of technical know-how and experts in reduced- and no-till dryland agriculture. Given the current increase in research, significant advancements in no-till farming technology and large-scale adoption by growers are anticipated in the coming decade. Specific advances for dryland crop production in the western United States since 1980 include:

- ! Understanding for timely and effective elimination of volunteer cereals and other grass weeds (*green bridge*) to control root disease.

- ! Continued development and release by university and USDA breeding programs of high-yielding winter and spring cereal cultivars having improved resistance to pests and high end-use quality.

- ! Availability of a wide array of affordable nonselective and in-crop herbicides. Weed control remains a pressing issue. The low profit margin of many crops grown under dryland conditions often does not allow for expensive chemical weed control programs.

! Placement of some of the fertilizer near the seed to improve early growth and grain yield in spring cereals.

! Rapid advances in no-till drill technology for precise placement of seed and fertilizer in one pass through standing residue.

! Finding that minimum tillage fallow can replace conventional intensive fallow to provide improved erosion protection with equal operating costs and without loss of wheat grain yield.

! Introduction of the wide V-blade adjustable-pitch sweep implement to effectively retain residue, clods, and surface roughness for wind erosion control and to retain soil moisture during summer fallow.

! Adoption of alternatives to cereals such as Canola, mustard, and chickpea to provide rotation and economic diversity in higher precipitation areas.

! Recognition of the need for uniform straw and chaff distribution by combines during cereal harvest to enhance drill performance, efficient growth, and optimum yield of the subsequent crop.

! Understanding that crop yield and fertilizer needs vary widely depending upon slope position and soil type. Combine yield monitors, GPS, and GIS systems allow the use of variable rate fertilizer application across the field.

! Finding that achievable amounts of crop residue cover (i.e., 25% to 50% compared with bare soils) on wind-erosion-prone summer fallow can reduce fine particulate (PM-10) concentrations to allowable levels during dust storms.

## **VII. NEEDS FOR RESEARCH**

Research needs for dryland crop production regions of the western United States include the following:

### **1. Stubble Management**

! Develop management methods for handling large quantities of winter wheat stubble in

intermediate and high precipitation areas without heavy tillage or burning. This includes low-impact tillage to facilitate planting as well as development of no-till drills that can pass through high residue loads on steep slopes and maintain accurate placement of seed and fertilizer.

! Determine why straw of various wheat cultivars decomposes at different rates, and ultimately breed cultivars having fast and slow decomposing straw for high and low precipitation areas, respectively.

### **2. Cultivar breeding**

! Continue and expand breeding efforts to develop high-yielding crop cultivars that can resist or tolerate fungal diseases occurring across a multitude of dryland environments. This is especially important for winter and spring cereal crops dominant in all dryland production regions of the western United States. A rotation crop that could break the *Rhizoctonia* root rot disease cycle in low-disturbance no-till systems would be particularly valuable.

! Develop standard height and tall winter wheat cultivars able to emerge from deep planting depths and low moisture conditions in summer-fallowed soils in low precipitation areas. Successful early fall establishment of winter wheat is critical for optimum grain yield and high straw production.

! Continued development of high-yielding spring wheat cultivars, including facultative spring wheat, which have vigorous early growth in cool soils to compete against broadleaf weeds.

! Develop perennial wheat cultivars that can provide an economically viable grain yield for 4 or more years before replanting is needed. Perennial wheat may be especially useful for shallow, rocky, or other soils of low inherent productivity or for soils prone to erosion.

! Field testing of new crops for more intensive and diverse crop rotations. This is important in all regions, and especially critical in wheat-summer fallow areas where few suitable non-cereal crops have yet been identified.

### 3. Reduced- and No-Till Systems

! In all cropping regions, develop economically viable and environmentally friendly cropping systems adaptable to reduced- and no-till technology.

! Refine low-impact tillage methods to reduce frozen soil water runoff and erosion from planted winter wheat fields.

! Characterize soil changes in quality and productivity associated with long-term no-till management.

