PRECISION NITROGEN MANAGEMENT: EVALUATING AND CREATING MANAGEMENT ZONES USING WINTER WHEAT PERFORMANCE

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of STEPHEN EDMOND TAYLOR find it satisfactory and recommend that it be accepted.

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PRECISION NITROGEN MANAGEMENT: EVALUATING AND CREATING MANAGEMENT ZONES USING WINTER WHEAT PERFORMANCE

Abstract

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Globally, around 60% of synthesized N is applied to cereal crops. In these cereal systems, nitrogen use efficiency (NUE) is approximately 33%. In other words, approximately one-third of applied N is recovered in harvested grain, leaving two-thirds of applied N for subsequent crops or as potential gaseous plant emissions, denitrification, surface runoff, volatilization, and leaching. Poor NUE represents not only a financial loss to the grower, but an environmental threat contributing to N_2O emissions and degradation of surface and ground waters through leached NO_3^-. Current fertilizer recommendation for the Inland Pacific Northwest region of the United States are based on uniform, whole-field applications that result in large variability in crop N use across field landscapes. Precision N management has been proposed as a solution to decrease negative environmental and economic impacts of variable crop N use and low NUE in cereal production systems.

Creating site-specific management zones (SSMZ) is a common method to generate prescription maps for variable N fertilizer applications. Areas of the field with similar attributes (e.g. soil properties, fertility, terrain) are grouped and treated as sub-field sections or SSMZ. Prescription fertilizer application maps are created based on SSMZ that estimate crop performance and the associated N fertilizer requirements, and then variable rate (VR) technologies are used to apply site-specific N fertilizer. This method of precision N management has had varying success in improving crop NUE and economic performance.

The objective of chapter 1 in this thesis is to evaluate site-specific wheat performance under VR and uniform N applications using yield, protein, NUE, and NUE components as performance criteria. The goal is to determine if current practices adequately improve crop performance with regards, not only to yield and protein, but to N fertilizer use efficiencies. The objective of chapter 2 is to evaluate the performance of rainfed, winter wheat among field divisions created using: 1) typical methods of SSMZ delineation; and 2) performance classifications derived from NUE and NUE components. These objectives could inform science-based evaluation and decision-support systems for precision N management that are based on easily measureable crop performance data.

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER 1

CHAPTER 2

LIST OF FIGURES

CHAPTER 1

APPENDIX A

Dedication

This thesis is dedicated to Morgan, Max, and Reese, of course.

Chapter 1

Evaluation of Variable Rate Nitrogen Application in Dryland Winter Wheat

Abstract

Site-specific or precision nitrogen (N) management has been proposed as a solution to decrease negative environmental and economic impacts of variable crop N use and low nitrogen use efficiencies (NUE) in cereal production systems. The current research objective is to evaluate site-specific wheat performance under variable rate (VR) and uniform N applications using yield, protein, NUE, and NUE components as performance criteria. The goal is to determine if current practices adequately improve dryland soft white winter wheat (SWWW) performance with regards not only to yield and protein, but to N fertilizer use efficiencies.

Sub-field management zones were created for three field sites in the inland Pacific Northwest Palouse region using yield and electrical conductivity (EC_a) data, a method that reflected current grower practices. Uniform and variable N fertilizer rates were applied in strips across all three sites. Paired points were established for each N fertilizer treatment. Performance criteria were calculated at all points and pairwise comparisons made to establish differences in crop performance under varying amounts of applied N fertilizer. Significant differences in NUE, N uptake efficiency, and N utilization efficiency ranged from 0% to increases of over 30%, 17%, and 25%, respectively. Spatial variability in grain protein response to N, and increases of 10 g kg^{-1} were observed as N fertilizer increased. Grain yield response to N fertilizer was small and significant differences were only observed between points that received starter fertilizer (19 kg N ha^{-1}) only and points receiving applied rates of 100 kg N ha^{-1}.

Varying N rates at these sites was most effective in areas of the field that were defined as low yielding zones. Decreasing N fertilizer application decreased potential N losses and money spent without taking yield penalties. Increasing N rates in zones defined as high yielding did not improve yield and decreased NUE, thereby increasing the potential for N losses and decreasing financial profits. By using a method of evaluation that takes into account fertilizer use efficiencies, it becomes possible to observe areas where VR fertilizer decisions need to be improved to meet performance goals beyond yield and protein.

Introduction

Globally, around 60% of synthesized N is applied to cereal crops (Ladha et al., 2005). In these cereal systems, nitrogen use efficiency (NUE) is approximately 33%. In other words, approximately one-third of applied N is recovered in harvested grain, leaving two-thirds of applied N for subsequent crops or as potential gaseous plant emissions, denitrification, surface runoff, volatilization, and leaching (Raun and Johnson, 1999). Poor NUE represents not only a financial loss to the grower, but an environmental threat contributing to N_2O emissions (Mosier et al., 1996) and degradation of surface and ground waters through leached NO_3^- (Huggins et al., 2001). Current fertilizer recommendation for the Inland Pacific Northwest (IPNW) region of the United States are based on uniform, whole-field applications (Koenig, 2013) that result in large variability in crop N use across field landscapes (Fiez et al., 1995).

Precision N management has been proposed as a solution to decrease negative environmental and economic impacts of variable crop N use and low NUE in cereal production systems. However, farmer implementation has remained low (McBratney et al., 2005). Creating site-specific management zones (SSMZ's) is a common method to generate prescription maps for N fertilizer applications. Areas of the field with similar attributes (e.g. soil properties, fertility, terrain) are grouped and treated as sub-field sections (Khosla et al., 2002; Fridgen et al., 2004). Prescription N fertilizer application maps are created based on SSMZ's that estimate crop performance and associated N fertilizer requirements. Variable rate (VR) technologies are then used to apply site-specific N fertilizer.

Methods to delineate management zones vary, but typically include collecting and integrating terrain layers such as elevation and slope (Long et al., 2015), apparent electrical conductivity (EC_a) data (Moral et al., 2010), historical yield data (Hornung et al., 2003), remotely sensed data (Mulla, 2013), and farmer's knowledge of field variability (Fleming et al., 2000). Using these data layers in combination to divide the field into management zones is usually accomplished with a combination of principle components analysis (PCA) and a fuzzy means clustering statistical analysis to find the optimal number and location of clusters or "zones." The optimal number and location of clusters is determined and evaluated using various cluster validation indices (Li et al., 2007; Vitharana et al., 2008; Zhang et al., 2010).

The use of SSMZ's has had varying success in improving crop NUE and economic performance. Huggins (2010) reported no yield or protein difference between VR and uniform application in some areas of the field, while other areas had higher yield in locations receiving variable rate applications (VRA) when compared to uniform applications. No economic analysis was performed, however areas that received less N but had higher yields would likely have higher economic returns, while areas with higher yields and higher N rates would require further analyses to determine economic returns. In an economic analysis, the cost of precision agriculture (PA) technology would also need to be considered for a complete idea of the value of

VRA. Long et al. (2015) reported no difference in grain protein and yield in VRA treatments compared to uniform application. Their economic analysis also reported no economic gain from VRA in their water-limited grain systems of northern Montana. Link et al. (2008) also reported no difference in yield between uniform and VRA, but did observe improvements in NUE with VRA. Improvements varied across landscape positions and overall, about 53% of site-specifically managed grids showed higher NUE while no economic improvement was observed (Link et al., 2008). Raun et al. (2002) observed NUE increases >15% in VRA wheat compared to uniform treatment and reported some increases in overall revenue from VRA (Raun et al., 2002).

Differences in results from VRA are likely due, in part, to differing methods of SSMZ delineation. The current research objective is to evaluate site-specific wheat performance under variable rate and uniform N applications using yield, protein, NUE, and NUE components (Huggins and Pan, 1993) as performance criteria. The goal is to determine if current practices adequately improve crop performance with regards, not only to yield and protein, but to N fertilizer use efficiencies.

Research Design and Methodology

Study Sites

Three different field sites in the dryland cropping systems of Eastern Washington were used for the research. The first site was 8.9 ha of a 43.5 ha on-farm field located northeast of Walla Walla, Walla Walla County, WA (-118.27702, 46.16650). The region is characterized by a Mediterranean-like climate with a mean annual temperature of 12.1°C, and an average annual precipitation of 474 mm (1981-2010 Normal data), the majority of which comes between September and April (Western Regional Climate Center, 2016). Loess deposits form the dominant soils having silt loam textures. This field consisted entirely of Walla Walla silt loam soil series (Coarse-silty, mixed, superactive, mesic Typic Haploxeroll) (Soil Survey Staff, 2014b).

The second and third sites were both located at Washington State University's Wilke Research and Extension Farm near Davenport, Lincoln County, WA. The fields used were plot 2 (-118.12260, 47.65350) and plot 6 (-118.12994, 47.65340) which are 10.5 ha and 12.0 ha plots, respectively. This region is also characterized by a Mediterranean-like climate with a mean annual temperature of 7.4°C, and an average annual precipitation of 353 mm (1981-2010 Normal data), the majority of which comes between September and April (Western Regional Climate Center, 2016). Loess deposits also form the dominant soils here with both plot 2 and plot 6 consisting of the soil series: Broadax silt loam with 7-25% slopes (fine-silty, mixed, superactive, mesic Calcic Argixerolls), Hanning silt loam with 0-7% slopes (fine-silty, mixed, superactive, mesic Pachic Argixerolls), and Mondovi silt loam (coarse-silty, mixed, superactive, mesic Cumulic Haploxerolls) soils (Soil Survey Staff, 2014a).

A summary of the weather data for harvest year 2015 is given in Table 1 with a comparison to normal weather summaries. Weather data was taken from the Western Regional Climate Center database (Western Regional Climate Center, 2016).

Creation of Management Zones

The creation of management zones was performed using simple methods that reflect common grower practices. Prescription maps for the Wilke plots were created using grain yield monitor data (1 year), NRCS web soil survey data, and spring soil EC_a data at 75 and 150 cm depths. Soil EC_a data was obtained from an electro-magnetic induction (EMI) field survey performed using a Geonics EM38-MK2 sensor (EM38-MK2, Geonics Limited, Ontario, Canada). Correlations between data layers were observed visually and it was found that negative correlations existed between soil EC_a and yield. These correlations matched well with soil series data from the NRCS web soil survey. Three management zones were created with different yield goals (high, medium, and low) using the visually observed correlations (Figure 1b).

At the Walla Walla site, no grain yield monitor data was available and the field was one continuous soil series. Soil EC_a data was collected in the fall of 2014 and spring of 2015. Regression kriging was used to create a yield map from hand-harvested points that received what was the uniform N rate in the remainder of the field outside the experimental plot. Management zones were created post-harvest so that the performance of different N rates within those zones could be analyzed and compared. Interpolated yield and spring EC_a data layers at 75 cm and 150 cm depths were created at breaks within, above, and below one standard deviation of the field means. The patterns were visually compared for correlations. High, medium, and low yielding zones were identified based on the standard deviation breaks. In this field there was a negative correlation between EC_a and yield. Using these standard deviation breaks, it was found that mean yield differences by zone were close to 673 kg ha^{-1} (10 bu ac^{-1}) (Appendix A, Figure 1). This led to the conclusion that the zones were capturing yield differences to a degree that would be significant to a grower (Figure 1a).

Agronomic Practices and Experimental Designs

At the Walla Walla site, anhydrous ammonia (AA) was deep-banded in the fall of 2014 using an Exactrix variable rate applicator. Applicator width was 4.57 m (15ft) with 30-cm disk spacing. There were 5 uniform rates (0, 40, 80, 110, 150 kg ha^{-1}) of N applied the length of the study area in a repeated, randomized block design. This experimental layout allowed for sampling that could capture crop response to differing N treatments at a spatial scale of 4.57-m (Figure 2). The field was seeded 4 days later in paired rows on 30-cm centers using a Yielder no-till drill. Starter fertilizer was applied with the seed equal to 19 kg N ha^{-1}. Thus, with starter fertilizer finishing the fertilizer treatment, total N rates were 19 (control), 60, 100, 130, and 170 kg N ha^{-1} (Table 2). Coverage maps from applicator showed target rates were not always met. However, a summary of actual total applied N is given in Table 2.

At both Wilke plot 2 and plot 6, starter fertilizer was placed with the seed as liquid ammonium polyphosphate (APP) and ammonium thiosulfate (ATS) at a rate of 10 kg ha^{-1}. Anhydrous ammonia (AA) was banded below the seed at the time of seeding using a Case IH direct-seed hoe drill. Variable rates of N were applied according to yield goals for each management zone. In plot 2, high yielding zones received a total of 125 kg N ha^{-1}, medium zones received 100 kg N ha^{-1}, and low yielding zones received 75 kg N ha^{-1} including N applied with starter. In plot 6, high yielding zones received a total of 100 kg N ha^{-1}, medium zones received 75 kg N ha^{-1}, and low yielding zones received 35 kg N ha^{-1} including N applied with starter. Strips across each plot were seeded and fertilized using uniform N rates that reflected field average yield goals and were the same as medium yielding zones (Figure 2). These strips served as comparison points for the VRA paired t-tests. A summary of the agronomic practices for each field site is given in Table 3.

Data Collection

A Simple Sequential Inhibition process was used in R (R version 3.2.2, 2015) to optimized sampling for geostatistical analysis at the Walla Walla site. Eighty-five locations were randomly identified within the study area that provided good coverage and allowed for low kriging error near the edges. At each of the 85 locations, additional points were added so that the 5 N rates were represented for a total of 425 sampling locations. Additional points were also added for each treatment to allow for geostatistical analysis at shorter lag distances. The total number of sampling locations came to 501, however agronomic factors (i.e. double-seeded areas or applied fertilizer errors) decreased that amount to 463 points with harvest data (Figure 2).

At the Wilke plots 2 and 6, sampling locations were chosen that represented each zone, and a paired point was selected within the uniform application strips. In plot 2, 5 pairs were created in the high yielding zones, 7 pairs were created in medium yielding zones, and 7 pairs created in the low yielding zones. In plot 6, 6 pairs were created in the high yielding zones, 5 in the medium yielding zones, and 3 in the low yielding zones (Figure 2).

Yield was measured at all sites by hand harvesting 1-m^2 areas at crop maturity. Harvested grain was bagged, dried, threshed using a stationary thresher, and then weighed to obtain yield measurements. Grain protein, test weight, and moisture data was obtained using near infrared reflectance (Infratec 1241 Grain Analyzer, FOSS, Denmark). Aboveground biomass samples were obtained at all Wilke sampling locations and at 72 locations in Walla Walla field where soil samples were also taken. This facilitated direct measurements of total plant N, and nitrogen harvest index (NHI). At the Walla Walla site, NHI was linearly related to grain N ($R^2 = 0.9358$) so total plant N could be predicted at sample locations where biomass was unmeasured. Total aboveground biomass was weighed and grain weight subtracted to get total aboveground residue biomass. Residue subsamples were ground to pass through a 1-mm sieve (Wiley Mill) and analyzed for total N by dry combustion (Elemental Combustion System, costech, Italy).

Soil samples were taken at all field sites in the: (i) fall of 2014 prior to planting; (ii) spring of 2015; and (iii) the fall of 2015 following harvest. At the Walla Walla site, soil augers with inside diameters of 7.5-cm were used to collect soil cores in 30 cm increments to 150 cm depth. Soil cores were mixed and subsamples for each 30 cm increment were taken for analysis, transported on ice and stored at 4°C until processing. A giddings probe (4-cm inside diameter) was used for both plots at the Wilke site. Soil samples were analyzed for gravimetric water by oven drying samples at 105°C for 48 hours. Soil inorganic N concentration (NH_4^+ and NO_3^{2-}) was determined using 1*M* KCl extraction procedure with inorganic N analysis performed on a continuous flow analyzer (Maynard et al., 2008). The extraction was done by adding 25 mLs of 1*M* KCl to 6 g of soil and shaking for 1 hour. The supernatant was filtered through an 8μm filter (Fisherbrand P8) and filtrate frozen until analysis on an automated spectrophotometer (AlpKem RFA-300, Austoria-Pacific International, Oregon, U.S.A.). Total N and C were determined using dry combustion (Elemental Combustion System, costech, Italy).

Analysis and Calculations

Wheat performance was evaluated using yield, protein, NUE, and NUE components (Huggins and Pan, 2003). Yield and protein were measured as mentioned above. NUE and components were determined using grain yield (G_w), grain N (N_g), aboveground plant N (N_t), N mineralization (N_{min}), applied N (N_f), and pre- and post-harvest root zone inorganic N. Grain N was calculated using protein measurements and the assumption of 5.7% N in grain protein (Koenig, 2013). Total above-ground plant N (N_t) was calculated using aboveground biomass weights and total N concentrations in the residue. Net N mineralization (N_{min}) was calculated using 1% total N in the top 30 cm of pre-plant soil samples and bulk density values from NRCS soil survey data for the corresponding soil series (Soil Survey Staff, 2014a; b). This N_{min} calculation is a derivation of the reported findings that 19 kg N ha^{-1} is mineralized for every 1% organic matter (OM) in the top 30 cm (Koenig, 2013). N supply (N_s) was estimated from a sum of pre-plant residual N (N_r), calculated N_{min} and N fertilizer application rate (N_f) for the Wilke plots (Equation 1). At Walla Walla, N_s was estimated from control points (19 kg ha^{-1} applied N) assuming 70% uptake efficiency (N_t N_s^{-1}) and adding N_f (Equation 2) (Brown, 2015). Calculations and abbreviations for NUE and NUE components are summarized in Table 4, which is adapted from previous work (Huggins and Pan, 1993; Dawson et al., 2008).

Nitrogen Supply, $N_s = N_r + N_{min} + N_f$ [Equation 1]

Nitrogen Supply, $N_s = (N_{t(control)} – N_{starter}) / 0.7) + N_f$ [Equation 2]

The estimation of N mineralization for the Wilke sites assumes that N fertilizer additions do not impact net N mineralization. In addition, for these sites, depositional N (N_d) and biologically fixed N were considered minimal and not included in the estimates of N_s. It is also unlikely, because of the low annual precipitation that much if any of the residual N leached out of the root zone.

Student's paired t-tests were performed using the *stats* package in R (R version 3.2.2, 2015). Analysis of variance (anova) was also performed for all groups at the Walla Walla site to observe treatment effects for each management zone. Analysis of variance allowed for a comparison of crop response to each N rate within low, medium, and high yielding zones at the Walla Walla field site (Table 7). R packages *stats* and *agricolae* were used to create the anova model and then perform a Tukey's pairwise comparison, respectively (R version 3.2.2, 2015; *agricolae* package version 1.2-3).

