A. Project Information

Final Report to CA Department of Food and Agriculture – FREP PROGRAM
Reporting for the period from September 1, 2013 – January 31, 2017

Grant Number: project #13-0267-SA

Project Title: Developing Nitrogen Management Strategies to Optimize Grain Yield and Protein Content while Minimizing Leaching Losses in California Wheat

Project Leaders:

Robert Hutmacher, Extension Specialist
UCD Plant Sci. Dept., UC West Side REC
P.O. Box 158, Five Points, CA 93624-0158
(559) 884-2411; cell: (559) 260-8957
rbhutmacher@ucdavis.edu

Steve Orloff, Farm Advisor, County Director
UCCE Siskiyou County
1655 S. Main St. Yreka, CA 96097
(530) 842-2711; Fax: (530) 842-6431
sborloff@ucdavis.edu

Steve Wright, Farm Advisor
UCCE Tulare County
4437 S. Laspina, Ste. B. Tulare, CA 93274; (559) 685-3309 Ext. 215 Fax: (559) 685-3319; sdwright@ucdavis.edu

Mark Lundy, Extension Specialist
UCD Plant Sci. Dept., UC Davis
One Shields Avenue, Davis, CA 95616
Phone: (530) 458-0570 Fax: (530) 458-4625
melundy@ucdavis.edu

B. Objectives

1. Compare yield and protein content of spring wheat varieties in response to a range of N application treatments to determine their N use efficiency.
2. Evaluate N management schemes utilizing different rates and split applications of N to determine the effectiveness of pre-plant applications versus delayed applications to more closely match plant uptake. The effect of these N schemes on yield and grain protein will be quantified in three different wheat production regions in California (southern San Joaquin Valley, Sacramento Valley, and northern intermountain area).

3. Determine the concentration of nitrate-N at different depths in soil profiles at the end of the season as a function of N rate and application timing for various locations/soil types to estimate nitrate accumulation or movement below the root zone and potential for deep percolation losses.
4. Assess the value of a soil nitrogen quick test for in-season soil nitrate-N evaluations in the 0 to 2-foot zone in the soil profile.
5. Measure the effect of N application timing and rate on flag leaf total N to determine if tissue N can be used to indicate needs for late-season N applications to achieve desired grain protein.
6. Evaluate the effectiveness of different slow release nitrogen sources to determine if the same or greater N response can be achieved with fewer applications.
7. As information is developed in the study, present information to appropriate grower groups, consultants and industry to give opportunities for feedback and to refine concepts of workable changes in N management approaches.

C. Abstract

Nitrogen (N) fertilizer management is a key determinant of the productivity, quality and profitability of spring wheat. In addition, N fertilizers can be a source of pollution when applied in excess of agroecosystem demand. In order to develop information that enables and encourages optimal use of N fertilizer in California wheat, the research described in this report investigated the effects of N fertilizer application rate and timing on spring wheat yield and protein across multiple cropping seasons in three major wheat growing regions of California. This work was supported by both CDFA-FREP and the California Wheat Commission, and the data included in the report span five seasons (2012-2016) and thirteen site-years for experiments conducted in the Sacramento Valley, the San Joaquin Valley, and the Intermountain Region using eleven varieties of spring wheat.

A quantitative assessment was performed of the relative contribution of N fertilizers applied either pre-plant, at the early vegetative growth stages (late-tillering/early jointing), at the transition from the vegetative to reproductive growth stage (late-boot/early heading) or at anthesis. In-season applications of N fertilizer increased grain yield, grain protein content and apparent fertilizer recovery compared to pre-plant applications. Overall, in-season applications increased rates of N recovery in grain by 23% compared to equivalent quantities applied pre-plant, with applications at the early vegetative stages increasing both grain yield and grain protein content. Applications during the reproductive stages primarily increased grain protein content only. While the degree of crop response to N fertilizer applications varied considerably among site-years, the overall effect of N timing was generally consistent across all regions and varieties in the study. In a subset of the trials, the use of slow-release and fertilizer sources was compared to urea at pre-plant and early-vegetative stages and found to have no measurable positive or negative effect compared to urea.

In order to account for the spatial and temporal variability of crop responses to N fertilizer application, and to develop diagnostic thresholds for soil and plant indicators of N deficiency/sufficiency, in-season plant-soil measurements were made at a subset of the trials corresponding to in-season application timings. Soil nitrate-N concentrations in the top 1 foot of the soil profile, relative canopy NDVI, and relative leaf chlorophyll concentrations each provided unique information about the likelihood of crop response to subsequent N fertilization During the early vegetative stages of growth, soil nitrate-N in the top 1 foot of soil was the best predictor of crop response to N fertilization; whereas, during the reproductive growth stages, canopy and leaf measurements were better predictors of crop response to N fertilization. Overall, these findings suggest that N fertilizer management in California wheat can be optimized by shifting more of the total N fertilizer application from pre-season to in-season. In addition, in-season applications can be guided in real-time by site-specific measurements of the plant-soil environment using relatively low-cost tools and methods.