### 4. Weed Control and Ecology

! Develop herbicides having different modes of action to control annual grass weeds such as downy brome, wild oats, and jointed goatgrass in cereal crops and to avoid the development of herbicide resistance in these persistent weed species.

! Conduct weed ecology studies for applying IPM (integrated pest management) concepts and principles for controlling weeds in reduced- and no-till systems.

### 5. Economics

! Develop management strategies to minimize economic impacts during the “transition period” changing from conventional farming to no-till, including: i) change in soil and weed ecology, ii) agronomic factors affecting crop yields, iii) equipment costs, and iv) extension of technical information on new farming techniques.

! Up-to-date economic analysis and farm enterprise budgets for new crops and cropping systems.

### 6. Precision Agriculture

! Develop and refine precision agriculture technology for variable landscapes to allow for more effective and economical use of fertilizer, herbicide, seed, and other inputs.

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### REFERENCES

- Allan, R.E. 1980. Influence of semidwarfism and genetic background on stand establishment of wheat. *Crop Sci.* 20:634-638.
- Appleby, A.P., and L.A. Morrow. 1990. The Pacific Northwest. p. 200-232. *In* W.W. Donald (ed.) *Systems of Weed Control in North America*. WSSA Monogr. 6. Weed Sci. Soc. Am., Champaign, IL.
- Boling, M., B. Frazier, and A. Busacca. 1998. General soil map, Washington. 1:750,000. Dept. of Crop and Soil Sciences, Washington State Univ., Pullman, WA.
- Bolton, F.E. 1983. Cropping practices: Pacific Northwest. p. 419-426. *In* H.E. Dregne and W.O. Willis (eds.) *Dryland Agriculture*. Agron. Monogr. 23. ASA, CSSA, and SSSA, Madison, WI.
- Bruehl, G.W. 1968. Ecology of *Cephalosporium* stripe disease of winter wheat in Washington. *Plant Dis. Reporter* 58:590-594.
- Bruehl, G.W., W.L. Nelson, F. Koehler, and O.A. Vogel. 1968. Experiments with *Cercospora* foot rot (strawbreaker) disease of winter wheat. *Wash. Agric. Exp. Stn. Bull.* 694, Pullman, WA.
- Busacca, A. J. 1989. Long Quaternary record in eastern Washington, U.S.A. interpreted from multiple buried paleosols in loess. *Geoderma* 45:105-122.