Finally, an examination of potential N savings was done by calculating total applied N for each management zone in all field sites. Total applied N was calculated using uniform rates, variable rates that were applied for these harvest years, and ideal rates from post-harvest paired-t and anova tests. Respective rates were multiplied by the total ha for each zone, and values summed to find total applied N for each field and treatment (Table 8). Ideal rates were used that maximized yield while optimizing protein and NUE components for each zone in all sites.

Results and Discussion

Grain Yield and Protein Concentrations

Lowering the N rate from uniform rates for each field in low yielding zones, as defined by our delineation, did not decrease yield at either Wilke or Walla Walla field sites (Table 5). At Wilke plot 6, lowering the N rate actually increased yield by 1,290 kg ha^{-1}, which was an increase of more than 40%. In this plot, the low yielding zones under uniform N management were the lowest yielding areas (3113 kg ha^{-1}), however lowering the N rate increased grain yield to the same level as the remainder of the field (about 4400 kg ha^{-1}).

In medium yielding zones at the Wilke site, there were no yield differences, which is an expected outcome as uniform and variable rates were essentially the same in these zones. At the Walla Walla field, when control points (19 kg N ha^{-1}) were compared to uniform rates (100 kg N ha^{-1}) in medium zones, grain yield decreased by 555 kg ha^{-1} (9%) with only using starter fertilizer (control), and grain protein decreased by 14 g kg^{-1} (15%) (Table 5).

For Wilke and Walla Walla sites, areas of the field defined as high yielding, no grain yield differences were observed from increasing N rate above uniform applications (Table 5). At Wilke plot 6, yields tended to be greater with VRT, but not quite at the 0.95 confidence level At the Walla Walla site, the highest N rate did increase grain protein levels by 10 g kg^{-1} (9.5%) when compared to uniform applications. Grain protein differences were not observed between uniform and higher, variable rates in high yielding zones for either Wilke plot 2 or 6.

Based on grain yield and protein data, uniform application led to over-applied N in low yielding zones at the Wilke and Walla Walla sites. This result is consistent with other research that found no yield and protein difference when applied nitrogen was decreased in areas of the field designated as “low yielding” (Huggins, 2010; Long et al., 2015).

Increasing applied N in high yielding zones, as we have defined them, was not advantageous with respect to yield or protein. In fact, it may be a disadvantage if grain protein is elevated to a degree that would results in discounts for soft white winter wheat (SWWW). In the 2015 harvest year, SWWW with protein levels below 105 g kg^{-1} received a +$0.05 price premium (“Northwest Grain Growers,” 2016). This suggests economic advantages for keeping lower N rates in high yielding zones as protein levels were unchanged in Wilke plots and increased in the Walla Walla plot, though increased mean grain protein concentrations still did not exceed 105 g kg^{-1} for this season. Protein concentrations across all zones at both Wilke plots were higher than the 2015 premium concentration of 105 g kg^{-1}, likely because the hot and dry weather led to water scarcity during grain fill, implying that all N rates were too high for both Wilke sites this harvest year. Overall, N rate could be lowered in low zones across all sites, and kept at uniform rate in high zones across all three field sites (Table 5).

N Use Efficiency Components

With regards to NUE and NUE components, at the Wilke plots, differences were only observed in low yielding zones (Table 6). In Wilke plot 2, NUE ranged from 12.1 kg grain kg^{-1} N supply (N_s) in low zones with VRA to 20.9 kg grain kg^{-1} N_s in medium zones with uniform rate. N uptake efficiency ranged from 0.41 kg total aboveground N (N_t) kg^{-1} N_s in low zones to 0.64 kg N_t kg^{-1} N_s in medium zones. Only N utilization efficiency was significantly different, and only in low zones. Interestingly, N utilization efficiency was higher at uniform rates than the lower, variable N rate, increasing from 29.0 kg grain kg^{-1} N_t with VRA in low zones and 35.2 kg grain kg^{-1} N_t in low zones with uniform rates.

In Wilke plot 6, N balance index increased by over 200% with a lower N rate compared to the uniform N rate in low yielding zones (Table 6). No significant treatment effects were observed for NUE, N_t/N_s or G_w/N_t for Wilke plot 6. Here, NUE ranged from 14.6 to 22.9 kg grain kg^{-1} N; N uptake efficiencies from 0.38 to 0.63 kg N_t kg^{-1} N_s; and N utilization efficiencies from 32.4 to 43.3 kg grain kg^{-1} N_t.

N efficiency components for both Wilke sites were generally low when compared to the Walla Walla site and other reported values for soft-white winter wheat (SWWW) in the literature. NUE values around 20.0 kg grain kg^{-1} N_s are common if high rates of N are applied, but are usually closer to 30-40 kg grain kg^{-1} N_s in more efficient areas of a field (Huggins and Pan, 1993; Fiez et al., 1995; Brown, 2015). Wilke NUE values from 12.1 to 22.9 kg grain kg^{-1} N_s and protein concentrations above 112 g kg^{-1} across all zones suggest that both plots have soil factors that lead to low crop N use and N fertilizer is likely over-applied. The hot, dry weather for this harvest year was likely a large contributing factor to these observations as well (Table 1). Interestingly, N uptake efficiencies were below 0.50 kg N_t kg^{-1} N_s in both Wilke plot low zones, but higher than 0.50 kg N_t kg^{-1} N_s in all other zones. Low zones in these fields are typically rocky, with shallow rooting depths. N fertilizer may be leaching through the rooting zone and unavailable to crops even at lower N rates applied with VRA, or crop N demand was low due to water restraints in shallow rooting zone areas in this study.

At the Walla Walla site generally, all efficiency measurements were higher than at the Wilke sites (Table 6). Typical reported NUE values for SWWW are between 20-40 kg grain kg^{-1} N_s in uniformly applied fields (Sowers et al., 1994; Huggins and Pan, 2003). NUE observations were generally at the higher end of that range, implying that soil N use was comparatively efficient for this site. In the low yielding zones that were defined, NUE increased by 15% over uniform application (100 kg N/ha) with a VRA of 60 kg N ha^{-1} and by 47% with only starter applied N (19 kg N ha^{-1}). No increase was observed in the N utilization efficiency when the VR was lowered to 60 kg N ha^{-1}, but when uniform rates were compared to the control it increased by 34%. Significant increases were also observed in N balance index (1.04 to 3.79 kg N_g kg^{-1} N_f) and N harvest index (0.80 to 0.83 kg grain N kg^{-1} N_t) for both the lower VR (60 kg N ha^{-1}) and the control (19 kg N ha^{-1}) when compared to uniform rates (100 kg N ha^{-1}) in low zones.

In the medium yielding zones we defined at the Walla Walla site, when the uniform rate was compared to the starter N rate (19 kg N ha^{-1}), NUE and all NUE components significantly increased (Table 6). NUE increased from 29.3 kg grain kg^{-1} N with uniform application to 48.5 kg grain kg^{-1} N at starter N points. N utilization efficiency increased from 51.2 to 60.7 kg grain kg^{-1} N_t when uniform rates were compared to starter N. Because N_s was calculated based on 70% uptake efficiency assumption (Brown, 2015) in control points, N uptake efficiency for areas receiving only starter fertilizer were implicitly 0.70 kg N_t kg^{-1} N_s. This was significantly different than the 0.58 kg N_t kg^{-1} N_s utilization efficiency observed in medium zones using the uniform rate. N balance index and N harvest index also increased from 1.01 to 4.11 kg N_g kg^{-1} N_f and 0.80 to 0.82 kg grain N kg^{-1} N_t, in comparing the uniform N rate with the control, respectively.

In high yielding zones at the Walla Walla site, uniform rates outperformed VRA in all variables excepting N utilization efficiency, where no differences were observed (Table 6). NUE increased from 24.3 kg grain kg^{-1} N_s at highest N rate (170 kg N ha^{-1}) to 27.3 kg grain kg^{-1} N_s at the next highest rate (130 kg N ha^{-1}) to 33.0 kg grain kg^{-1} N_s at the uniform rate. N uptake efficiency decreased by 17% from uniform application at the highest rate, and by 13% from uniform rate to the next highest N rate. N utilization efficiency did not increase from uniform application to the next highest rate, however, when compared to the highest VR (170 kg N ha^{-1}), it increased by 12%.

Since no yield penalty was observed by lowering the N rate in low zones, the starter fertilizer combined with residual soil N may have been sufficient to meet crop N needs this season. However, high variability in the yield (1126 kg ha^{-1}); low (82 g kg^{-1}) protein levels; and high N efficiencies for starter N rates suggest that more N was needed than just starter N. In the medium yielding zones, although all NUE and NUE components increased by lowering the N rate to only the starter fertilizer, there was a yield penalty of 555 kg ha^{-1}. This may indicate that a lower N rate (as in 60 kg N ha^{-1}) may have been sufficient to meet crop N needs in these zones without suffering a yield penalty. There was no yield or NUE advantage to increasing N rate in the Walla Walla high yielding zones beyond the uniform rate. Overall, residual N from previous crops and N mineralization provided sufficient N to meet most needs of the crop.

The anova test for the Walla Walla site showed that, in low yielding zones, while yields ranged from 5441 to 5847 kg ha^{-1}, significant yield differences between treatments were not observed at the α=0.95 level (Table 7). Grain protein concentration increased from 82 g kg^{-1} with control N rates to 123 g kg^{-1} at the highest applied N rate. All treatments were significantly different except the 100 and 130 kg N ha^{-1} rates. As expected, NUE and NUE components all decreased with increasing applied N. NUE ranged from 43.8 to 18.7 kg grain kg^{-1} N_s, N uptake efficiency ranged from 0.7 to 0.48 kg N_t kg^{-1} N_s, and N utilization efficiency ranged from 62.5 to 39.7 kg grain kg^{-1} N_t.

In medium yielding zones, maximum yield was reached at uniform N rates. Yields ranged from 5628 kg ha^{-1} at control rates (19 kg N ha^{-1}) to 6216 kg ha^{-1} at uniform rates (100 kg N ha^{-1}) (Table 7). Those two were the only applied N treatments that were significantly different with regards to yield. Protein levels increased with each treatment from 84 g kg^{-1} at lowest N rate to 113 g kg^{-1} at the highest N rate. NUE and NUE components all decreased with increasing rates of applied N. Similar patterns were observed in high yielding zones. Yields ranged from 6001 kg ha^{-1} with the control to 7095 kg ha^{-1} with the highest (170 kg N ha^{-1}) N treatment. However yields reached a maximum at uniform rates (Table 7). In high yielding zones, protein significantly increased with almost every N treatment, and all NUE and NUE components decreased with increasing applied N. It is also interesting to note that the highest grain protein concentration in high yielding zones was 105 g kg^{-1} at the highest applied N rate (170 kg N ha^{-1}), while low and medium yielding zones reached concentrations of 123 and 113 g kg^{-1}, respectively.

These data suggest that, in low yielding zones, residual and starter fertilizer was sufficient to meet crop N needs with regards to yield. However, it is likely that the next higher rate of 60 kg N ha^{-1} would have led to overall higher yields, and less yield variability compared to the control rates. This is based on the 98 g kg^{-1} grain protein levels observed with the 60 kg N ha^{-1} treatment. When yield is graphed on the y-axis and protein on the x-axis, it is possible to observe protein levels that were associated with maximum yield (Figure 3).

The yield and protein plot (Figure 3) indicated that maximum yields in medium zones was reached at approximately 100 g kg^{-1}. Thus, in the medium yielding zone uniform rates were more than sufficient and led to maximum yields. However, uniform rates did lower N efficiency components significantly, increasing the potential for greater N losses. High yielding zones had maximum yields with the uniform rate of N and most N efficiency measurements were significantly different than higher N rates. The low grain protein concentration (87 g kg^{-1}) at the lower, 60 kg N ha^{-1} rate suggest uniform rates were preferable in high yielding zones, as we have defined them, from the perspective of yield, grain protein, and N efficiency measurements (Table 7). Box plots with data points overlaid and pairwise comparison grouping for zones and treatments are given in Appendix A, Figure 2.

For the Walla Walla site, when the relationship between yield and NUE; yield and N utilization efficiency; and yield and N uptake efficiency without control points set at 0.70 kg N_t kg^{-1} N_s was graphed on a scatter plot with quadratic models fit to the data (Figure 3) it was observed that, across all zones, maximum yield was reached at an NUE value of around 35 kg grain kg^{-1} N_s, an N uptake efficiency values of 0.8 kg N_t kg^{-1} N_s , and an N utilization efficiency value of 50 kg grain kg^{-1} N_t (Figure 3). There is a lot of variability associated with these data however, the modeled values may help inform target efficiency values for future management decisions to maximize yield, NUE, and NUE components.

Potential N Savings

By calculating total applied N based on the hectare size of each zone within the field sites, we were able to quantify the total N savings possible through variable rate application (Table 8). Wilke plot 2 (10.5 ha) only decreased total applied N from uniform rates by 45 kg N, but if ideal rates had been applied for each zone it could have been closer to 100 kg N. Wilke plot 6 (12.0 ha) saved only 10 kg N through the applied variable rates, but if ideal rates had been applied 123 kg N could have been saved. At Wilke sites, greater field variability is likely needed to warrant investments in VR technologies. At the Walla Walla site (8.9 ha), VR N application actually increased total N applied by 5 kg N, but if ideal rates had been applied, total N savings would have been 279 kg N from uniform application. When calculated on an amount per unit area basis, ideal N fertilizer application based on these data could have saved approximately 30 kg N ha^{-1} at the Walla Walla site and approximately 10 kg N ha^{-1} at both Wilke sites, though for the Wilke sites all zones were still over-applied and more N savings were possible for this harvest year.

This analysis took into account the respective sizes of the management zones that we defined (Table 8). If the management zones did not represent large portions of the field, then N savings from variable rate application would likely be minimized and perhaps not worth the investment in VR technologies. No economic analysis was performed, but other studies have shown little to no economic improvement from VR application in dryland wheat systems (Long et al., 2015). These data show that the economic gain from varying N application comes by decreasing N rates in low yielding zones, rather than increasing N rates and thereby increasing yields in higher yielding zones. The extent of spatial variability, therefore, should be taken into account when considering VR technology investments.

Conclusions

Evaluation of crop performance using NUE and NUE components in tandem with yield and protein measurements allows an in-depth look at the response of soft-white winter wheat to variable rate N application. By using a method of evaluation that takes into account fertilizer use efficiencies, it becomes simple to see areas where VRA needs to be improved to meet performance goals beyond yield and protein. Varying N rates for Wilke plots 2 and 6, and an on-farm field site near Walla Walla was most effective in areas of the field that were defined as low yielding areas. Through decreasing N fertilizer application, potential N losses can be decreased, as well as money saved without taking yield penalties in these areas. A decrease in potential N losses is evidenced by 16% increase of NUE, as well as increases in N uptake efficiencies with lower rates of N fertilizer application. These values are similar to other reported values in cereal grain systems (Raun et al., 2002; Huggins and Pan, 2003). In these data, increases were not observed across all sites that received variable N application using the management zones we created. Increasing N rates in zones defined as high yielding did not improve yield and decreased NUE, thereby increasing the potential for N losses and decreasing financial profits.

Examining the relationships between yield and NUE components facilitated target values that were associated with maximum yields across different management zones (Figure 3). Target values could be used in aiding N fertilizer application decisions if relationships to other, easily measurable crop performance parameters are found (e.g. grain yield and protein). Much of the current management zone delineation is targeted towards charactering spatial variability in wheat yield (Link et al., 2008). Based on these data, the improvements needed in VRA involve the efficient use of N fertilizer. The evaluation of management zone performance is an area where much work is needed as the current state is largely focused on evaluating the spatial variability in yield without other crop performance measures. If yield, protein, NUE and other N efficiency components are measured and combined in an integrative way, then site-specific management decisions could help farmers make goals with regards to the fertilizer use as well as yield and protein, and then evaluate those decisions using the same tools.

In short, there is more research needed to develop site-specific management techniques that integrate fertilizer use efficiencies with yield and protein measurements, and then evaluate those site-specific management decisions using appropriate performance criteria. By including N use efficiency measurements in decision-support systems, more informed decisions can be made that allow farmer to target performance goals that include NUE and NUE components.

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Tables

Table 1. Annual normal temperature and precipitation data compared to harvest year weather data.

	Field	
	Walla Walla	**Wilke Plots 2 & 6**
Annual Normal Precip (mm)†	474	353
Sept 2014 - Aug 2015 Precip (mm)	375	297
	--	--
Annual Normal Temp (°C)†	12.1	7.4
2015 Mean Annual Temp (°C)	14.05	8.6

†Annual normal precipitation and temperature data is from NCDC 1981-2010 monthly Normal data

Table 2. Target and actual total applied N (kg ha^{-1}).

Field	Treatment	Target Applied N	Mean of Total Applied N	St Dev	CV	# Points	Range Low	Range High
Walla Walla		(kg ha^{-1})	(kg ha^{-1})		(%)		(kg ha^{-1})	(kg ha^{-1})
	(Control) 1	19.1	19.1	--		100	--	--
	2	60	59.9	2.0	3.3	95	53.1	67.5
	3	100	97.2	2.1	2.2	91	86.9	101.1
	4	130	133.4	4.5	3.3	94	116.6	145.9
	5	170	170.0	6.2	3.6	83	148.2	190.5

Table 3. Summary of agronomic practices for each field site.

Site	Harvest Year	Crop†	Previous Crop	Variety	Seeding Date	Seeding Rate	N Rate w/ Seed‡	N Rate below seed‡	Seeding Drill
						(kg ha^{-1})	(kg ha^{-1})	(kg ha^{-1})	
Walla Walla	2015	SWWW	Spring Peas	528/Ovation	10/7/2014	118	19	Variable	Yielder
Wilke Plots 2 & 6	2015	SWWW	Fallow	Crescent (club)	9/10/2014	78	10	Variable	Case IH direct-seed hoe

†Both field sites were planted to soft-white winter wheat (SWWW) in the fall of 2014.

‡Starter fertilizer applied with the seed was a combination of liquid ammonium polyphosphate solution (APP) and ammonium thiosulfate (ATS) fertilizer at both sites. Variable rates of N fertilizer were applied, according to prescribed treatments, below the seed and were done using anydrous ammonia (AA) for all locations.