D. Introduction

Nitrogen (N) fertilizer management is a key determinant of the productivity and profitability of spring wheat. Wheat growers are paid not only for crop yield, but also for grain protein content, and achieving acceptable protein content is a continual challenge for California wheat producers. This challenge is more extreme in certain contexts, such as in the Intermountain area where there is often a discount for wheat with less than 14% protein compared to 12-13% in many California markets, as well as for particular types of wheat, such as durum wheat grown in the San Joaquin Valley. Grain yield and protein content are often inversely related and influenced by environmental factors (Kibte and Evans, 1984) such the rate and application timing of N fertilizer. High rates of pre-season N fertilization can be attractive to growers due to the reduced cost of the pre-season forms of N and the ease of application. However, applying high rates of N pre-plant can also result in reduced grain protein content because average root-zone soil N levels available for plant N uptake may have declined once the crop reaches the grain filling stage, which is a critical time in determining grain protein. Additionally, very high early rates of N fertilization may cause excessive vegetative growth and lodging as well as increase N losses to the environment through pathways such as nitrate leaching.

For these reasons, this study evaluated how the timing of N applications affects the yield and protein content of spring wheats grown in diverse California environments. The goal of this work was to equip growers and crop consultants with a better understanding of the need for N at various stages of crop growth and to provide guidelines as to appropriate rates based on the use of in-field tests of the plant-soil environment. In experiments conducted over a five year period in the Intermountain Region, the Sacramento Valley, and the San Joaquin Valley, N fertilizer was applied at different rates and in different proportions at four crop growth stages: 1) pre-plant; 2) early-vegetative (late-tillering to early-jointing) 3) early reproductive (late-boot to early-heading); and 4) flowering (anthesis). For a given N application rate, some treatments received all of the N fertilizer pre-plant, whereas others received none until the early vegetative growth stage, and still others received a portion at each of two, three or four crop growth stages. For analyses of the effect of N application timing on wheat productivity, only trials where there were treatment variations in the amount of N applied at each stage of crop growth under investigation (pre-plant, early-vegetative, early reproductive, flowering) were included. A subset of the experiments were conducted on fields where the previous crop had been unfertilized to ensure low residual soil N concentrations and improve the ability to measure contributions to plant growth from fertilizer additions. All treatments were replicated four times in randomized complete blocks. For the majority of the study, urea was the form of fertilizer used, although a subset of treatments and site-years also included treatments with slow-release forms of fertilizer (ESN and SuperU) as points of comparison to equivalent applications of urea. Fertilizer applied pre-plant was lightly incorporated into the soil profile at the time of planting. In-season applications were broadcast-applied just before rain or irrigation events to ensure that the N was available in the crop root zone and that volatilization losses were minimized.

Prior to the start of the season, pre-plant soil samples were taken to assess baseline soil nitrate-N concentrations. During the season, soil samples were taken from the top foot of the soil profile at critical stages of crop development from a subset of treatments that varied in N rate and application timing. These samples were analyzed for nitrate-N using both laboratory and quick-test methods. In addition to soil monitoring, leaf chlorophyll and canopy NDVI (using atLEAF chlorophyll meter and Trimble Greenseeker NDVI meter, respectively) were measured on a periodic basis throughout the season. Leaf tissue samples were also collected at critical growth stages on a subset of samples in order to relate these proximal sensed measurements to a biophysical measurement. Yield was measured from a 100 ft^2 area per treatment-replication combination using a small plot combine harvester. Grain samples were corrected to 12% MC and cleaned via forced air. Subsequently, protein concentration was determined via NIR spectroscopy. Quantitative relationships between wheat productivity and N fertilizer application timing and totals were determined. In addition, relationships between proximal sensed plant measurements, in-season soil measurements and wheat productivity were determined and used to delineate crop fertilizer demand throughout the season as well as the likelihood of crop response to a post-measurement fertilizer application. Data were analyzed using a combination of linear and non-linear mixed-effects models with the ‘nlme’ package in R version 3.2.2 with fixed effects used to test hypotheses and random effects used to quantify variance relationships from generalized factors.

E. Work Description

Task 1. Selection of Research Sites, Finalization of Sampling Schemes, Sample-handling Protocols. *Investigators finalized sites, sampling plans and handling protocols before the start of each season. Sites included the UC Intermountain Research and Extension Center in Tulelake, CA, the UC Davis Agronomy Research Fields, the UC Davis Russell Ranch experimental plots and the UC Westside Research and Extension Center in Five Points, CA. Rates, treatment structures and sampling schemes evolved throughout the experiment as investigators learned more about overall N response and effect of timing, and the relative value of the various in-season measurements used.*

Task 2. Establishment of N Fertilizer Rate and Timing Treatments and collect samples and data.

Subtask a. choose varieties to use: *eleven varieties included over the course of the study.*

Subtask b. preplant soil sample collection and analysis: *samples collected from sites prior to the start of 2013-2016 seasons.*

Subtask c. planting and establishment of baseline fertilization needs (P, K) and residual nitrate: *samples collected from sites prior to the start of 2013-2015 seasons. Sites planted yearly.*

Subtask d. continue with split application treatments during season (begin in May and end in July at IREC; begin in winter and end in May in SJV and Sacramento. Valley): *accomplished annually 2013-2016*.

Subtask e. Harvest for yields, and collect samples for grain quality, protein in June in SJV and Sacramento Valley sites, September at IREC, all three years: *accomplished annually 2013-2016*.

Table 1. Indicates the average and the range of N fertilizer treatment rates (lb/acre) by application timing for reported data.