- Busacca, A. J. 1991. Loess deposits and soils of the Palouse and vicinity. p. 216-228. *In* Baker, V.R. and others. The Columbia Plateau, Ch. 8, *In* Morrison, R. B. (eds.) Quaternary Non-Glacial Geology of the United States. Geol. Soc. Am. Geology of North America, Vol.K-2.
- Cai, X., S.S. Jones, and T.D. Murray. 1998. Molecular cytogenetic characterization of *Thinopyrum* and wheat-*Thinopyrum* translocated chromosomes in a wheat-*Thinopyhrum* amphiploid. *Chromosome Res.* 6:183-189.
- Chepil, W.S. 1941. Relation of wind erosion to the dry aggregate structure of a soil. *Scientific Agric.* 21:488-507.
- Cook, R. J. and R.I. Papendick. 1972. Influence of water potential of soils and plants on root disease. *Ann. Review Phytopath.* 10:349-372.
- Cook, R.J. 1980. Fusarium foot rot of wheat and its control in the Pacific Northwest. *Plant Dis.* 64:1061-1066.
- Cook, R.J., W.F. Schillinger, and N.W. Christensen. 2002. Rhizoctonia root rot and wheat take-all in diverse direct-seed spring cropping systems. *Can. J. Plant Path.* 24:349-358.
- CTIC. 2001. Conservation Tillage Information Center. Crop residue management statistics. West Lafayette, IN. Web site <<http://www.ctic.purdue.edu>>.
- Daubenmire, R. 1970. Steppe vegetation of Washington. *Wash. Agric. Exp. Stn. Tech. Bull.* 62. Washington State Univ., Pullman, WA. 131 p.
- Donald, W.W. and A.G. Ogg, Jr. 1991. Biology and control of jointed goatgrass (*Aegilops cylindrica*): A review. *Weed Technol.* 5:3-17.
- Donaldson, E. 1996. Crop traits for water stress tolerance. *Am. J. Alternative Agric.* 11:89-94.
- Donaldson, E., W.F. Schillinger, and S.M. Dofing. 2001. Straw production and grain yield relationships in winter wheat. *Crop Sci.* 41:100-106.
- Douglas, C.L., Jr., P.M. Chevalier, B. Klepper, A.G. Ogg, Jr., and P.E. Rasmussen. 1999. Conservation cropping systems and their management. p. 73-95. *In* E.L. Michalson, R.I. Papendick, and J.E. Carlson (eds.) Conservation Farming in the United States: The Methods and Accomplishments of the STEEP Program. CRC Press, Boca Raton, FL.
- Elliott, L.F., D.E. Stott, C.L. Douglas, R.I. Papendick, G.S. Campbell, and H. Collins. 1999. Residue management issues for conservation tillage systems. p. 57-72. *In* E.L. Michalson, R.I. Papendick, and J.E. Carlson (eds.) Conservation Farming in the United States: The Methods and Accomplishments of the STEEP Program. CRC Press, Boca Raton, FL.
- Fiez, T.E., B.C. Miller, and W.L. Pan. 1994. Winter wheat yield and grain protein across landscape positions. *Agron. J.* 86:1026-1032.
- Fryrear, D.W. 1984. Soil ridges—clods and wind erosion. *Trans. ASAE* 27:445-448.
- Guy, S.O. and R.M. Gareau. 1998. Crop rotation, residue durability, and nitrogen fertilizer effects on winter wheat production. *J. Prod. Agric.* 11:457-461.
- Guy, S.O., and D.B. Cox. 2002. Reduced tillage increases residue groundcover in subsequent dry pea and winter wheat crops in the Palouse region of Idaho. *Soil Tillage Res.* 66:69-77.
- Hagedorn, D.J. (ed.). 1984. Compendium of pea diseases. APS Press. St. Paul, MN.
- Halvorson, A.R., F.E. Koehler, W.L. Pan, C.F. Engle, K.J. Morrison, and E.T. Field. 1986. Fertilizer guide: Winter wheat. Washington State Univ. Ext. Bull. 1390, Pullman, WA. 4p
- Hammel, J.E., R.I. Papendick, and G.S. Campbell. 1981. Fallow tillage effects on evaporation and seedzone water content in a dry summer climate. *Soil Sci. Soc. Am. J.* 45:1016-1022.
- Hatfield, J.L. 1983. Cropping practices: Pacific Southwest. p. 427-433. *In* H.W. Dregne and W.O. Willis (eds.) Dryland Agriculture. Agron. Monogr. 23. ASA, CSSA, and SSSA, Madison, WI.
- Holm, L., J. Doll, E. Holm, J. Pancho, and J. Herberger. 1997. *Salsola kali* L. p. 708-721. *In* World Weeds: Natural Histories and Distribution. John Wiley & Sons, New York.
- Horner, G.M., A.G. McCall, and F.G. Bell. 1944. Investigations in erosion control and reclamation of eroded land at the Palouse Conserv. Exp. Stn., Pullman, WA, 1931-42. *Tech. Bull. No. 860*, USDA, Washington, DC.
- Horning, L.B., L.D. Stetler, and K.E. Saxton. 1998. Surface residue and soil roughness for wind erosion protection. *Trans. ASAE* 41:1061-1065.