Table 4. Summary of nitrogen use efficiency terminology†.

G_w = grain yield
N_g = grain N
N_r = pre-plant residual N
N_{min} = N mineralization from soil organic matter
N_{ph} = post-harvest residual N
N_f = N fertilizer applied
N_s = N supply = $N_r + N_{min} + N_f$, or, $N_{t(control)}/0.7 + N_f$
N_t = aboveground N in plant at physiological maturity
G_w/N_s = Nitrogen Use Efficienty (NUE)
N_t/N_s = N uptake efficiency
G_w/N_t = N utilization efficiency
N_g/N_f = N balance index
N_g/N_t = N harvest index

† Table adapted from Huggins and Pan, 1993

Table 5. Grain yield (Gw) and protein comparison of variable rate applied (VRA) and uniform N rates at three field sites using paired t-tests.

Field	Zone (ha)†	Treatment	N Rate	*Sample Means (StDev)* Yield	Protein	n
Wilke Plot 2			(kg ha^{-1})	(kg ha^{-1})	(g kg^{-1})	
	Low	VRA	75	2633 (923)	138 (14)	7
	(3.29)	Uniform	102	3341 (1089)	130 (23)	--
		p-value	--	*0.1649*	*0.1131*	--
	Medium	VRA	100	4179 (1159)	128 (17)	7
	(4.85)	Uniform	102	4261 (1187)	136 (12)	--
		p-value	--	0.9043	0.09476*	--
	High	VRA	125	3984 (927)	132 (13)	5
	(2.33)	Uniform	102	4274 (1510)	125 (19)	--
		p-value	--	*0.7275*	*0.4244*	--
Wilke Plot 6						
	Low	VRA	35	4403 (451)	112 (24)	3
	(2.71)	Uniform	77	3113 (320)	112 (9)	--
		p-value	--	*0.03127***	*0.9877*	--
	Medium	VRA	75	5050 (1636)	134 (14)	5
	(4.49)	Uniform	77	4458 (718)	122 (33)	--
		p-value	--	*0.4541*	*0.2271*	--
	High	VRA	100	5588 (1138)	126 (16)	6
	(4.84)	Uniform	77	4663 (1378)	129 (10)	--
		p-value	--	*0.1083*	*0.4227*	--
Walla Walla						
	Low	VRA	19	5405 (1126)	82 (9)	11
	(1.36)	Uniform	100	5872 (969)	107 (19)	--
		p-value	--	*0.3227*	*0.00026***	--
	Low	VRA	60	5651 (767)	97 (13)	11
	(1.36)	Uniform	100	6004 (897)	104 (17)	--
		p-value	--	*0.1441*	*0.1498*	--
	Medium	VRA	100	--	--	--
	(5.62)	Control	19	5670 (782)	84 (11)	49
		Uniform	100	6225 (777)	98 (11)	--
		p-value	--	*<0.0001***	*<0.0001***	--
	High	VRA	130	6895 (799)	97 (9)	14
	(1.97)	Uniform	100	7073 (856)	94 (12)	--
		p-value	--	*0.5015*	*0.2835*	--
	High	VRA	170	7089 (945)	105 (12)	12
	(1.97)	Uniform	100	7135 (614)	95 (12)	--
		p-value	--	*0.8950*	*0.03219***	--

*Sample means were significantly different at the α=0.90 confidence level using pairwise t-test

**Sample means were significantly different at the α=0.95 confidence level using pairwise t-test

† Total hectares of each zone for the field are given beneath in parenthesis

Table 6. NUE (Gw/Ns), N uptake efficiency (Nt/Ns), N utilization efficiency (Gw/Nt), and N balance index (Ng/Nf) comparisons by zone using pairwise t-tests at three field sites.

Field	Zone (ha)†	Treatment	N Rate	Sample Means (StDev)					
				G_w/N_s	N_t/N_s	G_w/N_t	N_g/N_f	N_g/N_t	n
Wilke Plot 2			(kg ha^{-1})						
	Low	VRA	75	12.1 (4.4)	0.41 (0.11)	29.0 (4.7)	0.81 (0.28)	0.67 (0.07)	7
	(3.29)	Uniform	102	15.1 (4.0)	0.44 (0.11)	35.2 (7.5)	0.71 (0.25)	0.75 (0.06)	--
		p-value	--	*0.328*	*0.746*	*0.04223***	*0.566*	*0.05476**	--
	Medium	VRA	100	17.0 (6.6)	0.51 (0.17)	33.6 (7.0)	0.90 (0.24)	0.71 (0.06)	7
	(4.85)	Uniform	102	20.9 (6.6)	0.64 (0.15)	32.1 (4.9)	0.95 (0.23)	0.73 (0.07)	--
		p-value	--	*0.316*	*0.238*	*0.492*	*0.722*	*0.298*	--
	High	VRA	125	16.6 (3.1)	0.48 (0.10)	35.2 (4.7)	0.70 (0.13)	0.77 (0.05)	5
	(2.33)	Uniform	102	20.0 (7.7)	0.58 (0.26)	36.6 (6.9)	0.91 (0.38)	0.75 (0.06)	--
		p-value	--	*0.286*	*0.228*	*0.702*	*0.221*	*0.660*	--
Wilke Plot 6									
	Low	VRA	35	20.6 (5.4)	0.48 (0.043)	43.3 (11.3)	2.34 (0.33)	0.78 (0.044)*	3
	(2.71)	Uniform	77	14.6 (4.8)	0.38 (0.12)	38.7 (1.7)	0.76 (0.12)	0.72 (0.03)*	--
		p-value	--	*0.188*	*0.195*	*0.303*	*0.01253***	*0.071*	--
	Medium	VRA	75	18.9 (7.5)	0.57 (0.12)	32.4 (6.9)	1.85 (0.89)	0.72 (0.09)	5
	(4.49)	Uniform	77	20.3 (5.0)	0.54 (0.12)	39.7 (15.9)	1.19 (0.39)	0.74 (0.09)	--
		p-value	--	*0.544*	*0.803*	*0.195*	*0.124*	*0.438*	--
	High	VRA	100	21.1 (3.6)	0.55 (0.053)	38.3 (6.1)	1.23 (0.23)	0.80 (0.05)	6
	(4.84)	Uniform	77	22.9 (7.7)	0.63 (0.218)	36.7 (3.9)	1.31 (0.41)	0.79 (0.05)	--
		p-value	--	*0.626*	*0.477*	*0.284*	*0.640*	*0.565*	--
Walla Walla									
	Low	VRA	19	43.9 (5.5)	0.7 (0.0)	62.7 (7.8)	3.79 (0.91)	0.83 (0.02)	11
	(1.36)	Uniform	100	29.9 (8.6)	0.63 (0.12)	46.9 (8.3)	1.04 (0.16)	0.80 (0.01)	--
		p-value	--	*<0.0001***	*0.04181***	*<0.0001***	*<0.0001***	*0.0006761***	--
	Low	VRA	60	35.4 (9.7)	0.70 (0.29)	52.2 (7.6)	1.47 (0.32)	0.81 (0.01)	11
	(1.36)	Uniform	100	30.8 (8.4)	0.64 (0.12)	48.0 (7.6)	1.04 (0.17)	0.80 (0.01)	--
		p-value	--	*0.001438***	*0.1850*	*0.1240*	*0.001291***	*0.05502**	--
	Medium	VRA	100	--	--	--	--	--	--
	(5.62)	Control	19	48.5 (5.5)	0.7 (0.0)	60.7 (7.9)	4.11 (0.89)	0.82 (0.02)	49
		Uniform	100	29.3 (5.1)	0.58 (0.10)	51.2 (6.2)	1.01 (0.18)	0.80 (0.01)	--
		p-value	--	*<0.0001***	*<0.0001***	*<0.0001***	*<0.0001***	*<0.0001***	--
	High	VRA	130	27.3 (4.3)	0.54 (0.08)	51.1 (4.6)	0.81 (0.10)	0.80 (0.01)	14
	(1.97)	Uniform	100	33.0 (6.1)	0.62 (0.13)	53.6 (7.2)	1.11 (0.19)	0.81 (0.02)	--
		p-value	--	*0.0005235***	*0.01278***	*0.1388*	*<0.0001***	*0.0261***	--
	High	VRA	170	24.3 (3.8)	0.52 (0.08)	46.9 (5.6)	0.71 (0.08)	0.79 (0.02)	12
	(1.97)	Uniform	100	33.0 (6.4)	0.63 (0.13)	52.5 (6.8)	1.13 (0.14)	0.80 (0.01)	--
		p-value	--	*0.0004937***	*0.0149***	*0.04893***	*<0.0001***	*0.3071*	--

*Sample means were significantly different at the α=0.90 confidence level using pairwise t-test

**Sample means were significantly different at the α=0.95 confidence level using pairwise t-test

† Total hectares of each zone for the field are given beneath in parenthesis

Table 7. Means for NUE and NUE components with ANOVA by N treatment within each management zone.

Field	Zone (ha)†	N Rate	Sample Means‡ Gw	Protein	G_w/N_s	N_t/N_s	G_w/N_t	N_g/N_f	N_g/N_t
Walla Walla		(kg ha-^{1})	(kg ha-^{1})	(g kg^{-1})					
	Low								
	(1.36)	19	5441 a	82 c	43.8 a	0.70 a	62.5 a	3.81 a	0.82 a
		60	5604 a	98 b	35.1 b	0.70 a	51.5 b	1.47 b	0.81 ab
		100	5857 a	108 ab	30.1 b	0.64 ab	46.6 bc	1.05 bc	0.80 ab
		130	5495 a	111 ab	23.0 c	0.52 bc	44.5 bc	0.76 bc	0.80 ab
		170	5070 a	123 a	18.7 c	0.48 c	39.7 c	0.60 c	0.78 b
		P(>F)	*0.3*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
	Medium								
	(5.62)	19	5628 b	84 d	42.6 a	0.70 a	60.8 a	4.07 a	0.82 a
		60	5863 ab	88 d	34.2 b	0.60 b	57.6 a	1.40 b	0.81 ab
		100	6216 a	97 c	29.4 c	0.58 b	51.2 b	1.02 bc	0.80 bc
		130	6032 ab	105 b	24.4 d	0.52 c	47.4 c	0.77 c	0.80 c
		170	5885 ab	113 a	20.6 e	0.47 c	44.0 c	0.63 c	0.80 c
		P(>F)	*0.0435*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
	High								
	(1.97)	19	6001 b	84 d	43.2 a	0.70 a	61.8 a	4.29 a	0.82 a
		60	6555 ab	87 cd	37.2 b	0.65 ab	58.1 ab	1.57 b	0.81 ab
		100	6998 a	94 bc	32.0 c	0.61 bc	53.0 bc	1.11 bc	0.81 ab
		130	6720 ab	98 ab	27.0 d	0.53 c	50.9 cd	0.80 bc	0.80 b
		170	7095 a	105 a	25.3 d	0.54 c	46.8 d	0.71 c	0.79 b
		P(>F)	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*

† Total hectares of each zone for the field are given beneath in parenthesis.

‡Yield (Gw); Protein; N Use Efficiency (Gw/Ns); N utilization efficiency (Gw/Nt); N uptake efficiency (Nt/Ns); N Balance Index (Ng/Nf); N Harvest index (Ng/Nt). Within columns, means followed by the same letter are not significantly different at the 0.95 confidence level using Tukey pairwise comparison.

Table 8. Comparison of total applied N for different treatments using size of MZ (ha) and summed for each field.

Field	Treatment	Low Zone Applied N	Medium Zone Applied N	High Zone Applied N	Total Applied N
Wilke Plot 2†		(kg N)	(kg N)	(kg N)	(kg N)
(10.5 ha)	**Uniform**	336	495	238	1068
	Variable	247	485	291	1023
	Ideal††	247	485	238	970
Wilke Plot 6‡					
(12.0 ha)	**Uniform**	209	346	373	927
	Variable	95	337	484	916
	Ideal	95	337	373	804
Walla Walla§					
(8.9 ha)	**Uniform**	136	562	197	895
	Variable	82	562	256	900
	Ideal	82	337	197	616

†Wilke plot 2 low, medium, and high zone represented 3.29, 4.85, and 2.33 ha, respectively. Uniform rate was 102 kg N ha^{-1} for the entire plot. Variable rates were 75, 100, and 125 kg N ha^{-1} for low, medium, and high zones respectively.

‡Wilke plot 6 low, medium, and high zones represented 2.71, 4.49, and 4.84 ha, respectively. Uniform rate was 77 kg N ha^{-1}. Variable rates were 35, 75, and 100 kg N ha^{-1} for low, medium, and high zones, respectively.

§Walla Walla site low medium, and high zones represented 1.36, 5.62, and 1.97 ha, respectively. Uniform rate was 100 kg N ha^{-1}. Variable rates were 60, 100, and 130 kg N ha^{-1}, respectively.

††Ideal treatments were based on post-harvest paired-t and anova tests. They were: for Wilke plot 2; 75, 100, 100 kg N ha^{-1} for low, medium, and high zones, respectively; for Wilke plot 6; 35,75,75 kg N ha^{-1} for low, medium, and high zones, respectively; and for Walla Walla; 60,60, 100 kg N ha^{-1} for low, medium, and high zones, respectively.

Figures

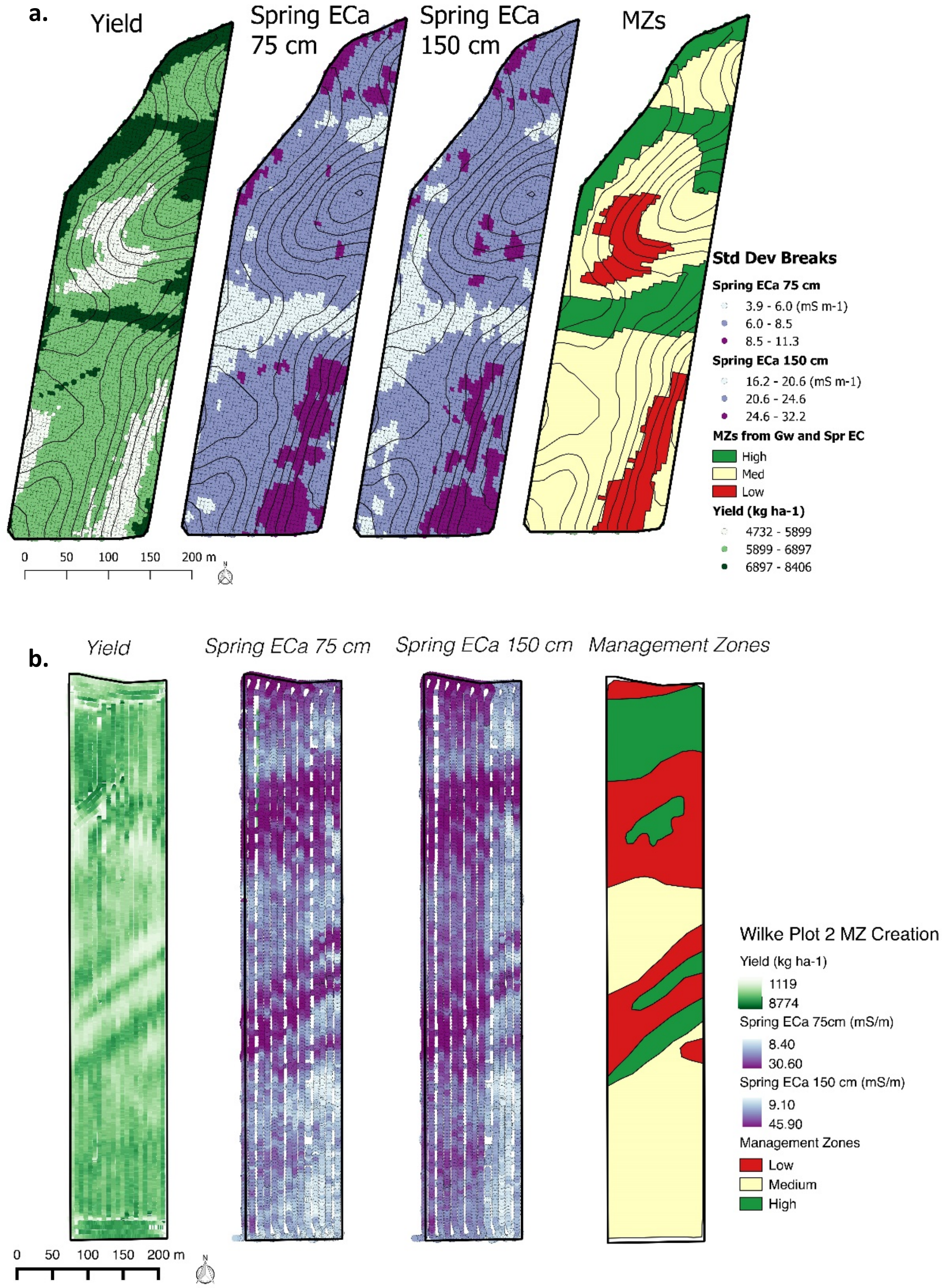

Figure 1. Management zone creation for Walla Walla (a) and Wilke plot 2 (b) sites using yield and spring EC_a data. Wilke plot 6 management zones were created using the same process as Wilke plot 2 shown above.