Region	Site	Year		Preplant	Early Vegetative	Early Reproductive	Flowering	Total
				lb / acre N				
Intermountain	IREC	2011 -2012	mean	90	50	30	30	200
			range	0 - 250	0 - 200	0 - 100	0 - 50	0 - 350
Intermountain	IREC	2012 - 2013		90	50	30	30	200
				0 - 250	0 - 200	0 - 100	0 - 50	0 - 350
Intermountain	IREC	2013 - 2014		120	40	20	10	190
				0 - 300	0 - 250	0 - 75	0 - 50	0 - 300
Intermountain	IREC	2014 - 2015		90	70	20	10	190
				0 - 300	0 - 300	0 - 75	0 - 50	0 - 300
Intermountain	IREC	2015 - 2016		70	80	10	10	170
				0 - 240	0 - 240	0 - 120	0 - 50	0 - 300
Sac. Valley	UCD	2013 - 2014		120	40	20	10	190
				0 - 300	0 - 150	0 - 100	0 - 50	0 - 300
Sac. Valley	Russell Ranch	2013 - 2014		50	50	20	0	120
				0 - 100	0 - 150	0 - 50	0 - 0	0 - 175
Sac. Valley	UCD	2014 - 2015		90	80	10	10	190
				0 - 300	0 - 300	0 - 100	0 - 50	0 - 300
Sac. Valley	Russell Ranch	2014 - 2015		70	60	0	0	130
				0 - 180	0 - 150	0 - 0	0 - 0	0 - 180
Sac. Valley	UCD	2015 - 2016		70	80	10	10	170
				0 - 240	0 - 240	0 - 120	0 - 50	0 - 300
San Joaq. Valley	WSREC	2012 - 2013		50	50	30	30	160
				0 - 227	0 - 100	0 - 50	0 - 50	0 - 277
San Joaq. Valley	WSREC	2013 - 2014		70	60	30	20	180
				0 - 300	0 - 300	0 - 100	0 - 90	0 - 300
San Joaq. Valley	WSREC	2015 - 2016		70	80	10	10	170
				0 - 240	0 - 240	0 - 120	0 - 40	0 - 300
		Overall	mean	81	61	18	14	174
			range	0 - 300	0 - 300	0 - 120	0 - 90	0 - 350

Task 3. Tissue Sampling (Spring-SJV & Sacramento Valley sites, summer at IREC)

Subtask a. plant tissue / leaf samples collected at research sites across subset of treatments: *accomplished annually at IREC and Sacramento Valley sites and in a single year at SJV site. Tissue sampling occurred on a subset of proximal sensed plots to confirm established relationship between leaf tissue N content and leaf chlorophyll; proximal sensed measurements were used on a broader number of treatments.*

Subtask b. tissue samples submitted for analyses (late Spring, SJV and Sacramento Valley sites, late summer at IREC site): *accomplished annually at IREC and Sacramento Valley sites and in a single year at SJV site. Tissue sampling occurred on a subset of proximal sensed plots to confirm established relationship between leaf tissue N content and leaf chlorophyll; proximal sensed measurements were used on a broader number of treatments.*

Table 2. Indicates site-years for reported data where in-season soil nitrate-N concentrations were measured in the top foot and canopy NDVI and leaf chlorophyll measurements were taken via Greenseeker NDVI and atLEAF chlorophyll meters, respectively.

Region	Site	Year	In-season sampling		
			soil nitrate	canopy NDVI	leaf chlorophyll
Intermountain	IREC	2011 -2012			
Intermountain	IREC	2012 - 2013			
Intermountain	IREC	2013 - 2014	x	x	x
Intermountain	IREC	2014 - 2015	x	x	x
Intermountain	IREC	2015 - 2016	x	x	x
Sac. Valley	UCD	2013 - 2014	x	x	x
Sac. Valley	Russell Ranch	2013 - 2014	x	x	x
Sac. Valley	UCD	2014 - 2015	x	x	x
Sac. Valley	Russell Ranch	2014 - 2015	x	x	x
Sac. Valley	UCD	2015 - 2016	x	x	x
San Joaq. Valley	WSREC	2012 - 2013			
San Joaq. Valley	WSREC	2013 - 2014			
San Joaq. Valley	WSREC	2015 - 2016			

<u>Task 4. Deep post-harvest soil sample collection, Handling (June or July, SJV and Sacramento
Valley sites, September at IREC sites, 2014, 2015, 2016)</u>
Subtask a. Samples collected beginning in June at SJV site each year, July in Sacramento Valley site each year, and in September each year at IREC northern CA site: *samples collected to 8 feet in a subset of site-years (6)*.

<u>Task 5. Laboratory Analysis (fall and winter, 2014, 2015, 2016)</u>
Subtask a. Grinding of samples followed by nutrient analysis (Nitrate-N, limited ammonium-N, P, K to represent the site conditions) using widely accepted protocols for each parameter: *accomplished annually 2013-2016.*
Subtask b. Protein analysis – standard accepted whole grain protein protocols: *accomplished annually via NIR spectroscopy 2013-2016.*

<u>Task 6. Data Analysis and Interpretation (each year, various times of year)</u>
Subtask a. Data entry, quality control of raw data: *accomplished annually 2013-2016.*
Subtask b. Statistical analysis, regression analysis, correlations: *accomplished annually 2013-2016.*
Subtask c. data summary presentations, interpretation, analysis: *accomplished annually 2013-2016.*

Task 7. Reporting and Outreach. (2014, 2015, 2016)

Over twenty presentations were made during the reporting period to various extension audiences that included growers, researchers and industry professionals in the state of California. In addition, five extension publications and three agricultural press stories were published related to the work. At least two manuscripts are in preparation for submission to peer-reviewed journals. Finally, the data developed in the course of this grant will help to underpin web-based N decision support tools currently under development.