- Idaho Agricultural Statistics Service. 2000. Idaho agricultural statistics. Idaho Dept. of Agric., Boise, ID.
- Inglis, D. A., and R. J. Cook. 1986. The persistence of chlamydospores of *Fusarium culmorum* in wheat-field soils of eastern Washington. *Phytopathology* 76:1205-1208.
- Janosky, J.S., D.L. Young, and W.F. Schillinger. 2002. Economics of conservation tillage in a wheat-fallow rotation. *Agron. J.* 94:527-531.
- Kennedy, A.C. 1998. The rhizosphere and spermosphere. p. 389-407. *In* D.M. Sylvia, J.J. Fuhrman, R.G. Hartel, and D.A. Zuberer (eds.). *Principles and Applications of Soil Microbiology*. Prentice-Hall, NJ.
- Klepper, B., P.E. Rasmussen, and R.W. Rickman. 1983. Fertilizer placement for cereal root access. *J. Soil Water Conserv.* 38:250-252.
- Koehler, F.E., V.L. Cochran, and P.E. Rasmussen. 1987. Fertilizer placement for nutrient flow and crop response in conservation tillage. p. 57-65. *In* L.F. Elliott (ed.) *STEEP-Conservation Concepts and Accomplishments*. Washington State Univ. Publ., Pullman, WA.
- Leggett, G.E. 1959. Relationships between wheat yield, available moisture and nitrogen in eastern Washington dryland areas. *Wash. Agr. Exp. Stn. Bull.* 609:1-16, Pullman, WA.
- Leggett, G.E., R.E. Ramig, L.C. Johnson, and T.W. Massee. 1974. Summer fallow in the Northwest. p. 110-135. *In* *Summer Fallow in the United States*. USDA-ARS, Washington, DC.
- Lindstrom, M.J., F.E. Koehler, and R.I. Papendick. 1974. Tillage effects on fallow water storage in the eastern Washington dryland region. *Agron. J.* 66:312-316.
- Luebs, R.E. 1983. Water conservation: Pacific Southwest. p. 125-136. *In* H.E. Dregne and W.O. Willis (eds.) *Dryland Agriculture*. Agron. Monogr. 23. ASA, CSSA, and SSSA, Madison, WI.
- Mahler, R.L., and R.E. McDole. 1987. The relationship of soil pH and crop yield in northern Idaho. *Univ. of Idaho Current Info. Ser. No. 811*, Moscow, ID.
- Mahler, R.L. and S.O. Guy. 1998. Northern Idaho fertilizer guide: Spring wheat. *Univ. of Idaho Current Info. Ser. No. 921*, Moscow, ID. 8 p.
- Massee, T.W. and F.H. Siddoway. 1970. Summer fallow soil water losses on intermountain dryland and its effect on cropping winter wheat. *Agron J.* 62:722-725.
- Massee T., and H. McKay. 1979. Improving dryland wheat production in eastern Idaho with tillage and cropping methods. *Univ. of Idaho Agric. Exp. Stn. Bull.* 581, Moscow, ID.
- McCall, M.A. 1925. The soil mulch in the absorption and retention of moisture. *J. Agric. Res.* 30:819-831.
- McCool, D.K. 1990. Crop management effects on runoff and soil loss from thawing soil. p.171-176. *In* K.R. Cooley (ed.) *Proc. Intl. Symp. Frozen Soil Impacts on Agricultural, Range, and Forest Lands*, Spokane, WA, 21-23 March. CRREL Special Rpt. 90-1. US Army Corps of Engineers, Cold Regions Res. and Eng. Lab., Hanover, NH.
- Miller, R.P., M.J. Singer, and D.R. Nielsen. 1988. Spatial variability of wheat yield and soil properties on complex hills. *Soil Sci. Soc. Am. J.* 52:1133-1141.
- Montana Agricultural Statistics Service. 2000. Montana agricultural statistics. Montana Dept. of Agric., Helena, MT.
- Naffziger, L.M., and G.M. Horner. 1958. Effect of cropping and tillage practices on runoff and erosion in the Palouse area of Washington and Idaho. *Trans. ASAE* 1:34-35.
- NRCS. 2001. NRCS-USDA, Washington, DC. Web site <<http://www.nhq.nrcs.usda.gov/>>.
- Ogg, A.J., Jr. 1993. Control of downy brome (*Bromus tectorum*) and volunteer wheat (*Triticum aestivum*) in fallow with tillage and promamide. *Weed Technol.* 7:686-692.
- Ogg, A.G., Jr., R.W. Smiley, K.S. Pike, J.P. McCaffrey, D.C. Thill, and S.S. Quisenberry. 1999. Integrated pest management for conservation systems. p. 97-127. *In* E.L. Michalson, R.I. Papendick, and J.E. Carlson (eds.) *Conservation Farming in the United States—The Methods and Accomplishments of the STEEP Program*. CRC Press, Boca Raton, FL.