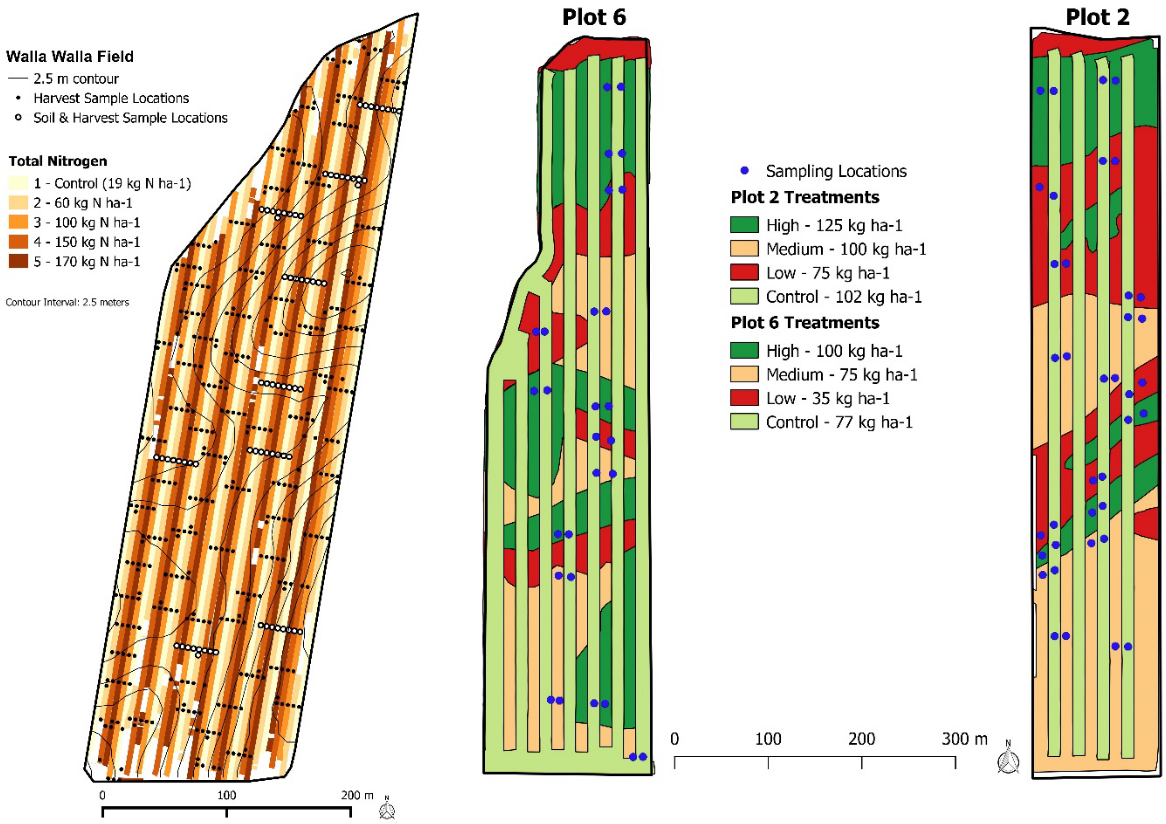

Figure 2. Experimental design and sampling locations for Walla Walla site and Wilke plots 2 and 6.

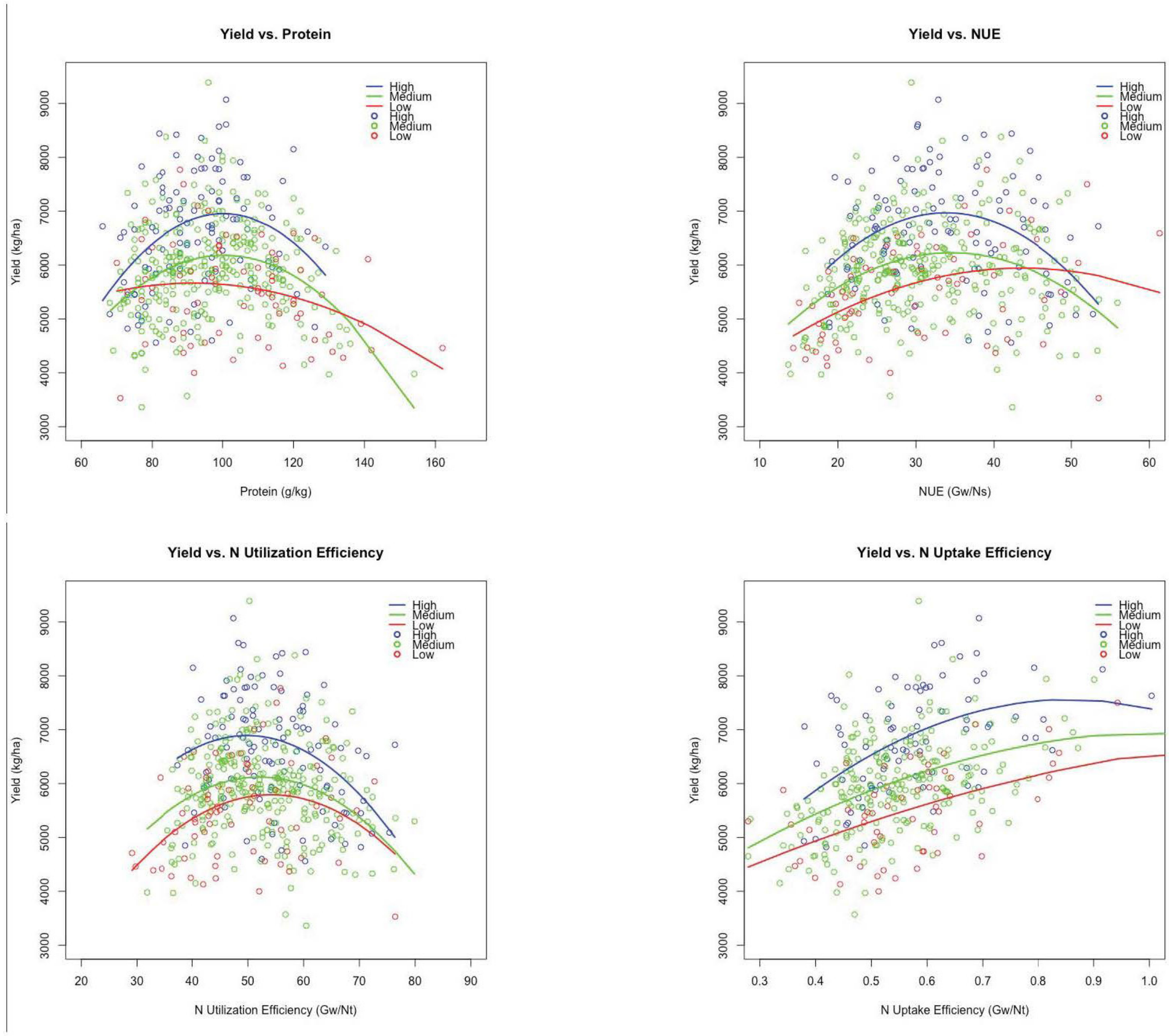

Figure 3. Yield (kg ha^{-1}) plotted with grain protein (g kg^{-1}); N use efficiency (NUE) (G_w N_s^{-1}); N utilization efficiency (G_w N_t^{-1}); and N uptake efficiency (N_t N_s^{-1}). Quadratic models are fitted to high, medium, and low, yielding data to approximate protein, NUE, and NUE component values that were associated with maximum yields.

CHAPTER 2

Management Zone Delineation Based on NUE Performance: a Decision-Support and Evaluation System for Precision N Applications

Abstract

Creating site-specific management zones (SSMZ) is a common method to generate prescription maps for nitrogen (N) fertilizer applications in site-specific or precision agriculture systems. The use of SSMZs has had varying success in improving crop nitrogen use efficiency (NUE) and economic performance. The current research objective is to evaluate the performance of rainfed, soft white winter wheat (SWWW) among field divisions created using: 1) typical principle components analysis (PCA) and fuzzy clustering of terrain and soil apparent electrical conductivity (EC_a) data; and 2) divisions based on performance classifications derived from NUE and NUE components. The overall research goals are to: 1) determine if current practices of MZ delineation adequately represent spatial differences in crop performance; and 2) develop a method of MZ delineation that is based solely on easily measurable components of crop performance.

Terrain and EC_a were obtained for two field sites in the inland Pacific Northwest Palouse region. PCA and fuzzy means clustering were used to divide the fields into clusters or zones. Grain yield, protein, and other performance criteria were measured and calculated at grouped points receiving variable rates of N fertilizer. Performance classification criteria were created that reflected crop performance goals regarding maximum yield and N uptake efficiency. Groups were classified based on 4 performance criteria to identify areas of the field that performed similarly. Different N rates were then analyzed for MZs created using clustering and

performance classification criteria. Results of the clustering analysis and performance zone classification only captured significant differences between zones at one of the two sites. At the site where differences between zones were significant, grain protein ranged from 82 g kg^{-1} to 116 g kg^{-1} and NUE increased by 81% to 118% from highest N rate to the lowest across all zones. Performance class zones captured similar responses to N rates across all performance classes. The development of management zones based on performance criteria provides basis for the creation of management zones and the evaluation of N fertilizer decisions made within those management zones. The advantages to this method are in the management interpretation of performance classes as well as detailed evaluation of VR decisions increasing crop performance with regards to yield and protein as well as NUE and NUE component measurements.

Introduction

Spatial and temporal variation of crop nitrogen (N) use in the inland Pacific Northwest (IPNW) dryland wheat systems is well documented (Fiez et al., 1995, Huggins et al., 2010a, Huggins et al., 2010b). This is also true in rainfed and irrigated systems around the United States and world. Mamo et al. (2003) found, in a Minnesota rainfed corn system, that only about 50% of the field had a yield response to N and yield averages ranged from 8.1 to 10.9 Mg ha^{-1} across 3 years of data collection. Long and coworkers (1999) found, in a dryland winter wheat system in Montana, yield variability for a single year ranging from 1,285 to 3,591 kg ha^{-1} and protein ranging from 119.5 to 149.1 g kg^{-1}. Reyniers et al. (2006) found yields ranging from about 2,000 to 9,000 kg ha^{-1} in a central Belgium winter wheat system.

Precision N management has been proposed as a solution to decrease the environmental and economic impacts of variable crop performance and low nitrogen use efficiencies (NUE) in cereal production systems (Raun et al., 2002). However, farmer implementation has remained low (McBratney et al., 2005). Creating site-specific management zones (SSMZ's) is a common method to generate prescription maps for N fertilizer applications. Areas of the field with similar attributes (e.g. soil properties, fertility, terrain) are grouped and treated as sub-field sections (Khosla et al., 2002; Fridgen et al., 2004). Prescription fertilizer application maps are created based on SSMZ's that estimate crop performance and associated N fertilizer requirements. Variable rate (VR) technologies are then used to apply site-specific N fertilizer.

The use of SSMZ's has had varying success in improving crop NUE and economic performance. Huggins (2010a) reported no yield or protein difference between VR and uniform application in some areas of the field, while others had higher yield in locations receiving variable rate applications (VRA) when compared to uniform applications. No economic analysis was performed, however areas that received less N but had higher yields would likely have higher economic returns, while areas with higher yields and higher N rates would require further analyses to determine economic returns. In an economic analysis, the cost of precision agriculture (PA) technology would also need to be considered for a complete idea of the values of VRA.

Long et al. (2015) reported no difference in grain protein and yield in VRA treatments compared to uniform application. Their economic analysis also reported no economic gain from VRA in their water-limited grain systems of northern Montana. Link et al. (2008) also reported no difference in yield between uniform and VRA, but did observe improvements in NUE with

VRA. Improvements varied across landscape positions and overall, about 53% of site-specifically managed grids showed higher NUE while no economic improvement was observed. Raun and coworkers (2002) observed NUE increases >15% in VRA wheat compared to uniform treatment and reported some increases in overall revenue from VRA.

Differences in results from VRA are likely due, in part, to differing methods of SSMZ delineation. A complete description of methods used to delineate SSMZ's would be a large undertaking, but they typically include some combination of collecting and integrating terrain layers such as elevation and slope (Long et al., 2015), soil apparent electrical conductivity (EC_a) data (Moral et al., 2010), historical yield data (Hornung et al., 2003; Huggins, 2010a), remotely sensed data (Mulla, 2013), and farmer's knowledge of field variability (Fleming et al., 2000). Using those data layers in combination to divide the field into management zones is usually done with a combination of principle components analysis (PCA) and a fuzzy means clustering statistical analysis to find the optimal number and location of clusters or "zones" that are evaluated using cluster validation indices (Li et al., 2007; Vitharana et al., 2008; Zhang et al., 2010).

Past research on appropriate methods to characterize variability in wheat performance has largely focused on yield as the measure of wheat performance. With the ability to evaluate spatial variability in crop NUE and NUE components (Huggins and Pan, 1993), evaluation of variable rate N management should move beyond yield and protein to assessing the ability of wheat crops to efficiently use fertilizer inputs. Because crop performance is an integration of all soil and landscape properties affecting growth, it is logical to define variability in crop performance by NUE and NUE components. These kinds of analyses may allow for site-specific N recommendations and a more in depth evaluation of fertilizer applications (Fiez et al., 1995).

The current research objective is to evaluate the performance of rainfed, soft white winter wheat (SWWW) among field divisions created using: 1) typical PCA and fuzzy means clustering of terrain and EC_a data; and 2) divisions based on performance classifications derived from NUE and NUE components (Huggins and Pan, 2003). The research goals are to: 1) determine if current practices of MZ delineation adequately represent spatial differences in crop performance; and 2) develop a method of MZ delineation that is based solely on crop performance. This new method will be based on relationships between N fertilizer efficiencies and measurements of grain yield and protein and could provide a science-based decision-support and evaluation system for precision N management that is based on measureable crop performance data.

Research Design and Methodology

Study Site

Two different field sites in the dryland cropping systems of Eastern Washington were used for the research. The first site was 8.9 ha of a 43.5 ha on-farm site located northeast of Walla Walla, WA (-118.27702, 46.16650). The region is characterized by a Mediterranean-like climate with a mean annual temperature of 12.1°C, and an average annual precipitation of 474 mm, the majority of which comes between September and April (Western Regional Climate Center, 2016). Loess deposits form the dominant soils having silt loam textures. This field consisted entirely of Walla Walla silt loam series (Coarse-silty, mixed, superactive, mesic Typic Haploxeroll) (Soil Survey Staff, 2014).

The second site was 4.6 ha of Washington State University's Cook Agronomy Farm (CAF). This field is located northeast of Pullman, WA (-117.07760, 46.78023). Also characterized by a Mediterranean-like climate, the field has a mean annual temperature of 8.7°C, and an average annual precipitation of 517 mm, the majority of which comes between September and April (Western Regional Climate Center, 2016). Loess deposits also form the dominant soils at this site with silt loam textures. This field varied in soil series and included Naff (Fine-silty, mixed, superactive, mesic Typic Argixerolls), Palouse (Fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls), and Thatuna (Fine-silty, mixed, superactive, mesic Oxyaquic Argixerolls) soil series (Soil Survey Staff, 2015).

A summary of weather data for harvests years 2010 at CAF site and harvest year 2015 for Walla Walla site is given in Table 1 with a comparison to normal weather summaries. Weather data was taken from the Western Regional Climate Center database (Western Regional Climate Center, 2016).

Agronomic Practices and Experimental Designs

At the Walla Walla site, anhydrous ammonia (AA) was deep-banded in the fall of 2014 using an Exactrix variable rate applicator. Applicator width was 4.57 m (15ft) with 30-cm disk spacing. There were 5 uniform rates (0, 40, 80, 110, 150 kg ha^{-1}) of N applied the length of the study area in a repeated, randomized block design. This experimental layout allowed for sampling that could capture crop response to differing N treatments at a spatial scale of 4.57 m (Figure 1a). The field was seeded 4 days later in paired rows on 30-cm centers using a Yielder no-till seeding drill. Starter fertilizer was applied with the seed equal to 19 kg N ha^{-1}. Thus, with starter fertilizer finishing the fertilizer treatment, total N rates were 19 (control), 60, 100, 130, and 170 kg N ha^{-1}. Coverage maps from applicator showed target rates were not always met. However, a summary of actual total applied N is given in Table 2.

At the CAF site, grid points were established in 1999 as part of long-term, whole-field network. In the fall of 2009, variable rates were applied in 3 m^2 quadrants around the grid points in 4.6 ha of the field for this study. Soft white winter wheat ('OR102') was planted in paired rows with 30-cm centers using a no-till seeding drill (Horsh-Anderson) equipped with hoe-type openers. Urea ammonium nitrate (32-0-0) fertilizer was applied at four different rates (0, 48, 76, and 104 kg N ha^{-1}) to achieve total N rates, including 9 kg N ha^{-1} of starter fertilizer, of 9 (control), 57, 85, and 113 kg N ha^{-1} (Figure 1b). A summary of the agronomic practices for each field site is given in Table 3.

Data Collection

A Simple Sequential Inhibition process was used in R (R version 3.2.2, 2015) to optimized sampling for geostatistical analysis at the Walla Walla site. 85 locations were randomly identified within the study area that provided good coverage and allowed for low interpolation error near plot edges. At each of the 85 locations, additional points were added so that the 5 N rates were represented for a total of 425 sampling locations. Additional points were also added to allow for geostatistical analysis at shorter lag distances. The total number of sampling locations came to 501, however agronomic factors (e.g. double-seeded areas or applied fertilizer mistakes) decreased that amount to 463 points with harvest data (Figure 1a). The CAF grid points were established in 1999 to allow geostatistical analysis and provided sufficient data to aid the interpolation of plot maps using data collected at quadrants surrounding the grid points.

Yield was measured at the Walla Walla site by hand harvesting 1-m^2 areas at crop maturity. Harvested grain was bagged, dried, threshed using a stationary thresher, and then weighed to obtain yield measurements. Grain protein, test weight, and moisture data was obtained using near infrared reflectance (Infratec 1241 Grain Analyzer, FOSS, Denmark). Aboveground biomass samples were obtained at 72 locations where soil samples were also taken. This facilitated the calculation of total plant N, and nitrogen harvest index (NHI). NHI was linearly related to grain N (R^2 = 0.9358) so total plant N could be predicted at each sample location where biomass was unmeasured. Total aboveground biomass was weighed and grain weight subtracted to get total aboveground residue biomass. Residue subsamples were ground to pass through a 1-mm sieve (Wiley Mill) and analyzed for total N by dry combustion (Elemental Combustion System, costech, Italy).

Soil N and total aboveground biomass data was unavailable for the CAF study, however grain yield, protein, and moisture data was available. These data were used to calculate N balance index defined as grain N (N_g) divided by total N fertilizer applied (N_f). Grain N was calculated using grain protein concentration measurements obtained using near infrared reflectance (Infratec 1241 Grain Analyzer, FOSS, Denmark) and the assumption of 5.7% N in grain protein (Koenig, 2013).The spatial variability in N balance index will be the only performance measurement besides yield and protein used for this site.