F. Data/Results

Overall spring wheat response to N

Over the 13 site-years, a wide range of wheat productivity and fertilizer N use was measured across treatments and years (Table 3). The overall average grain yield (6500 lb acre^{-1}) and protein concentration (12.6%) correspond to statewide averages, and average grain N recovery and N fertilizer use efficiency were 145 lb acre^{-1} and 0.39, respectively.

The yield response of wheat to N fertilization followed a quadratic response [y = a*(N rate)^2 + b*(N rate) + c], and the overall yield response was positive between 0 and 241 lb acre^{-1} fertilizer N applied (Figure 1; Table 4). There were no significant interactions among regions with respect to the intercept or the quadratic term, but trials in the San Joaquin Valley did have a lower overall N rate response than the Intermountain Region and the Sacramento Valley ($P < 0.001$).

The grain protein response also followed a quadratic response, with interactions among the regions in grain protein outcomes as a function of N fertilizer applied (Figure 2; Table 5). Overall, grain protein content was higher in the Intermountain Region, and the rate of response to N fertilization was less than in the Sacramento Valley and the San Joaquin Valley ($P < 0.001$) (Figure 2; Table 5). In the Sacramento Valley and the San Joaquin Valley, grain protein responded up to 310 and 254 lb acre^{-1} fertilizer N applied, whereas there was a positive grain protein response to N fertilization across all rates of application in the Intermountain Region.

The grain N recovery, calculated as the grain yield multiplied by the total N content in the grain, combines both the yield and protein responses and gives an integrated overall picture of crop N response. Overall, crops in these trials were responsive to fertilizer N between 0 and 267 lb acre^{-1} fertilizer N applied (Figure 3; Table 6). However, as with grain protein, there were significant interactions between the regions with respect to the rate of response to N ($P = 0.002$). Specifically, the trials in the Sacramento Valley responded to N fertilization at a higher rate than those in the Intermountain Region or the San Joaquin Valley (Table 6).

Table 3. Indicates the mean and range of treatment values for the grain yield (lb/acre), grain protein concentration (%), grain nitrogen (N) recovery (lb/acre) and apparent N fertilizer use efficiency (FUE) for each of the thirteen site-years included in the report.

Region	Site	Year		Yield (lb/acre)	Protein (%)	Grain N recovery (lb/acre)	Apparent N FUE
Intermountain	IREC	2011 -2012	mean	8240	13.4	194	0.52
			range	5750 - 9050	9.6 - 15.3	97 - 231	0.35 - 0.76
Intermountain	IREC	2012 - 2013		6980	13.7	168	0.47
				3960 - 7720	11.4 - 15.8	79 - 191	0.31 - 0.72
Intermountain	IREC	2013 - 2014		5260	13.5	126	0.43
				1720 - 6840	11 - 15.2	40 - 171	0.3 - 0.63
Intermountain	IREC	2014 - 2015		5350	13.2	124	0.40
				3290 - 5790	11.1 - 14.5	64 - 147	0.25 - 0.49
Intermountain	IREC	2015 - 2016		8080	13.8	196	0.02
				7500 - 8470	13.5 - 14.5	180 - 213	-0.07 - 0.22
Sac. Valley	UCD	2013 - 2014		8040	11.6	165	0.55
				4240 - 8820	8 - 13.3	59 - 201	0.4 - 0.80
Sac. Valley	Russell Ranch	2013 - 2014		4980	9.6	85	0.45
				3730 - 5840	8.1 - 10.7	54 - 107	0.41 - 0.46
Sac. Valley	UCD	2014 - 2015		6000	11.4	122	0.42
				3240 - 7080	7 - 13.7	40 - 155	0.22 - 0.72
Sac. Valley	Russell Ranch	2014 - 2015		5120	10.2	94	0.43
				3590 - 5850	8.6 - 11.8	56 - 121	0.24 - 0.57
Sac. Valley	UCD	2015 - 2016		6800	13.6	162	0.33
				6020 - 7580	10.5 - 15	111 - 195	0.17 - 0.78
San Joaq. Valley	WSREC	2012 - 2013		8350	12.5	183	0.36
				7270 - 8970	10.2 - 13.3	130 - 210	0.26 - 0.62
San Joaq. Valley	WSREC	2013 - 2014		7200	12.9	163	0.33
				4520 - 7870	10.4 - 14.1	83 - 184	0.12 - 0.54
San Joaq. Valley	WSREC	2015 - 2016		4130	14.6	106	0.31
				3810 - 4490	12.2 - 15.5	82 - 118	-0.23 - 0.57
		Overall	mean	6500	12.6	145	0.39
			range	1720 - 9050	7 - 15.8	40 - 231	-0.23 - 0.80

Fertilizer use efficiency can be inferred from the grain N recovery responses for a given rate of N application by expressing the grain N recovery beyond what was attained at the zero N application rate as a percentage of the rate of fertilization. At yield maximizing rates of N fertilization (241 lb acre^{-1} fertilizer N applied), apparent fertilizer recovery was 44%, 61% and 41% in the Intermountain Region, the Sacramento Valley, and the San Joaquin Valley, respectively, and 49% overall.