- Pan, W.L., and A.G. Hopkins, Jr. 1991. Plant development and N and P use in winter barley: I. Evidence of water stress induced P deficiency in an eroded toposequence. *Plant & Soil* 135:9-19.
- Papendick, R.I. 1996. Farming systems and conservation needs in the northwest wheat region. *Am. J. Alternative Agric.* 11:52-57.
- Papendick, R.I. (ed.). 1998. Farming with the wind: Best management practices for controlling wind erosion and air quality on Columbia Plateau croplands. Washington State Univ. College of Agric. and Home Econ. Misc. 0208, Pullman, WA.
- Papendick, R.I., M.J. Lindstrom, and V.L. Cochran. 1973. Soil mulch effects on seedbed temperature and water during fallow in eastern Washington. *Soil Sci. Soc. Am. Proc.* 37:307-314.
- Papendick, R.I., D.K. McCool, and H.A. Krauss. 1983. Soil conservation: Pacific Northwest. p.273-290. *In* H.E. Dregne and W.O. Willis (eds.) *Dryland Agriculture*. Agron. Monogr. 23. ASA, CSSA, and SSSA, Madison, WI.
- Papendick, R.I., and D.K. McCool. 1994. Residue management strategies: Pacific Northwest. p.14. *In* J.L. Hatfield and B.A. Stewart (eds.) *Crop Residue Management*. Lewis Publishers, Boca Raton, FL.
- Papendick, R.I., F.L. Young, K.S. Pike, and R.J. Cook. 1995. Description of the region. *In* R.I. Papendick and W.C. Moldenhauer (eds.) *Crop Residue Management to Reduce Erosion and Improve Soil Quality: Northwest*. CRR-40. USDA-ARS, Washington, DC.
- Payne, W.A., P.E. Rasmussen, C. Chen, R. Goller, and R.E. Ramig. 2000. Precipitation, temperature, and tillage effects upon productivity of a winter wheat-dry pea rotation. *Agron. J.* 92:933-937.
- Pikul, J.L., Jr., J.F. Zuzel, and D.E. Wilkins. 1992. Infiltration into frozen soil as affected by ripping. *Trans. ASAE* 35:83-90.
- Ramig, R.E., R.R. Allmaras, and R.I. Papendick. 1983. Water conservation: Pacific Northwest. p.105-124. *In* H.E. Dregne and W.O. Willis (eds.) *Dryland Agriculture*. Agron. Monogr. 23. ASA, CSSA, and SSSA, Madison, WI.
- Rasmussen, P.E. 1996. Fertility management in dryland conservation cropping systems of the Pacific Northwest. *Am. J. Alternative Agric.* 11:108-114.
- Rasmussen, P.E. and R.R. Allmaras. 1986. Sulfur fertilization effects on winter wheat yield and extractable sulfur in semiarid soils. *Agron. J.* 78:421-425.
- Rasmussen, P.E., H.P. Collins, and R.W. Smiley. 1989. Long-term management effects on soil productivity and crop yield in semi-arid regions of eastern Oregon. *Stn. Bull.* 675. USDA-ARS and Oregon State Univ. Agric. Exp. Stn., Corvallis, OR.
- Rasmussen, P.E., C.L. Douglas, Jr., H.P. Collins, and S.L. Albrecht. 1998. Long-term cropping system effects on mineralizable nitrogen in soil. *Soil Biol. Biochem.* 30:1829-1837.
- Rasmussen, P.E., and C.L. Douglas, Jr. 1992. The influence of tillage and cropping-intensity on cereal response to nitrogen, sulfur, and phosphorus. *Fert. Res.* 31:15-19.
- Roget, D.K., S.M. Neate, and A.D. Rovira. 1996. The effect of sowing point design and tillage practice on the incidence of rhizoctonia root rot, take-all, and cereal cyst nematode. *Aust. J. Exp. Agric.* 36:683-693.
- Saxton, K., D. Chandler, L. Stetler, B. Lamb, C. Claiborn, and B.-H. Lee. 2000. Wind erosion and fugitive dust fluxes on agricultural lands in the Pacific Northwest. *Trans. ASAE* 43:623-630.
- Schillinger, W.F., and F.E. Bolton. 1993. Fallow water storage in tilled vs. untilled soils in the Pacific Northwest. *J. Prod. Agric.* 6:267-269.
- Schillinger, W.F., and R.I. Papendick. 1997. Tillage mulch depth effects during fallow on wheat production and wind erosion control factors. *Soil Sci. Soc. Am. J.* 61:871-876.
- Schillinger, W.F., E. Donaldson, R.E. Allan, and S.S. Jones. 1998. Winter wheat seedling emergence from deep sowing depths. *Agron. J.* 90:582-586.
- Schillinger, W.F. 2001. Minimum and delayed conservation tillage for wheat-fallow farming. *Soil Sci. Soc. Am. J.* 65:1203-1209.