A digital elevation model (DEM) of the Walla Walla 8.9-ha plot was created using a survey grade differential global positioning system (DGPS) comprised of a base station and a rover unit (Trimble AgGPS 542 RTK). Elevation data with corresponding Easting and Northing values were collected in the spring of 2015. The projection used was Universal Transverse Mercator (UTM) with World Geodetic Systems (WGS) 1984 zone 11N datum. A central location was selected for the base unit to be placed so that it could remain stationary for 2 hours to calculate its position and facilitate continuous communication with the rover unit. The survey resulted in 5,946 Easting and Northing points with associated elevation data for the 8.9-ha plot. The DEM was then generated using Inverse Distance Weighted (IDW) interpolation to raster cell size of 5-m. Terrain attributes derived from the resulting DEM were slope (degrees), aspect, curvature, plan curvature, and profile curvature (ESRI ArcGIS v. 10.2). Aspect was transformed to trasp = $(1-\cos((\pi/180)(\text{aspect}-30)))/2$.

A kinematic survey of apparent electrical conductivity was obtained from an electro-magnetic induction (EMI) field survey using a Geonics EM38-MK2 sensor (EM38-MK2, Geonics Limited, Ontario, Canada) coupled with a Trimble AgGPS 542 DGPS. The EM38 obtained EC readings at 75-cm and 150-cm depths. EC_a readings were coupled with Easting and Northing locations using HGIS (StarPal 1997) software package. The resulting text files were imported into R statistical software (R version 3.2.2, 2015) for interpolation using a thin plate spline model. The 463 geo-referenced harvest sample data points (Figure 1a) were combined with the terrain attributes calculated from the 5-m raster and EC_a measurements for subsequent statistical analyses. CAF terrain and apparent electrical conductivity (EC_a) data was collected in the fall and spring of 2000. This historical data was used for subsequent MZ creation and data interpolation (Uberuaga, 2010).

Analysis and Calculations

Wheat performance at the Walla Walla site was evaluated using yield, protein, NUE, and NUE components (Huggins and Pan, 2003). Yield and protein were measured as mentioned above. NUE and components were determined using grain yield (G_w), grain N (N_g), aboveground plant N (N_t), N mineralization (N_{min}), applied N (N_f), and pre- and post-harvest root zone inorganic N. Grain N was calculated using protein measurements and the assumption of 5.7% N in grain protein (Koenig, 2013). N_t was calculated using aboveground biomass weights and total N in the residue. At Walla Walla site, N_s was estimated from control points assuming 70% uptake efficiency (N_t N_s^{-1}) and adding N_f (Equation 1) (Brown, 2015). NUE, NUE components, and their calculations are summarized in Table 4, which is adapted from previous work (Huggins and Pan, 1993; Dawson et al., 2008).

As mentioned above, N balance index (N_g N_f^{-1}) will be the only performance index used at the CAF site, coupled with grain yield and protein data. This simple index was related to N uptake efficiencies at the Walla Walla site (Figure 4) and uses data easily obtained from combined-mounted yield monitor and grain protein sensors.

Nitrogen Supply, $N_s = (N_{t(control)} - N_{starter}) / 0.7) + N_f$ [Equation 1]

Spatial Analysis and MZ creation

To create management zones using current-state procedures, terrain and EC_a data were run through a Principle Components Analysis (PCA) and the resulting principle components were clustered using a fuzzy means clustering analysis (R version 3.2.2, 2015; *cluster* package version 2.0.4). This method of management zone delineation has been widely used (Fridgen et al., 2004; Li et al., 2007; Zhang et al., 2010). Silhouette width was used as a measure for the appropriateness of the number of clusters or "zones" chosen (Maechler et al., 2016). Silhouette width is an integrated measure of the dissimilarity within a cluster as well as average dissimilarity between a point and other clusters to which it doesn't belong. Values near 1 are considered well-clustered, and values near -1 are considered poorly-clustered (Rousseeuw, 1987). Sampled data points were overlaid on resulting clusters (Figures 2, 3) and clustering assignments made based on all clustering outcomes.

The first question to be answered with the fuzzy means clustering analysis results was: did the resulting clusters group together areas of the field that performed differently than other clusters based on grain yield, grain protein, NUE, and NUE components at the Walla Walla site and grain yield, grain protein, and N balance index at the CAF location? This was examined using a two-way analysis of variance (ANOVA) with N treatment and clustering assignments as independent variables. It was then observed whether cluster and N treatment were significant predictors of crop performance measurements in the ANOVA model. Once it was observed if crop measurements were significantly different between clusters and treatments, then appropriate pairwise comparisons were made between different N rates and levels of clustering that resulted from silhouette width validation.

Performance classifications were developed to separate wheat performance into four classes based on grain protein concentration and N balance index (Figure 5). Performance classifications are helpful in identifying areas of a field that perform similarly given some criteria. They aid in the identification of management conditions that contributed to low or high N fertilizer use efficiency and also have potential to aid in evaluating management decisions and making N application decisions in the future. Target grain protein values were obtained by plotting grain protein on x-axis, grain yield on y-axis, fitting a quadratic model to the data, and observing grain protein values where maximum yield was obtained (Figure 4). Target N balance index values were obtained by plotting N uptake efficiency (N_t N_s^{-1}) on the x-axis, N balance index (N_g N_f^{-1}) on the y-axis, fitting a quadratic model to the data, and finding N balance index value where 0.50 N uptake efficiency values were obtained (Figure 4). This was done for the Walla Walla site, however because data to calculate N uptake efficiency values at the CAF site were unavailable, N balance index target values from the Walla Walla site were used. This was possible because target N balance index values can be arbitrarily chosen depending on grower's desired goals or expectations for field N uptake efficiencies. Using target values, performance classification criteria were developed that facilitated the separation of the fields into similar performing areas. Groups of sampled points at the Walla Walla and CAF sites were then classified by the points that represented a single, uniform N application rate across the field (100 kg N ha^{-1} for Walla Walla and 84 kg N ha^{-1} for CAF). This was done to create data similar to what a grower who applied a single, uniform rate across a field would have. The performance classification for these N rates was then extended to points within the same group (see Figure 1a and 1b). Two-way ANOVA and then Tukey's pairwise comparisons were made to examine the significance of performance classification and N treatment effects in locations that performed similarly according to the established criteria (Figure 5). R packages *stats* and *agricolae* were used to create the ANOVA model and then perform Tukey's pairwise comparisons, respectively (R version 3.2.2, 2015; *agricolae* package version 1.2-3).

Results and Discussion

<u>Clustering Analysis</u>

At the Walla Walla site, PCA yielded 7 principle components (Table 5). Examining the proportion of variation, 95% of the variation was described with the first 5 principle components. Eigenvectors indicated that elevation and EC_a data were the most significant predictors of variance in the first principle component (PC), which explain 40% of the variation, while transformed aspect and profile curvature were the most significant in PC2, the addition of which led to 61% of the variation being explained. Terrain and EC_a data fuzzy c-means clustering analysis indicated 2 or 3 zones would be appropriate using silhouette width as clustering validation (Rousseeuw, 1987). Silhouette widths were 0.24 and 0.21 for 2 and 3 zones, respectively (Figure 2).

At the CAF site, PCA yielded 8 principle components with 93% of the variation described with the first 5 principle components (Table 6). Eigenvectors indicated that curvature, profile curvature, and planar curvature were the most significant predictors of variance in the first PC, which explain 32% of the variation, while spring and fall EC_a were the most significant predictors in the second PC. The first two PC explained 56% of variation (Table 6). Terrain and EC_a data fuzzy c-means clustering analysis indicated 2, 3, or 4 zones would be appropriate using silhouette width as clustering validation (Figure 3). Those different levels of clusters were all examined for treatment effects. Silhouette widths were 0.2, 0.19, and 0.21 for 2, 3 and 4 clusters, respectively.

Performance Classification Criteria

The relationship between yield and protein at Walla Walla and CAF sites indicated maximum yield was obtained at protein concentrations around 100 g kg^{-1}. N balance index values that correlated with N uptake efficiencies of 0.50 were around 1.0 for the Walla Walla site (Figure 4). Those two values were chosen to represent goals for winter wheat performance, and were used in creating performance class criteria (Figure 5). Grouping harvest points using these criteria allowed interpretation of treatment response within performance class zones.

One of the potential advantages of performance classification is the N management interpretation associated with each performance class. Performance class 1 is defined as areas where grain protein concentrations were greater than or equal to 100 g kg^{-1} and N balance index was greater than or equal to 1.00 kg N_g kg N_f^{-1}. These are areas where maximum yield was obtained based on grain yield and protein relationships (Figure 4) and N efficiency goals were reached, where the goal was 50% N uptake efficiency. No changes in N fertilizer management would be advised in these locations. Performance class 2 is defined as areas where grain protein concentrations were greater than or equal to 100 g kg^{-1} and N balance index was less than 1.00 kg N_g kg N_f^{-1}. These are areas where maximum yield was likely obtained, however N uptake efficiency was lower than 50% indicating a lower N rate may be applied and maximum yields still obtained with higher efficiency. Performance class 3 is defined as areas where grain protein concentrations were less than 100 g kg^{-1} and N balance index was greater than or equal to 1.00 kg N_g kg N_f^{-1}. These are areas where grain yield could have been increased, but N efficiency goals were met. Increasing N fertilizer rate in these areas would potentially increase yield while maintaining high efficiencies. Performance class 4 is defined as areas where grain protein concentrations were less than 100 g kg^{-1} and N balance index was less than 1.00 kg N_g kg N_f^{-1}. In these locations neither grain yield nor N use efficiency goals were obtained. The N fertilizer management interpretation for this classification is more complicated and may require management decisions that move beyond N rate and toward N timing (e.g. split spring/fall fertilizer applications).

The criteria used for performance classes were similar to those used in Brown, 2015 where 5 performance classes were formed and criteria started with N utilization efficiency values of 45 kg grain kg N_t^{-1} or greater as the first division, then N uptake efficiency values of greater than or equal to 0.5 kg N_t kg N_s^{-1}, and finally N use efficiency values greater than or equal 30 kg grain kg N_s^{-1} (Brown, 2015). Grain protein concentration values of 100 g kg^{-1} at the Walla Walla site, while correlated with maximum yields (Figure 4) were also correlated with N utilization efficiency values of 50 kg grain kg N_t^{-1} at the Walla Walla site (data not shown). N balance index values of 1.0 kg N_g kg N_f^{-1} were correlated with N uptake efficiency values of 0.5 kg N_t kg N_s^{-1}.

Using performance classification criteria described in Figure 5 and N rates that represented potential uniform rates by growers (100 kg N ha^{-1}) at the Walla Walla site, resulted in 136 class 1 points representing 26 groups; 41 class 2 points representing 7 groups; 130 class 3 points representing 22 groups; and 131 class 4 points representing 22 groups (Table 10). Using performance classification criteria and N rates that represented potential uniform rates by growers (84 kg N ha^{-1}) at the CAF site resulted in 50 class 1 points representing 13 groups; 24 class 2 points representing 6 groups; 12 class 3 points representing 3 different groups; and 62 class 4 points representing 16 different groups. The amount of points in each grouping suggests that in these fields, there were not many locations where decreasing N rate (class 2 interpretation) would be advisable, and at the CAF there were not many locations where increasing N rate would be advisable (class 3 interpretation). This would lead us to believe, based on our performance criteria and interpretations, that uniform rates are meeting performance goals in some areas (class 1 interpretation), and in most other areas different N management strategies beyond changing N rate should be explored (class 4 interpretation).

Treatment Response in Fuzzy means Clustered Zones

When the clustering or zone designation for each sampling location was analyzed for its significance in predicting crop performance measures, it was observed that clustering was only significant at the Walla Walla site and the 3 or 4 clustering level at the CAF site, but not for all performance measures (Tables 7, 8). This indicated that clustering analysis was able to separate crop performance to a degree that there was significant between clusters.

At the Walla Walla site, when performance measures for the clustering analysis that resulted in 2 zones were analyzed, grain yield means ranged from 5940 to 6586 kg ha^{-1} in zone 1 and from 5413 to 6058 kg ha^{-1} in zone 2 (Table 7). In both zones the 100 kg N ha^{-1} treatment results in maximum yields, but that treatment was not significantly different than the next lowest N rate of 60 kg N ha^{-1} in either zone. Grain protein concentration means varied from 84 to 108 g kg^{-1} in zone 1 and 83 to 116 g kg^{-1} in zone 2. Both zones grain protein concentration increased with increasing applied N. NUE ranged from 21.5 to 42.9 kg grain kg total N supply $(N_s)^{-1}$ across the whole field and differences between clusters were not found to be significant at the α=0.95 level. NUE deceased significantly with increasing applied N in both zones. There was also no statistical difference observed between clusters in N uptake efficiency. Through the whole field N uptake efficiency means ranged from 0.49 to 0.70 kg N_t kg N_s^{-1}. Nitrogen utilization efficiencies means ranged from 45.8 to 60.9 kg grain kg N_t^{-1} in zone 1 and ranged from 42.6 to 61.8 kg grain N_t^{-1} in zone 2. Decreasing the N rates led to increased N utilization efficiencies in both zones. Nitrogen balance index means ranged from 0.71 to 4.14 kg N_g kg N_f^{-1} in zone 1 and from 0.60 to 4.03 kg N_g kg N_f^{-1} in zone 2. Decreasing N rates also led to increased N balance index in both zones.

At the Walla Walla site, when performance measures for the clustering analysis that resulted in 3 zones were analyzed, grain yield means ranged from 6045 to 6673 kg ha^{-1} in zone 1, 5755 to 6383 kg ha^{-1} in zone 2, and 5345 to 5973 kg ha^{-1} in zone 3 (Table 7). Grain protein concentrations ranged from 79 to 108 g kg^{-1} in zone 1, 86 to 114 g kg^{-1} in zone 2, and 86 to 114 g kg^{-1} in zone 3. When N treatment effects on efficiency measurements within each zone was analyzed, it was found that NUE means ranged from 23.0 to 44.3 kg grain kg N_s^{-1} in zone 1, from 20.9 to 42.1 kg grain kg N_s^{-1} in zone 2, and 21.1 to 42.3 kg grain kg N_s^{-1} in zone 3. For all zones, NUE increased with decreasing applied N. There was no statistical difference observed between clusters in N uptake efficiency. Through the whole field N uptake efficiency means ranged from 0.49 to 0.70 kg N_t kg N_s^{-1}. Utilization efficiencies were significantly predicted by clustering, and ranged from 46.6 to 63.6 kg grain kg N_t^{-1} in zone 1, 43.2 to 60.2 kg grain kg N_t^{-1} in zone 2, 43.1 to 60.1 kg grain kg N_t^{-1} in zone 3. As expected, decreasing applied N increased N utilization efficiency. Nitrogen balance index means ranged from 0.67 to 4.12 kg N_g kg N_f^{-1} in zone 1, from 0.71 to 4.15 kg N_g kg N_f^{-1} in zone 2, and from 0.57 to 4.01 kg N_g kg N_f^{-1}. Decreasing N rates also led to increased N balance index in both zones.

Results of the clustering analysis at the CAF were not found to be significant predictors of crop performance at the 2 cluster level and only for grain yield and protein concentrations at the 3 and 4 cluster levels (Table 9). Applied N treatment effects were still examined within clusters at each level of clustering and no significant differences were found in grain yield or protein data within zones. Only control points (9 kg N ha^{-1}) were significantly different than other rates of applied N with respect to N balance index. Field average for grain yield across all treatments was 4797 kg ha^{-1} with a range of 1603 to 8567 kg ha^{-1}. Average grain protein concentration across all treatments was 107 g kg^{-1} with a range from 71 to 211 g kg^{-1}. Field average N balance index at the CAF site was 1.08 kg N_g kg N_f^{-1} with a range of 0.53 to 2.88 kg N_g kg N_f^{-1} when control points were removed, and 8.43 kg N_g kg N_f^{-1} with a range of 4.35 to 14.2 kg N_g kg N_f^{-1} when only control points were analyzed (data not shown).

The observed NUE values for the Walla Walla site are similar to those reported in other literature for dryland, SWWW cropping systems where typical values range from 20-40 kg grain kg N_s^{-1} (Fiez et al., 1995; Huggins and Pan, 2003). It was interesting to note that cluster was a significant predictor of wheat performance at the Walla Walla site and at CAF, but not for all levels of clustering. This may indicate that fuzzy clustering analyses are not accurately reflecting zones of similar crop performance at this site, or that soil properties vary enough with clusters based on terrain and EC_a that other predictors would need to be used to appropriately divide the field into management zones. This is one potential advantage of management zones created using remote sensing data that is converted to indices related to plant N uptake and use (Mulla, 2013). When performance classification criteria were applied to sample means of crop performance measures within zones and for each treatment (Tables 7, 8) it was observed that N rates at which the crop performed better, according to that criteria, were similar across zones, and usually the lower N rates performed as well as the higher rates at both sites.

Treatment Response in Performance Class Zones

When performance measures for the zones based on performance criteria were analyzed at the Walla Walla site, significant differences between N rates were observed in grain yield at points classified as performance zones 1, 2, 3 and 4 (Table 9). Grain yield ranged from 5738 to 6423 kg ha^{-1} in performance zone 1, from 5088 to 5773 kg ha^{-1} in performance zone 2, from 6011 to 6696 kg ha^{-1} in performance zone 3, and from 5465 to 6150 kg ha^{-1} in performance zone 4. In all performance zones, highest mean yield was observed at the 100 kg N ha^{-1} rate and lowest mean yield was observed at the control N rate of 19 kg N ha^{-1}. Mean grain protein concentrations ranged from 90 g kg^{1} at the lowest N rate to 119 g kg^{-1} at the highest N rate in performance zone 1, from 81 g kg^{-1} at the lowest N rate to 115 g kg^{-1} at the highest N rate in performance zone 2, from 82 g kg^{-1} at the lowest N rate to 109 g kg^{-1} at the highest N rate in performance zone 3, and from 79 g kg^{-1} at the lowest N rate to 110 g kg^{-1} at the highest N rate in performance zone 4. Across all performance zones, NUE ranged from 19.2 kg grain kg N_s^{-1} to 45.4 2 kg grain kg N_s^{-1} and increased with decreasing rate of applied N across all performance zones. Uptake efficiencies at the Walla Walla site ranged from 0.47 kg N_t kg N_s^{-1} at the highest N rate to 0.7 kg N_t kg N_s^{-1} across all performance zones and increased with decreasing N rate. Utilization efficiencies ranged from 41.1 to 64.8 kg grain kg N_t^{-1} across all performance zones and N rates and increased with decreasing N rate. N balance index ranged from 0.55 at the highest N rate in zone 2 to 4.59 kg N_g kg N_f^{-1} at the lowest N rate in zone 1 and increased with decreasing rate of applied N.