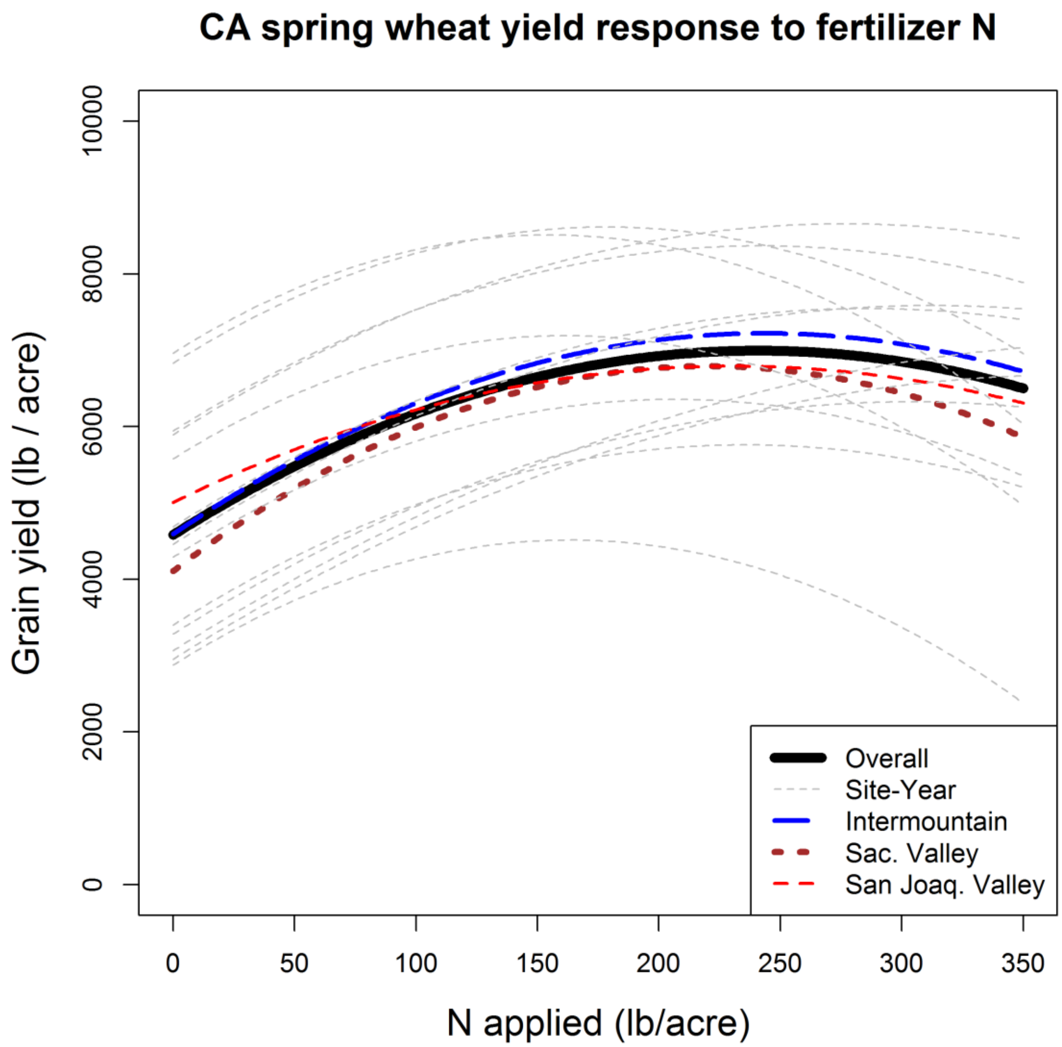

Figure 1. Grain yield response of spring wheat to applied N fertilizer across 13 site-years in the Intermountain Region, the Sacramento Valley and the San Joaquin Valley. Parameter values for response are presented in Table 4.

Table 4. Parameter values and associated standard error (SE) estimates for quadratic response [y= a*(N rate)^2 + b*(N rate) + c] of wheat grain yield to fertilizer N applications across 13 site-years in the Intermountain Region, the Sacramento Valley and the San Joaquin Valley.

Grain Yield (lb /acre) Parameter Values									
	intercept ± SE			slope ± SE			quadratic ± SE		
Intermountain	4592	±	1047	21.58	±	1.72	-0.044	±	0.012
Sac. Valley	4107	±	739	24.38	±	1.39	-0.055	±	0.009
San Joaq. Valley	5007	±	1201	15.50	±	1.78	-0.034	±	0.013
Overall	4581	±	417	20.03	±	0.67	-0.042	±	0.005