- Smiley, R.W., A.G. Ogg, Jr., and R.J. Cook. 1992. Influence of glyphosate on severity of rhizoctonia root rot and growth and yield of barley. *Plant Dis.* 76:937-942.
- Smiley, R.W. 1996. Diseases of wheat and barley in conservation cropping systems of the semiarid Pacific Northwest. *Am. J. Alternative Agric.* 11:95-103.
- Smith, E.G. and D.L. Young. 2000. Requiem for summer fallow. *Choices* 1:24-25.
- Smith, J.L., and L.F. Elliott. 1990. Tillage and residue management effects on soil organic matter dynamics in semiarid regions. p. 69-88. *In* R.P. Singh et al. (eds.) *Dryland Agriculture: Strategies for Sustainability*. *Advances in Soil Sci.*, Vol. 13. Springer-Verlag, New York.
- Smith, V.T., L.C. Wheeting, and S.C. VanDecaveye. 1946. Effects of organic residues and nitrogen fertilizers on a semiarid soil. *Soil Sci.* 61:393-410.
- Soil Survey Staff. 1999. *Soil Taxonomy*. 2nd Ed. Agriculture Handbook 436. USDA-NRCS. U.S. Gov. Printing Office, Washington, DC. 869 p.
- USDA. 1978. Palouse cooperative river basin study. SCS; Forest Service; and Economics, Statistics, and Cooperative Extension Service. USDA. U.S. Gov. Printing Office, Washington, DC.
- USDA. 1999. Census of agriculture. California state and county data. National Agricultural Statistics Service. USDA, Washington, DC.
- USDA-FSA. 2000. The conservation reserve program 20th signup. USDA - Farm Service Agency, Washington, DC.
- Utah Agricultural Statistics Service. 2000. *Utah agricultural statistics*. Utah Dept. of Agriculture, Salt Lake City, UT.
- Weller, D.M., R.J. Cook, G. MacNish, E.N. Bassett, R.L. Powelson, and R.R. Petersen. 1986. Rhizoctonia bare patch of small grain favored by reduced tillage in the Pacific Northwest. *Plant Dis.* 70:70-73.
- Wiese, M.V. 1987. *Compendium of wheat diseases*. 2nd ed. Amer. Phytopathological Soc., St. Paul, MN.
- Wilkins, D.E. 1996. Tillage, seeding and fertilizer application technologies. *Am. J. Alternative Agric.* 11:83-88.
- Wuest, S.B., S.L. Albrecht, and K.W. Skirvin. 2000. Crop residue position and interference with wheat seedling development. *Soil Tillage Res.* 55:175-182.
- Young, D.L., H.R. Hinman, and W.F. Schillinger. 2001. Economics of winter wheat - summer fallow vs. continuous no-till spring wheat in the Horse Heaven Hills, Washington. Washington State Univ. Ext. Bull. 1907, Pullman, WA. 35 p.
- Young, F.L. 1988. Effect of Russian thistle (*Salsola iberica*) interference on spring wheat (*Triticum aestivum*). *Weed Sci.* 36:594-598.
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