At the CAF site, grain yield means ranged from 3348 kg ha^{-1} at the 84 kg N ha^{-1} rate in performance zone 2, and 6900 kg ha^{-1} at the 84 kg N ha^{-1} rate in performance zone 3 (Table 10).

Differences in grain yield between N treatments were not significant at α=0.95 level, indicating large variation in yield response to N within performance zones, but performance classification and the interaction were both significant at α=0.95 level. Grain protein concentration means ranged from 86 g kg^{-1} at the lowest N rate in performance zone 4 to 140 g kg^{-1} at the lowest N rate in performance zone 2, however grain protein concentration differences between applied N rates were not significantly different at the α=0.95 level. Mean grain protein concentrations were highest in performance zone 2 and lowest in performance zones 3 and 4. This matches with performance classification interpretation of over-applied N with class 2, under-applied N in class 3, and differences in N timing or management needed with class 4. N balance index means ranged from 8.43 kg N_g kg N_f^{-1} in the lowest, control N rate (9 kg N $ha^{-1}$to 0.80 kg N_g kg N_f^{-1} at the highest N rate. N balance index differences between applied N rates were only significantly different at α=0.95 level for the control points when compared to all other N rates, and performance classification was not significant in the ANOVA model. The extremely high N balance index values at control points suggests there were large amounts of residual soil N from the previous hard red spring wheat crop. This is also evidenced in the large N balance index values at the highest, 112 kg N ha^{-1} rate.

The amount of variation in performance within performance zones suggests that classification based on one rate of applied N does not necessarily represent the type of response those locations will have to a change in applied N. This was especially true at the CAF site where large variation resulted in no statistical differences in crop performance based on grain yield, protein, and N balance index. This was explored by changing the performance criteria and observing areas where performance class changed. N balance index criteria was increased to 1.10

kg N_g kg N_f^{-1} and classification maps were recreated using interpolated grain protein and N balance index maps for visualization of changes in classification (Figure 6). Locations where performance class changed from class 1 to class 2 indicate areas where N rates could have been lowered and efficiency goals still met at the lower, 1.0 N balance cut-off.

The value of zones based on performance criteria is in the management interpretation of the zones. By using criteria that is easily measured and calculated using grain yield and grain protein data, these types of classification and performance expectations can be set by growers and then prescription maps created, and evaluated using that criteria. The increase in quality and availability of protein sensor will aid in improved VR decisions based on N efficiency measurements as we have defined here (Long et al., 2008).

Conclusions

The development of management zones based on performance criteria provides basis for the creation of management zones (MZ) and the evaluation of N fertilizer decisions made within those zones. When MZ delineation methods using fuzzy clustering analysis of terrain and soil EC_a data, and MZ delineation methods using performance classification were evaluated using grain yield, protein concentration, NUE and NUE derived measures, both were able to capture slight differences in crop performance at the Walla Walla and CAF sites. When performance measure response to different N rates was evaluated, there were different responses to N within zones at the Walla Walla site, but not at the CAF site. Increasing the availability and decreasing the price of protein sensor and yield monitor technologies will help with the implementation of MZ delineation based on performance criteria. The advantages to this method are in the management interpretation of performance classes as well as detailed evaluation of VR decisions increasing crop performance with regards to yield and protein as well as NUE and NUE component measurements. Using yield monitor and grain protein sensor data can make management zone delineation more accessible to growers who could collect high density field data, calculate efficiency measurements like N balance index, and then create performance classifications based on their crop performance goals. More research is needed to understand the relationship between easily obtainable crop performance measures like grain yield, protein, and N balance index with NUE and NUE components so that performance goals and criteria include fertilizer use efficiency measures.

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Tables

Table 1. Annual normal precipitation and temperature summaries compared to harvest year weather data.

	Field	
	Walla Walla	CAF†
Annual Normal Precip (mm)††	474	517
Sept - Aug of HY Precip (mm)†	375	436
	--	--
Annual Normal Temp (°C)††	12.1	8.7
HY Mean Annual Temp (°C)†	14.05	9.1

†Harvest Year (HY) for Walla Walla was 2015 and 2010 for Cook Agronomy Farm (CAF). Precipitation is given as Sept -Aug representing the growing season

††Mean Annual Precipitation and Temperature data is from NCDC 1981-2010 monthly Normal data

Table 2. Summary of actual total applied N rates (kg ha^{-1}) for Walla Walla site.

Field	Treatment	Target total N rate (kg ha^{-1})	Mean of total Applied N (kg ha^{-1})	St Dev	CV	# Points	Range Low	Range High
Walla Walla								
	1 (Control)	19.1	19.1	--		100	--	--
	2	60	59.89	1.97	0.03	95	53.10	67.50
	3	100	97.15	2.13	0.02	91	86.90	101.10
	4	130	133.4	4.46	0.03	94	116.60	145.90
	5	170	170	6.19	0.04	83	148.20	190.50

Table 3. Summary of agronomic practices for each field site.

Site	Harvest Year	Crop	Previous Crop	SWWW Variety	Seeding Date	Seeding Rate (kg ha^{-1})	†N Rate w/ Seed (kg ha^{-1})	††N Rate below seed (kg ha^{-1})	Seeding Drill
Walla Walla	2015	WW	Spring Peas	528/Ovation	10/7/2014	118	19	Variable	Yielder
Cook Agronomy Farm	2010	WW	Hard Red Spring Wheat	OR 102 (Clearfield)	10/17/2009	117	9	Variable	Horsch-Anderson

† Starter fertilizer applied with the seed was a combination of liquid APP and ATS fertilizer at both sites

††Variable rates of N fertilizer applied below the seed were done using anydrous ammonia (AA) at the Walla Walla site and urea ammonium nitrate (32-0-0) at the CAF

Table 4. Summary of nitrogen use efficiency terminology†.

G_w = grain yield

N_g = grain N

N_r = pre-plant residual N

N_{min} = N mineralization from soil organic matter

N_{ph} = post-harvest residual N

N_f = N fertilizer applied

N_s = N supply = $N_r + N_{min} + N_f$ OR $N_{t(control)}/0.7 + N_f$

N_t = aboveground N in plant at physiological maturity

G_w/N_s = Nitrogen Use Efficienty (NUE)

N_t/N_s = N uptake efficiency

G_w/N_t = N utilization efficiency

N_g/N_f = N balance index

N_g/N_t = N harvest index

† Table adapted from Huggins and Pan, 1993

Table 5. Principle components analysis eigenvectors and summary of components for Walla Walla terrain and EC_a data.

Importance of components

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Standard deviation	1.6663	1.2325	1.0388	0.8507	0.7416	0.44476	0.39215
Proportion of Variance	0.3967	0.217	0.1542	0.1034	0.07857	0.02826	0.02197
Cumulative Proportion	0.3967	0.6137	0.7678	0.8712	0.94977	0.97803	1.00000

				Eigenvectors			
	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**
Elevation (m)	0.502938	-0.22776	0.182002	-0.30251	0.16049	0.65576	-0.33877
Slope (deg)	0.214617	-0.16392	-0.78141	0.092765	0.547295	-0.06055	0.06825
Transformed Aspect	0.090525	0.59496	0.318455	0.48483	0.53424	0.116104	-0.04962
Plan Curvature	0.335488	-0.3274	-0.02919	0.772965	-0.39763	0.132161	0.079708
Profile Curvature	-0.35882	0.420758	-0.47243	0.071587	-0.33196	0.558156	-0.21015
EC_a 75-cm	0.481705	0.355768	-0.15708	-0.0683	-0.27499	-0.46065	-0.56941
EC_a 150-cm	0.468459	0.395574	-0.07838	-0.23991	-0.21301	0.107834	0.709483

Table 6. Principle components analysis eigenvectors and summary of components for CAF terrain and EC_a data.

Importance of components

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Standard deviation	1.6091	1.3749	1.176	1.0111	0.73298	0.62211	0.43525	1.53E-06
Proportion of Variance	0.3237	0.2363	0.173	0.1278	0.06716	0.04838	0.02368	0.00E+00
Cumulative Proportion	0.3237	0.56	0.733	0.8608	0.92794	0.97632	1.00000	1.00E+00

Eigenvectors

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Spring 2000 EC_a	-0.03034	0.65402	-0.24164	0.038599	-0.16591	0.031091	0.694955	6.23E-08
Fall 2000 EC_a	-0.12565	0.529844	-0.47573	0.168223	0.041869	-0.05411	-0.66646	-6.18E-08
Elevation (m)	0.337196	0.103682	-0.02388	-0.71045	-0.43894	-0.39792	-0.13869	2.25E-08
Slope (deg)	0.022105	-0.27747	-0.61951	-0.42091	0.112435	0.586455	0.070664	1.54E-08
Transformed Aspect	-0.06516	0.398068	0.570292	-0.27741	-0.04226	0.62655	-0.20188	3.99E-08
Curvature	0.606076	0.066107	-0.00281	0.162826	0.133966	0.098843	-0.01822	-0.75745
Profile Curvature	-0.52297	-0.17504	-0.04338	0.085994	-0.64143	0.079945	-0.03467	-0.51726
Plan Curvature	0.473322	-0.10158	-0.06166	0.421242	-0.57814	0.291735	-0.07966	0.398379

Table 7. ANOVA and pairwise comparison of Walla Walla winter wheat crop performance in clusters derived from terrain and apparent electrical conductivity (EC_a) data.

Field (#clusters)†	Cluster	N Rate	Sample Means‡ Gw	Protein	$G_w N_s^{-1}$	$N_t N_s^{-1}$	$G_w N_t^{-1}$	$N_g N_f^{-1}$	$N_g N_t^{-1}$	Performance Class§	n
Walla Walla		(kg ha^{-1})	(kg ha^{-1})	(g kg^{-1})							
(2 clusters)	1										
		19	5940 a	84 e	42.9 a	0.70 a	60.9 a	4.14 a	0.82 a	3	55
		60	6214 ab	87 e	35.0 b	0.62 b	57.9 ab	1.50 b	0.81 b	3	53
		100	6586 b	98 cd	30.0 c	0.59 b	50.9 cd	1.09 c	0.80 bc	3	45
		130	6362 b	100 bc	24.7 d	0.52 c	50.1 de	0.83 d	0.80 cd	2	43
		170	6349 ab	108 ab	21.5 e	0.49 c	45.8 ef	0.71 d	0.79 d	2	38
	2										
		19	5413 a	83 e	--	--	61.8 a	4.03 a	--	3	45
		60	5686 ab	91 de	--	--	57.5 bc	1.39 b	--	3	42
		100	6058 b	98 cd	--	--	50.9 cd	0.98 c	--	4	46
		130	5834 b	109 a	--	--	45.5 ef	0.72 d	--	2	51
		170	5822 ab	116 a	--	--	42.6 f	0.60 d	--	2	45
Treatment Significance††	*P(>F)*	--	*0.0003*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	--	5
Cluster Significance††	*Pr(>F)*	--	*< 0.0001*	*0.0011*	*0.190*	*0.650*	*0.0070*	*0.0116*	0.278	--	463
Interaction††	*Pr(>F)*	--	*0.5872*	*0.0185*	*0.441*	*0.224*	*0.0418*	*0.0847*	*0.977*	--	--
(3 clusters)	1										
		19	6045 a	79 a	44.3 a	0.70 a	63.6 a	4.12 a	0.82 a	3	33
		60	6320 ab	85 b	36.3 b	0.62 b	59.1 b	1.48 b	0.81 b	3	32
		100	6673 b	94 c	31.4 c	0.59 b	53.3 c	1.07 c	0.80 bc	3	28
		130	6468 b	100 d	26.2 d	0.52 c	50.1 d	0.81 d	0.80 cd	2	25
		170	6434 ab	108 e	23.0 e	0.49 c	46.6 e	0.67 d	0.79 d	2	21
	2										
		19	5755 a	86 a	42.1 a	--	60.2 a	4.15 a	--	3	31
		60	6029 ab	91 b	34.2 b	--	55.8 b	1.51 b	--	3	29
		100	6383 b	100 c	29.3 c	--	49.9 c	1.10 c	--	1	29
		130	6177 b	106 d	24.0 d	--	46.7 d	0.84 d	--	2	28
		170	6143 ab	114 e	20.9 e	--	43.2 e	0.71 d	--	2	31
	3										
		19	5345 a	86 a	42.3 a	--	60.1 a	4.01 a	--	3	36
		60	5619 ab	91 b	34.4 b	--	55.6 b	1.37 b	--	3	34
		100	5973 b	101 c	29.4 c	--	49.8 c	0.96 c	--	2	34
		130	5767 b	106 d	24.2 d	--	46.6 d	0.70 d	--	2	41
		170	5733 ab	114 e	21.1 e	--	43.1 e	0.57 d	--	2	31
Treatment Significance	*P(>F)*	--	*0.0002*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	--	5
Cluster Significance	*Pr(>F)*	--	*<0.0001*	*<0.0001*	*0.00152*	*0.943*	*<0.0001*	*0.0196*	*0.173*	--	463
Interaction	*Pr(>F)*	--	*0.500669*	*0.0599*	*0.68643*	*0.767*	*0.197*	*0.184*	*0.997*	--	--

† Number of clusters was created using fuzzy c-means analysis and validated using silhouette width. Dividing the field into both 2 and 3 clusters was evaluated using a two-way ANOVA and Tukey's pairwise comparison.

‡Yield (Gw); Protein; N Use Efficiency (Gw Ns^{-1}); N utilization efficiency (Gw Nt^{-1}); N uptake efficiency (Nt Ns^{-1}); N Balance Index (Ng Nf^{-1}); N Harvest index (Ng Nt^{-1}). Within columns, means were calculated using coefficients from two-way ANOVA model. Means followed by the same letter are not significantly different at the 0.95 confidence level using Tukey pairwise comparison.

§ Performance classification uses sample mean values and criteria outlined in Figure 5

††Significance of treatment and cluster in predicting wheat performance was analyzed using results from two-way ANOVA. Results are given as p-value (Pr(>F)) for cluster and treatment coefficient in ANOVA model. If clustering was not significant, performance was analyzed as one cluster for entire plot. Significance of interaction term is given as (Pr(>F)), and pairwise groups combined for criteria with significant (α=0.95) interaction of independent variables (e.g. protein in 2 clusters).

Table 8. ANOVA and pairwise comparison of Cook Agronomy Farm (CAF) winter wheat crop performance in clusters derived from terrain and apparent electrical conductivity (EC_a) data.

Field (#clusters)†	Cluster	N Rate	Sample Means‡ Gw	Protein	$N_g N_f^{-1}$	Performance Class§	n
CAF		(kg ha^{-1})	(kg ha^{-1})	(g kg^{-1})			
(2 clusters)	1						
		9	4591 a	102 a	8.43 a	1	19
		56	4960 a	105 a	1.52 b	1	17
		84	4677 a	110 a	1.00 bc	1	18
		112	4966 a	112 a	0.80 c	2	21
	2						
		9	--	--	--	--	19
		56	--	--	--	--	16
		84	--	--	--	--	20
		112	--	--	--	--	20
Treatment Significance††	*P(>F)*	--	*0.322*	*0.388*	*<0.0001*	--	4
Cluster Significance††	*Pr(>F)*	--	*0.214*	*0.352*	*0.149*	--	*150*
Interaction††	*Pr(>F)*	--	*0.869*	*0.793*	*0.407*	--	--
(3 clusters)	1						
		9	4957 a	98 b	8.43 a	3	13
		56	5289 a	102 b	1.52 b	1	12
		84	5063 a	105 b	1.01 bc	1	12
		112	5323 a	108 b	0.80 c	2	14
	2						
		9	4593 ab	90 b	--	3	13
		56	4925 ab	95 b	--	3	13
		84	4699 ab	98 b	--	3	13
		112	4959 ab	101 b	--	2	15
	3						
		9	4193 b	120 a	--	1	12
		56	4525 b	124 a	--	1	8
		84	4299 b	127 a	--	1	13
		112	4558 b	130 a	--	2	12
Treatment Significance	*P(>F)*	--	*0.29275*	*0.298*	*<0.0001*	--	4
Cluster Significance	*Pr(>F)*	--	*0.00254*	*<0.0001*	*0.129*	--	*150*
Interaction	*Pr(>F)*	--	*0.99479*	*0.954*	*0.511*	--	--
(4 clusters)	1						
		9	4922 a	94 b	8.43 a	3	10
		56	5240 a	97 b	1.52 b	3	10
		84	5017 a	100 b	1.01 bc	1	8
		112	5281 a	103 b	0.80 c	2	12
	2						
		9	4058 b	112 a	--	1	11
		56	4376 b	115 a	--	1	7
		84	4183 b	118 a	--	1	9
		112	4417 b	122 a	--	2	10
	3						
		9	4304 b	113 a	--	1	7
		56	4622 b	116 a	--	1	7
		84	4429 b	120 a	--	1	12
		112	4663 b	123 a	--	2	9
	4						
		9	5049 a	92 b	--	3	10
		56	5367 a	96 b	--	3	9
		84	5174 a	99 b	--	3	9
		112	5408 a	102 b	--	2	10
Treatment Significance	*P(>F)*	--	*0.263*	*0.3376*	*<0.0001*	--	4
Cluster Significance	*Pr(>F)*	--	*<0.0001*	*0.0003*	*0.954*	--	*150*
Interaction	*Pr(>F)*	--	*0.995*	*0.8066*	*1.0000*	--	--

† Number of clusters was created using fuzzy c-means analysis and validated using silhouette width. Dividing the field into 2, 3, and 4 clusters was evaluated using anova and a Tukey's pairwise comparison.

‡ Yield (Gw); Protein; N Balance Index (Ng/Nf). Within columns, means were calculated using coefficients from two-way ANOVA model. Means followed by the same letter are not significantly different at the 0.95 confidence level using Tukey pairwise comparison.

§ Performance classification uses sample mean values and criteria outline in Figure 5.

††Significance of treatment and cluster in predicting wheat performance was analyzed using results from two-way ANOVA. Results are given as p-value (Pr(>F)) for cluster and treatment coefficient in ANOVA model. If clustering was not significant, performance was analyzed as one cluster for entire plot. Significance of interaction term is given as (Pr(>F)).

Table 9. ANOVA and pairwise comparison of winter wheat crop performance at Walla Walla site using performance classification as grouping method.