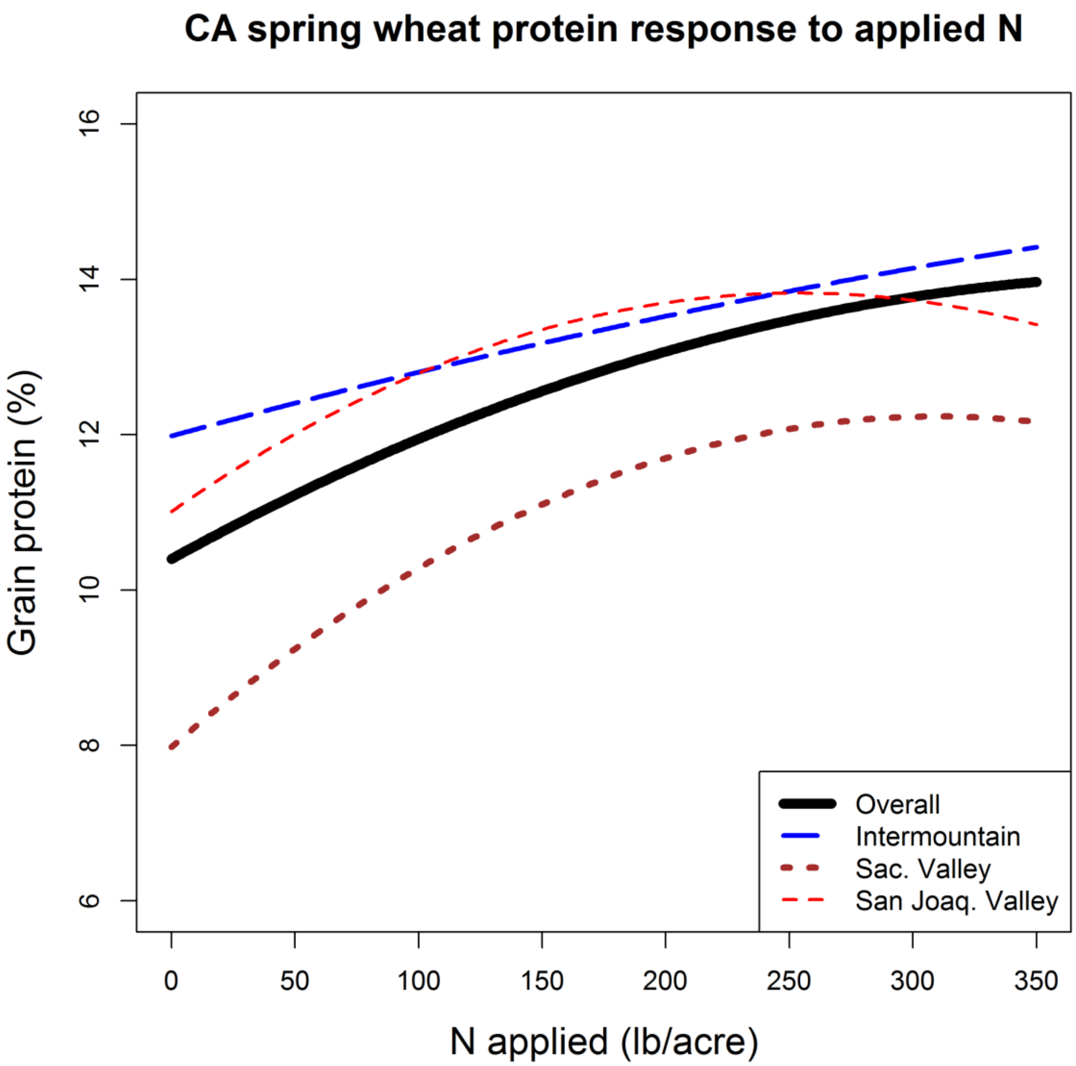

Figure 2. Grain protein response of spring wheat to applied N fertilizer across 13 site-years in the Intermountain Region, the Sacramento Valley and the San Joaquin Valley. Parameter values for response are presented in Table 5.

Table 5. Parameter values and associated standard error (SE) estimates for quadratic response [y= a*(N rate)^2 + b*(N rate) + c] of wheat grain protein to fertilizer N applications across 13 site-years in the Intermountain Region, the Sacramento Valley and the San Joaquin Valley.

Grain Protein (%) Parameter Values									
	intercept ± SE			slope ± SE			quadratic ± SE		
Intermountain	11.98	±	0.95	0.0087	±	0.0023	-0.000005	±	0.000024
Sac. Valley	7.98	±	0.63	0.0275	±	0.0019	-0.000044	±	0.000025
San Joaq. Valley	11.01	±	1.03	0.0222	±	0.0024	-0.000044	±	0.000025
Overall	10.40	±	0.93	0.0176	±	0.0009	-0.000021	±	0.000009

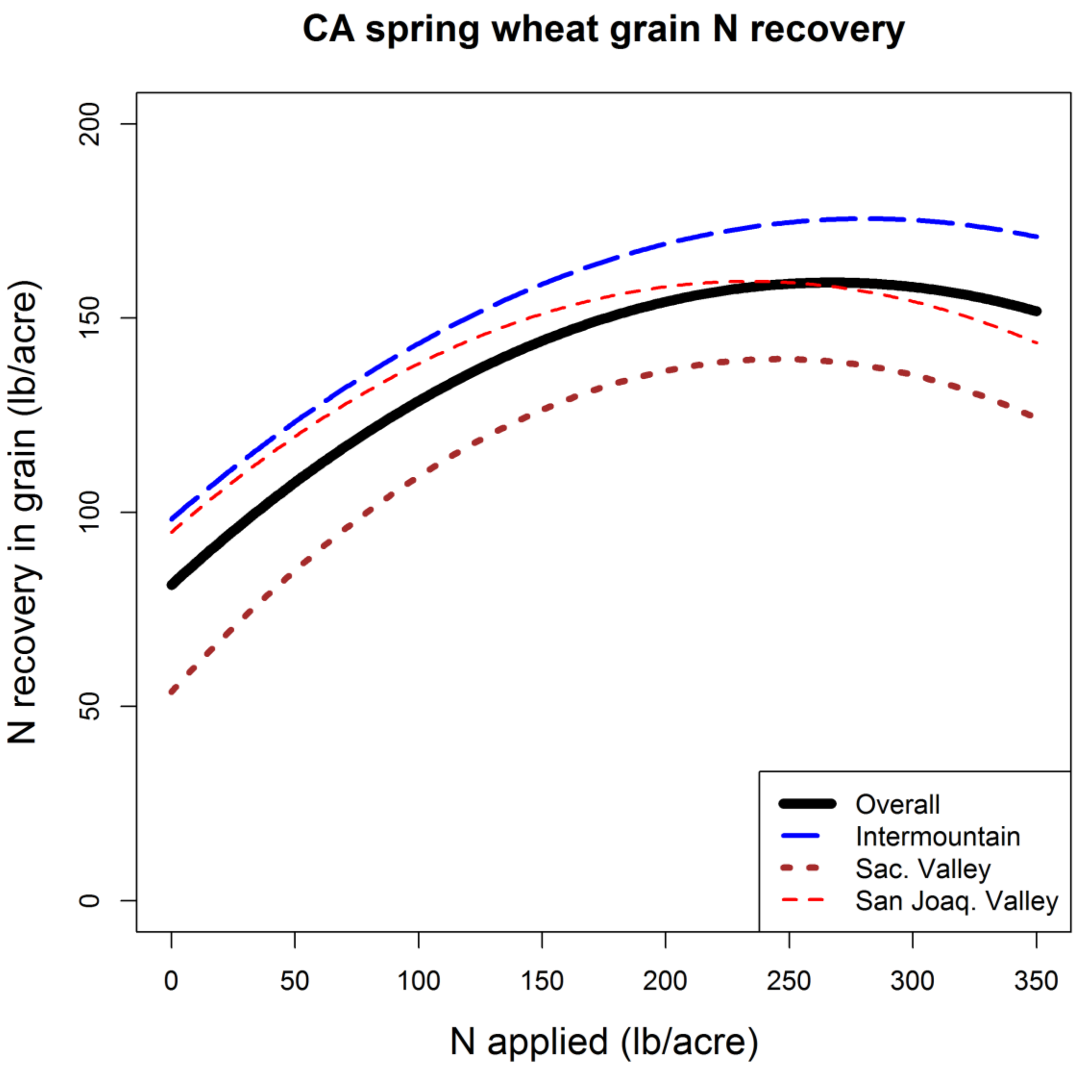

Figure 3. Grain N recovery of spring wheat as a function of applied N fertilizer across 13 site-years in the Intermountain Region, the Sacramento Valley and the San Joaquin Valley. Parameter values for response are presented in Table 6.

Table 6. Parameter values and associated standard error (SE) estimates for quadratic response [y= a*(N rate)^2 + b*(N rate) + c] of wheat grain N recovery as a function of fertilizer N applications across 13 site-years in the Intermountain Region, the Sacramento Valley and the San Joaquin Valley.

Grain N Recovery (lb / acre) Parameter Values									
	intercept ± SE			slope ± SE			quadratic ± SE		
Intermountain	98	±	38	0.550	±	0.044	-0.0010	±	0.0003
Sac. Valley	54	±	24	0.696	±	0.036	-0.0014	±	0.0002
San Joaq. Valley	95	±	40	0.552	±	0.046	-0.0012	±	0.0004
Overall	81	±	12	0.580	±	0.017	-0.0011	±	0.0001

There were eleven varieties included in the experiment overall (Hank, WB9518, WB9668, Yecora Rojo, BlancaGrande515, Summit515, Volante, Patwin, Patwin515, Cal Rojo, WB9229), and a subset of the trials explicitly included crop varieties as a treatment in a split plot design. Within the trials that included variety as a treatment in a split plot design, seven total varieties were tested (Hank, WB9518, WB9668, Yecora Rojo, BlancaGrande515, Summit515, and Volante). Among these, there was not a significant difference among varieties in crop response to fertilizer N (P = 0.29).

Effect of N application timing on wheat yield and quality

Overall, in-season applications of N fertilizer resulted in more efficient fertilizer use than applications made pre-plant. In-season N applications made at the early vegetative stages of crop growth (mid-tillering to early-jointing) resulted in a higher rate of crop yield response compared to an equivalent amount of fertilizer N applied pre-plant (P < 0.001). Grain protein was also significantly higher in crops where fertilizer was applied mid-tillering to early-jointing versus pre-plant in the Intermountain Region and the Sacramento Valley (P > 0.001) but not in the San Joaquin Valley trials. Figure 4 depicts average differences for 150 lb ac^{1} N applied pre-plant versus at tillering across all trials separated by region.

Crops in the Sacramento Valley had a significantly higher grain yield response to fertilizer N at the early-reproductive stages (late-boot to early-heading) compared to an equivalent amount of fertilizer N applied pre-plant (P < 0.001). However, for crops in the Intermountain Region and the San Joaquin Valley there was not a significant yield increase for late-boot to early-heading applications of N compared to pre-plant applications. For grain protein, there was a significant increase across all regions for applications made at the early-reproductive growth stage compared to those made pre-plant (P < 0.001). Figure 5 depicts average differences in grain yield and protein content for 60 lb ac^{1} N applied pre-plant versus at the late-boot to early heading stage.

Applications of N fertilizer made at the flowering (anthesis) stage of growth resulted in a higher grain protein response compared to equivalent amounts applied pre-plant for crops across all regions (P < 0.001). However, there were no differences in yield based on changes in fertilizer application timing from pre-plant to flowering. Figure 6 depicts average differences in grain yield and protein content for 30 lb ac^{1} N applied pre-plant versus at the late-boot to early heading stage.

Grain N recovery was significantly higher for in-season applications of N compared to pre-plant applications of N for all in-season application timing tested in these trials across all regions. Figure 7 depicts differences in grain N recovery between pre-plant and in-season N application timings for 150 lb $acre^{-1}$ at the mid-tillering to early-jointing stage, 60 lb $acre^{-1}$ at the late-boot to early-heading stage, and 30 lb $acre^{-1}$ at the flowering stage. Overall, after correcting for differences in fertilizer application rates across the timings, in-season applications resulted in rates of grain N recovery that were 23% ± 3% higher for in-season N applications compared to pre-plant applications (P < 0.001). For average rates of application (167 lb $acre^{-1}$), this resulted in a 10% increase in fertilizer use efficiency compared to N fertilizer applied pre-plant.