Field	Performance Zone†	N Rate	Gw	Protein	$G_w N_s^{-1}$	$N_t N_s^{-1}$	$G_w N_t^{-1}$	$N_g N_f^{-1}$	$N_g N_t^{-1}$	Performance Class§	n
			Sample Means‡								
Walla Walla		(kg ha^{-1})	(kg ha^{-1})	(g kg^{-1})							
	1										
		19	5738 a	90 def	40.3 a	0.70 a	56.2 bc	4.59 a	0.81 bcde	3	31
		60	6019 a	93 cdef	32.2 b	0.61 abcd	54.2 bcd	1.56 d	0.81 bcde	3	28
		100	6423 b	111 ab	27.9 c	0.63 abc	44.4 fg	1.16 def	0.80 cdef	1	27
		130	6127 ab	109 ab	22.0 d	0.50 e	45.4 efg	0.80 fgh	0.80 bcdef	2	28
		170	6056 ab	119 a	18.5 e	0.47 e	41.4 g	0.67 gh	0.80 def	2	22
	2										
		19	5088 a	81 f	42.4 a	0.70 ab	63.0 ab	3.56 c	0.83 ab	3	8
		60	5369 a	93 cdef	34.3 b	0.68 abc	53.7 bcde	1.42 de	0.81 abcde	3	9
		100	5773 b	106 abcd	30.0 c	0.59 bcde	46.4 defg	0.95 defgh	0.80 bcdef	2	7
		130	5477 ab	108 abc	24.1 d	0.54 cde	45.5 efg	0.75 fgh	0.80 cdef	2	9
		170	5406 ab	115 ab	20.6 e	0.47 e	42.2 fg	0.55 h	0.77 f	2	8
	3										
		19	6011 a	82 f	44.7 a	0.70 ab	62.6 ab	4.13 b	0.82 ab	3	31
		60	6292 a	87 ef	36.5 b	0.63 abc	58.1 bc	1.46 d	0.81 abcd	3	27
		100	6696 b	95 cde	32.2 c	0.66 abc	52.3 cde	1.14 defg	0.81 bcde	3	23
		130	6400 ab	103 bcd	26.4 d	0.54 cde	48.3 def	0.80 fgh	0.80 bcdef	2	26
		170	6329 ab	109 ab	22.9 e	0.51 de	45.0 efg	0.67 h	0.79 ef	2	23
	4										
		19	5465 a	79 f	43.7 a	0.70 ab	64.8 a	3.66 c	0.83 a	3	26
		60	5746 a	86 ef	35.5 b	0.60 bcd	59.1 ab	1.32 de	0.82 abc	3	28
		100	6150 b	86 ef	31.3 c	0.51 de	58.7 abc	0.86 efgh	0.81 abcd	4	24
		130	5854 ab	101 bcd	25.4 d	0.52 de	49.5 def	0.73 gh	0.80 bcdef	2	29
		170	5783 ab	110 ab	21.9 e	0.47 e	45.7 efg	0.61 h	0.80 bcdef	2	24
	Treatment Significance††	*P(>F)*	*0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	--	5
	Zone Significance††	*Pr(>F)*	*<0.0001*	*<0.0001*	*<0.0001*	*0.0069*	*<0.0001*	*<0.0001*	*<0.0001*	--	463
	Interaction††	*Pr(>F)*	*0.0716*	*0.0083*	*0.276*	*0.0293*	*0.0059*	*<0.0001*	*0.0321*	--	--

† Performance zones were calculated from treatment 3 values using criteria outlined in Figure 5

‡Yield (Gw); Protein; N Use Efficiency (Gw Ns^{-1}); N utilization efficiency (Gw Nt^{-1}); N uptake efficiency (Nt Ns^{-1}); N Balance Index (Ng Nf^{-1}); N Harvest index (Ng Nt^{-1}). Within columns, means were calculated using coefficients from two-way ANOVA model. Means followed by the same letter are not significantly different at the 0.95 confidence level using Tukey pairwise comparison.

§ Performance classification uses sample mean values and criteria outlined in Figure 5

††Significance of treatment and cluster in predicting wheat performance was analyzed using results from two-way ANOVA. Results are given as p-value (Pr(>F)) for cluster and treatment coefficient in ANOVA model. If clustering was not significant, performance was analyzed as one cluster for entire plot. Significance of interaction term is given as (Pr(>F)), and pairwise groups combined for criteria with significant (α=0.95) interaction of independent variables (e.g. protein).

Table 10. ANOVA and pairwise comparison of winter wheat crop performance at Cook Agronomy Farm (CAF) site using performance classification as grouping method.

Field	Performance Zone†	N Rate	Sample Means‡ Gw	Protein	$N_g N_f^{-1}$	Performance Class§	n
CAF		(kg ha^{-1})	(kg ha^{-1})	(g kg^{-1})			
	1						
		9	4370 bcd	113 a	8.43 a	1	12
		56	5211 abc	114 a	1.52 b	1	10
		84	4692 bcd	120 a	1.01 bc	1	13
		112	4914 abcd	121 a	0.80 c	2	15
	2						
		9	3962 cd	129 b	--	1	6
		56	4021 cd	131 b	--	1	6
		84	3348 d	136 b	--	1	6
		112	4422 bcd	137 b	--	2	6
	3						
		9	5171 abcd	91 c	--	3	3
		56	4442 bcd	93 c	--	3	3
		84	6900 a	99 c	--	3	3
		112	6442 ab	99 c	--	4	3
	4						
		9	4812 abcd	87 cd	--	3	16
		56	5295 abc	89 cd	--	3	14
		84	4747 bcd	95 cd	--	3	16
		112	4930 abcd	95 cd	--	4	16
	Treatment Significance††	*P(>F)*	*0.1948*	*0.253*	*<0.0001*	--	4
	Zone Significance††	*Pr(>F)*	*<0.0001*	*<0.0001*	*0.12*	--	*148*
	Interaction††	*Pr(>F)*	*0.0435*	*0.334*	*0.376*	--	--

† Performance zones were calculated from values observed at 84 kg N ha^{-1} using criteria outlined in Figure 5

‡ Yield (Gw); Protein; and N Balance Index (Ng Nf^{-1}). Within columns, means followed by the same letter are not significantly different at the 0.95 confidence level using Tukey pairwise comparison.

§ Performance classification uses sample mean values and criteria outline in Figure 5

††Significance of treatment and cluster in predicting wheat performance was analyzed using results from two-way ANOVA. Results are given as p-value (Pr(>F)) for cluster and treatment coefficient in ANOVA model. If clustering was not significant, performance was analyzed as one cluster for entire plot. Significance of interaction term is given as (Pr(>F)), and pairwise groups combined for criteria with significant (α=0.95) interaction of independent variables (e.g. yield (G_w).

Figures

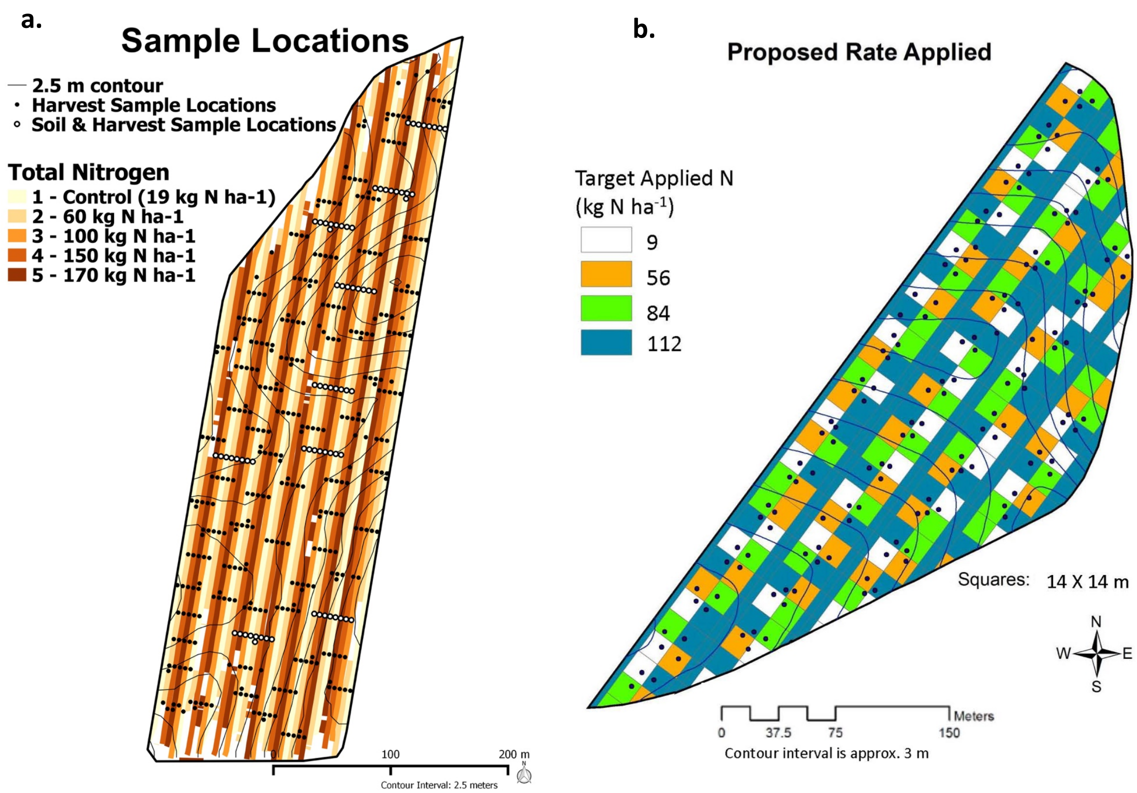


Figure 1. Walla Walla site sample locations overlaid on N rates (a) and CAF grid points with variable N rates surrounding each (b).

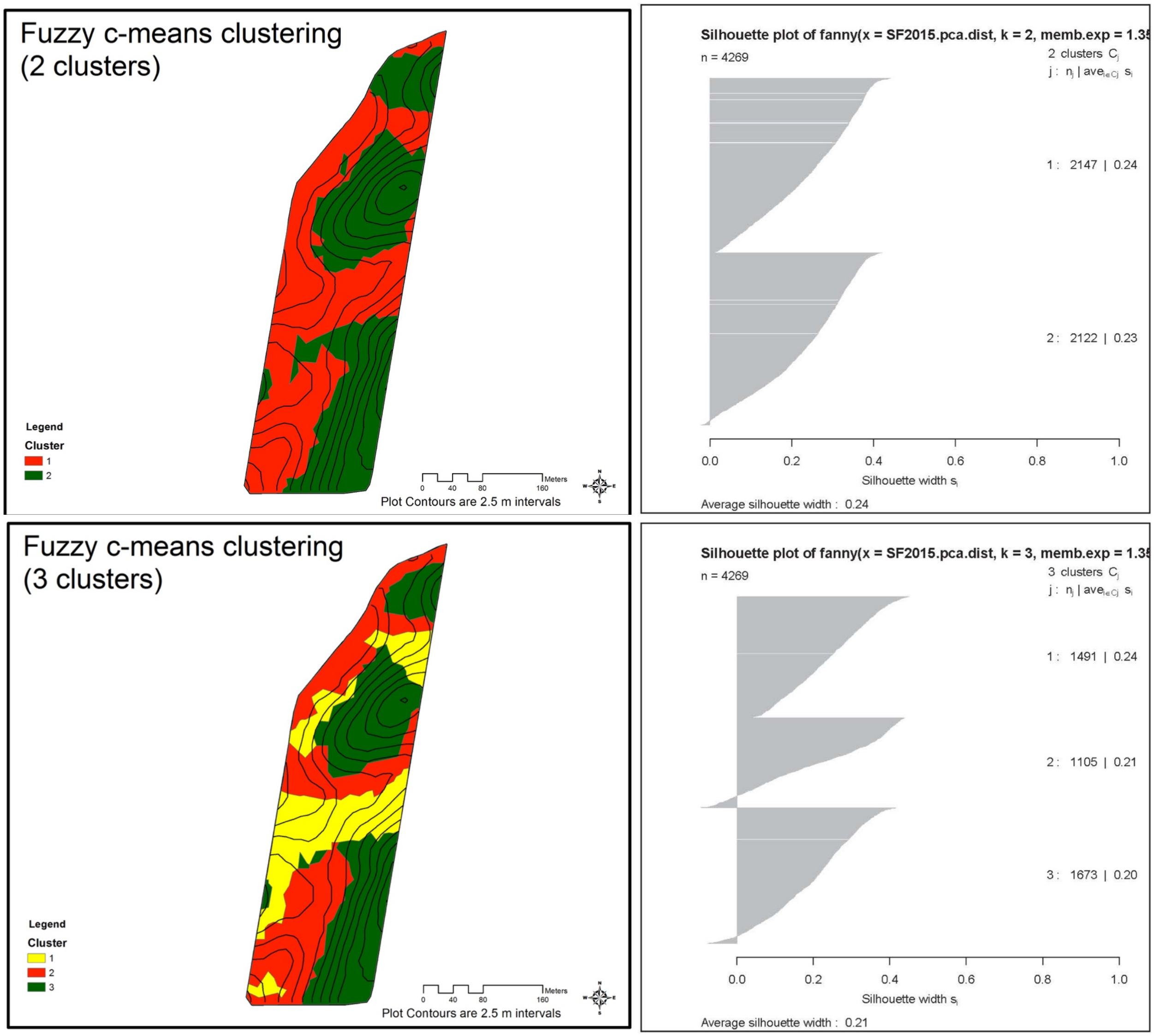


Figure 2. Clustering results for Walla Walla site using PCA and fuzzy c-means clustering analysis for 2 clusters (top) and 3 clusters (bottom) with silhouette width validation.

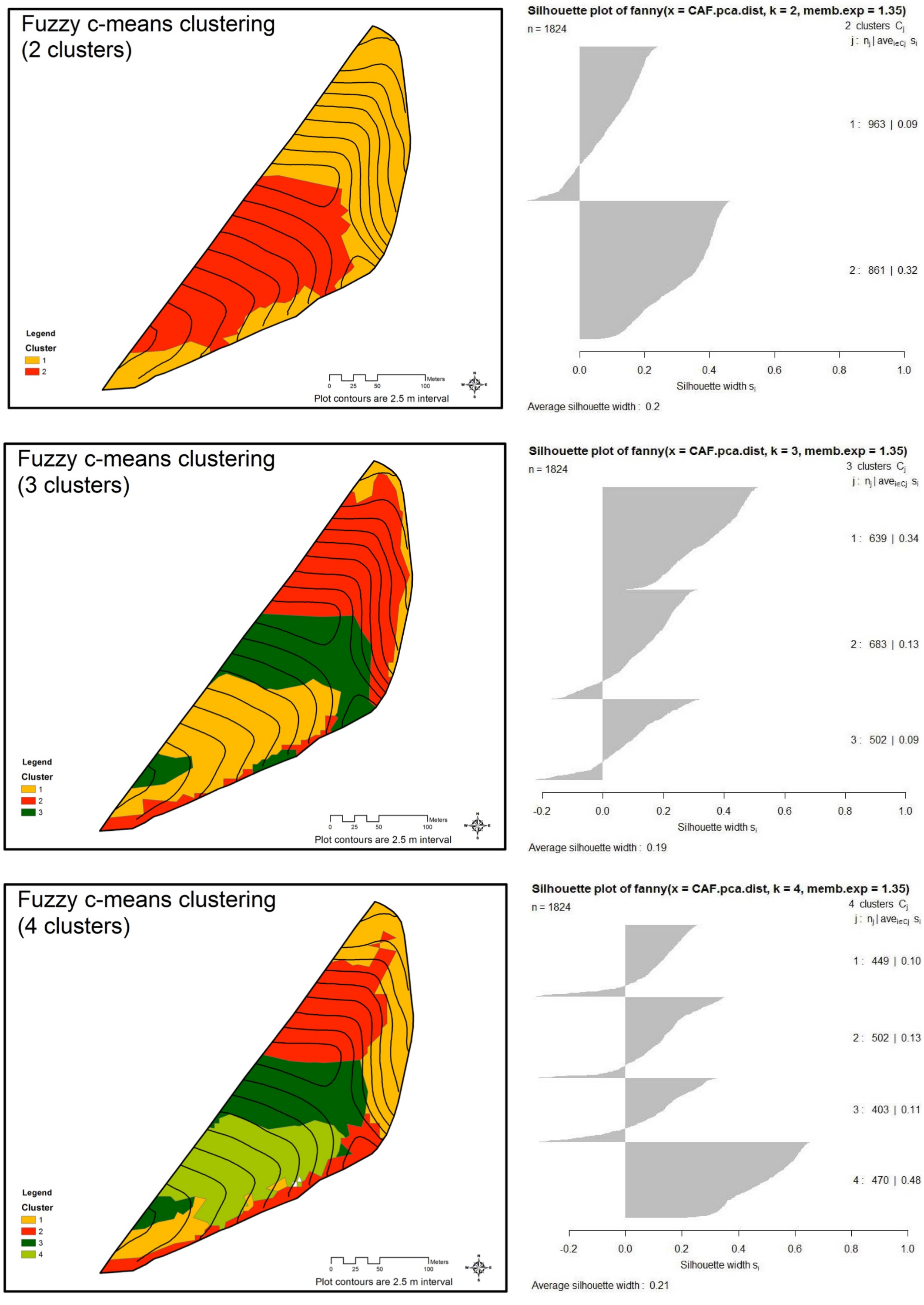


Figure 3. Clustering results for Cook Agronomy Farm (CAF) site using PCA and fuzzy c-means clustering analysis for 2 clusters (top), 3 clusters (middle), and 4 clusters (bottom) with silhouette width validation.

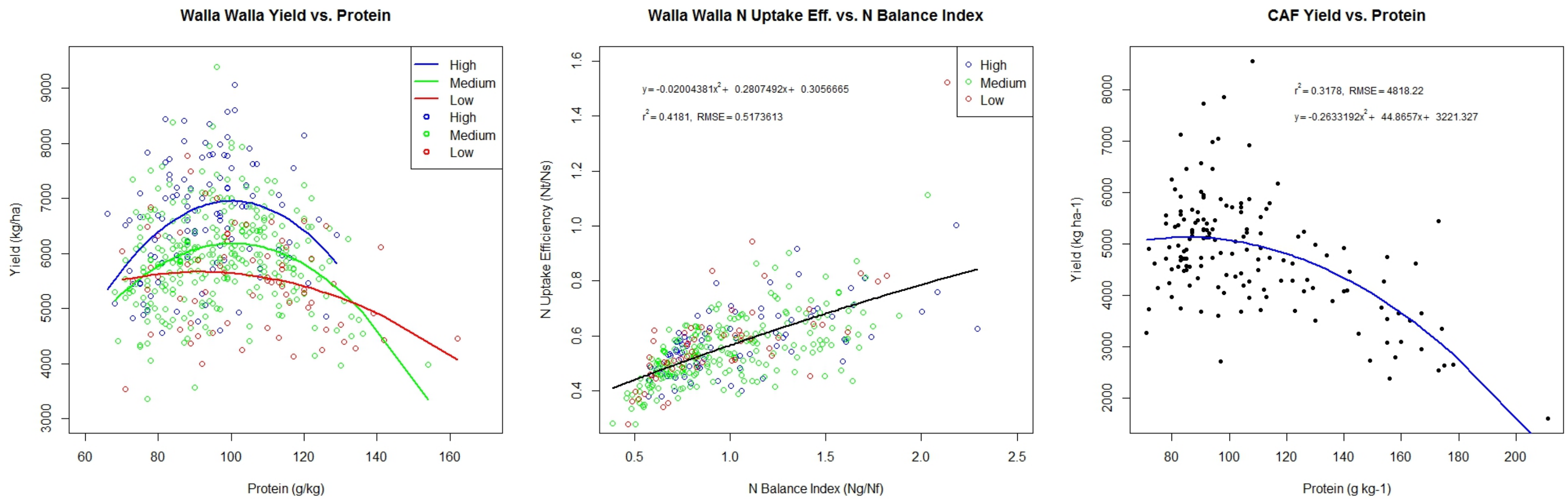


Figure 4. Plots of Walla Walla yield and protein (left), Walla Walla N uptake efficiency and N balance index (middle) and Cook Agronomy Farm (CAF) yield and protein (right) with fitted quadratic models. These relationships were used to find target values for grain protein where yield was maximized and N balance index values that related to N uptake efficiencies of 0.5. Target values were then used in performance classification criteria.

Step	Performance Criteria	Performance Class
1	Protein is equal to or greater than 100 g kg^{-1}	
	If yes, go to Step 2	
	If no, go to Step 3	
2	N_g N_f^{-1} is equal to or greater than 1.00 kg N_g kg N_f^{-1}	
	If yes.................	**Class 1**
	If no.................	**Class 2**
3	N_g N_f^{-1} is equal to or greater than 1.00 kg N_g kg N_f^{-1}	
	If yes.................	**Class 3**
	If no.................	**Class 4**

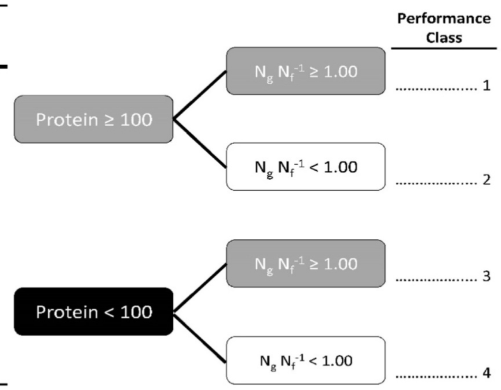


Figure 5. Dichotomous key to the classification of soft white winter wheat performance based on optimal grain protein and N balance index values. Figure adapted from Brown, 2015

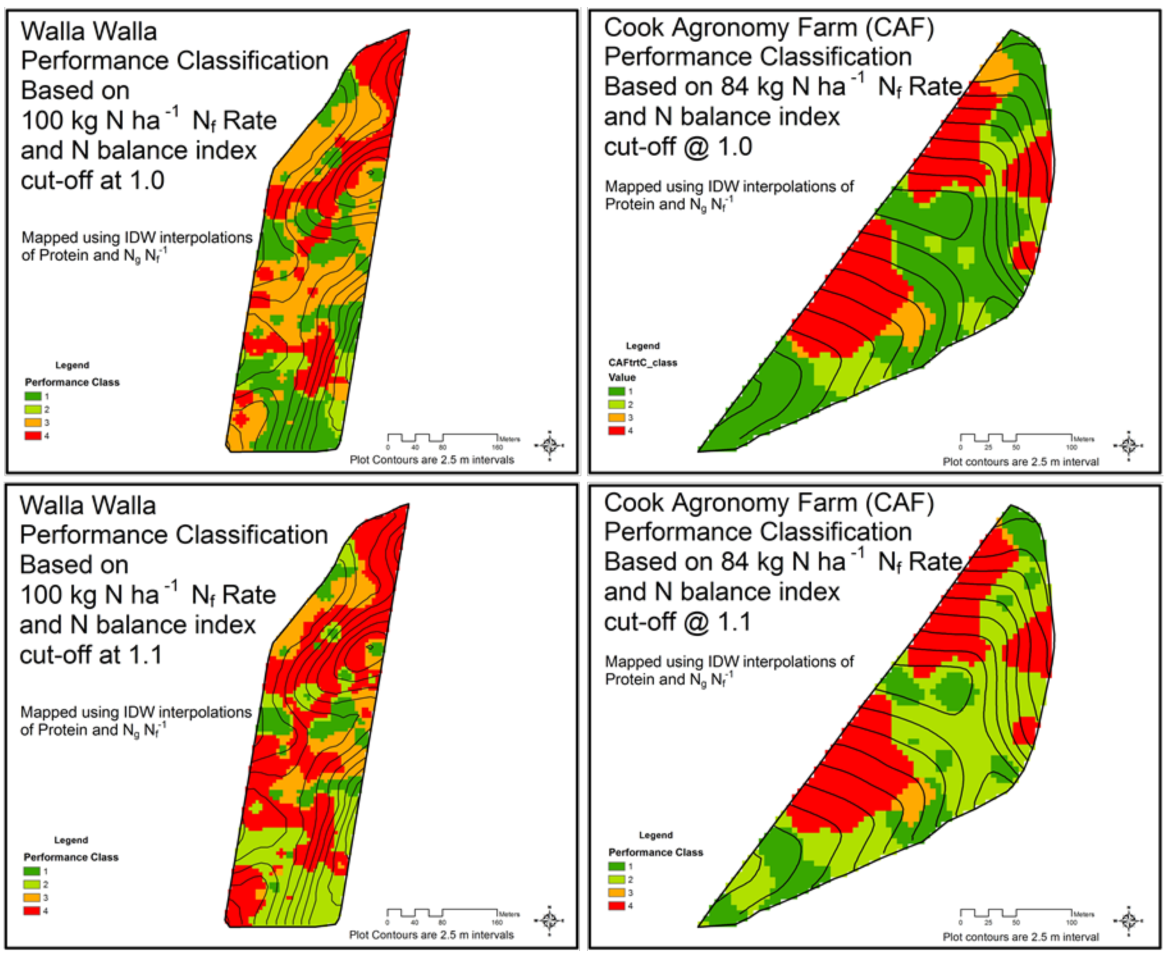
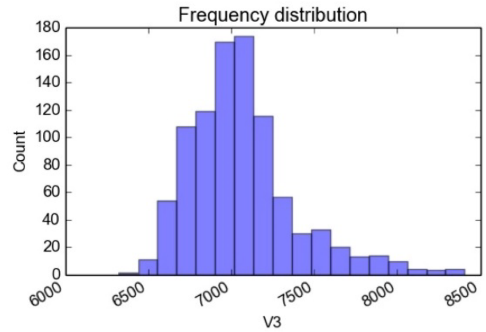


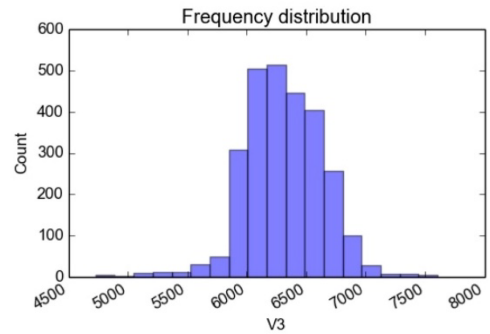
Figure 6. Performance Classification maps for visualization of spatial variability in crop performance. Maps were created using inverse distance weighted (IDW) interpolations of grain protein concentration and N balance index in raster calculator (ArcGIS) to assign performance classes.

APPENDIX A

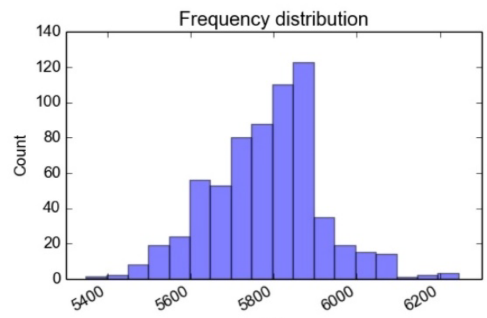
High Yielding Zone:
Count: 941
Unique values: 941
Minimum value: 6325.141353
Maximum value: 8405.810474
Range: 2080.669120
Sum: 6647417.084617
Mean value: 7064.205191 kg/ha = 105.0 bu/ac
Median value: 7024.245921
Standard deviation: 322.055887
Coefficient of Variation: 0.045590



Medium Zone:
Count: 2689
Unique values: 2689
Minimum value: 4732.083226
Maximum value: 7605.042508
Range: 2872.959282
Sum: 16971585.099019
Mean value: 6311.485719 kg/ha = 93.8 bu/ac
Median value: 6295.263383
Standard deviation: 318.117945
Coefficient of Variation: 0.050403



Low Zone:
Count: 653
Unique values: 653
Minimum value: 5349.232308
Maximum value: 6245.002418
Range: 895.770110
Sum: 3775737.992590
Mean value: 5782.140877 kg/ha = 85.9 bu/ac
Median value: 5795.083739
Standard deviation: 131.807531
Coefficient of Variation: 0.022796



Whole Field
Count: 4269
Unique values: 4269
Minimum value: 4732.083226
Maximum value: 8405.810474
Range: 3673.727248
Sum: 27312539.150706
Mean value: 6397.877524 kg/ha = 95.1 bu/ac
Median value: 6343.623667
Standard deviation: 498.849270
Coefficient of Variation: 0.077971

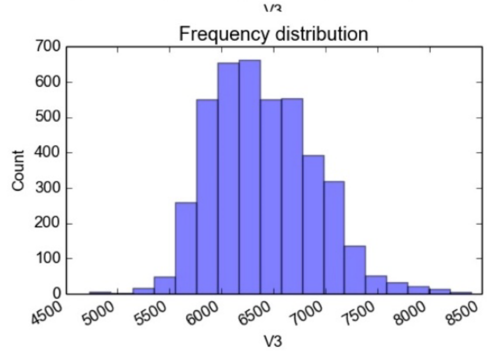
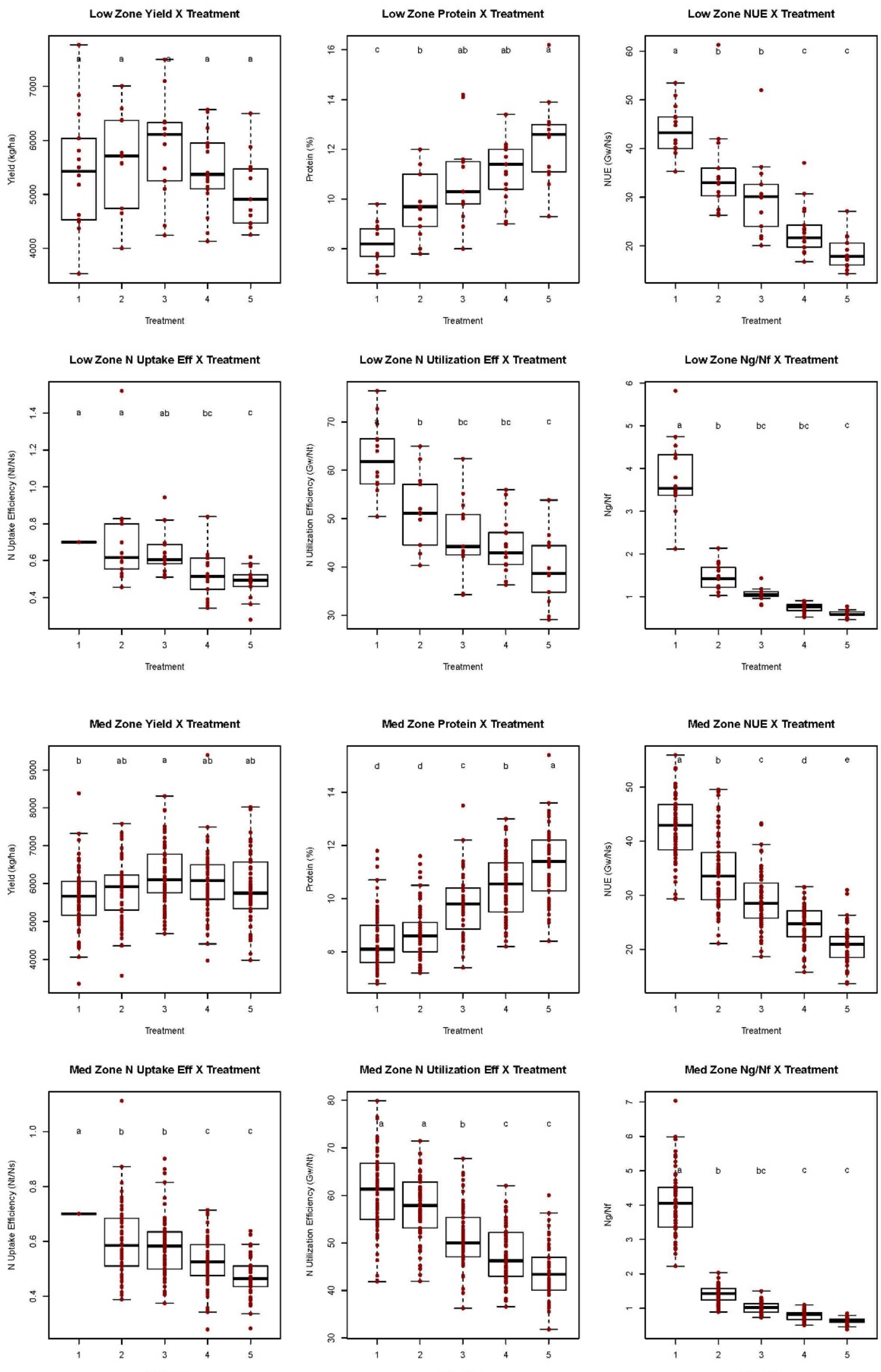


Figure 1. Summary statistics for interpolated yield data broken out by management zone. These data indicate the zones have captured yields that are different enough to be significant to a grower.


Low Zone Yield X Treatment
Yield (kg/ha)
Treatment
Low Zone Protein X Treatment
Protein (%)
Treatment
Low Zone NUE X Treatment
NUE (Gw/Ns)
Treatment
Low Zone N Uptake Eff X Treatment
N Uptake Efficiency (Nt/Ns)
Treatment
Low Zone N Utilization Eff X Treatment
N Utilization Efficiency (Gw/Nt)
Treatment
Low Zone Ng/Nf X Treatment
Ng/Nf
Treatment
Med Zone Yield X Treatment
Yield (kg/ha)
Treatment
Med Zone Protein X Treatment
Protein (%)
Treatment
Med Zone NUE X Treatment
NUE (Gw/Ns)
Treatment
Med Zone N Uptake Eff X Treatment
N Uptake Efficiency (Nt/Ns)
Treatment
Med Zone N Utilization Eff X Treatment
N Utilization Efficiency (Gw/Nt)
Treatment
Med Zone Ng/Nf X Treatment
Ng/Nf
Treatment

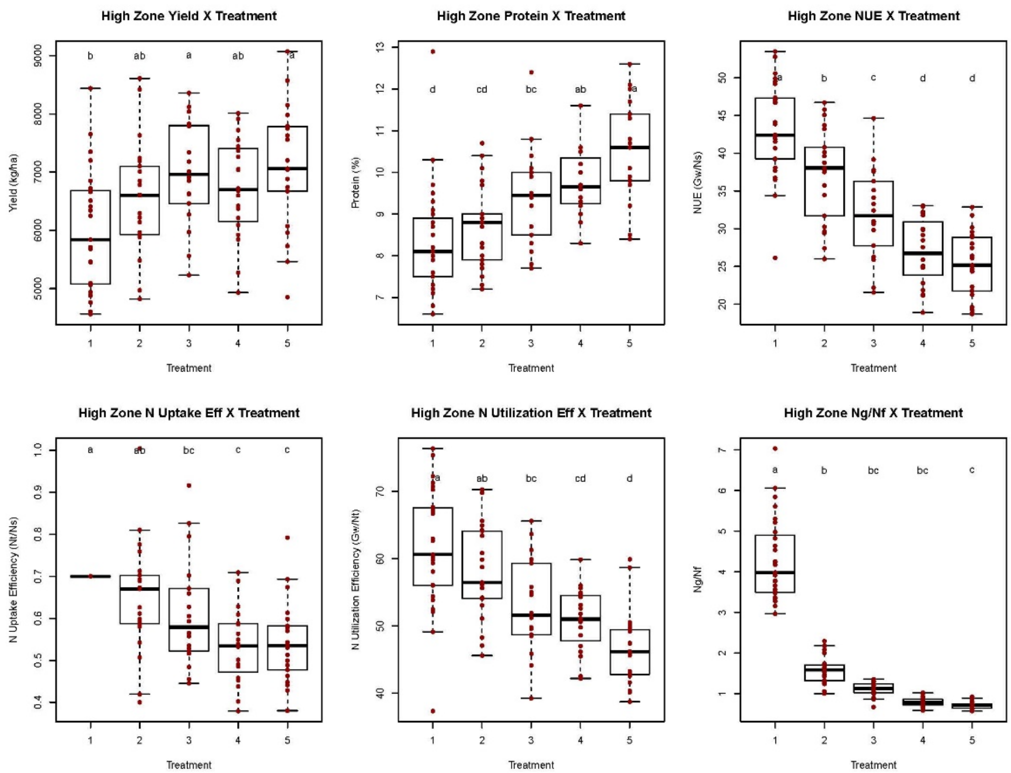


Figure 2. Box plot of Walla Walla site low, medium, and high yielding zone performance criteria. The boxes represent approximations of 95% confidence intervals and dark lines represent median values. Red dots are the actual data points. Letters indicate grouping calculated using Tukey's pairwise comparisons at α=0.95 confidence level.