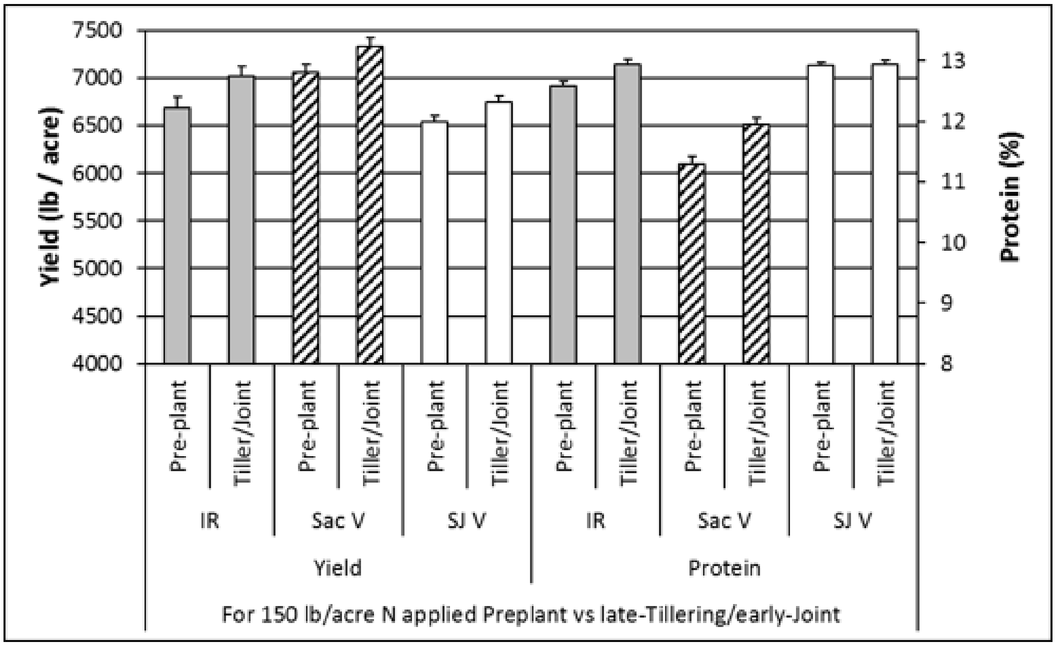

Figure 4. The effect of 150 lb/acre N fertilizer applied either pre-plant or at the early-vegetative (mid-tillering to early joint) stage of growth on wheat grain yield and protein content for 11 site-years of trials conducted in the Intermountain Region (IR—5 site years), the Sacramento Valley (Sac V—3 site years), or the San Joaquin Valley (SJ V—3 site years).

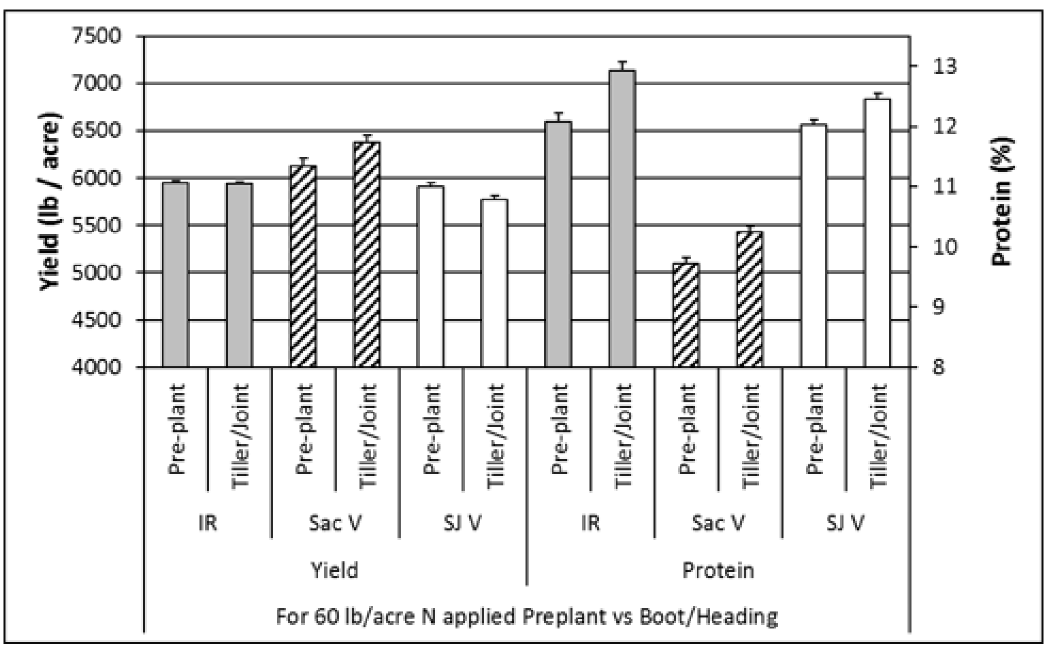

Figure 5. The effect of 60 lb/acre N fertilizer applied either pre-plant or at the early-reproductive (late-boot to early heading) stage of growth on wheat grain yield and protein content for 11 site-years of trials conducted in the Intermountain Region (IR—5 site years), the Sacramento Valley (Sac V—3 site years), or the San Joaquin Valley (SJ V—3 site years).

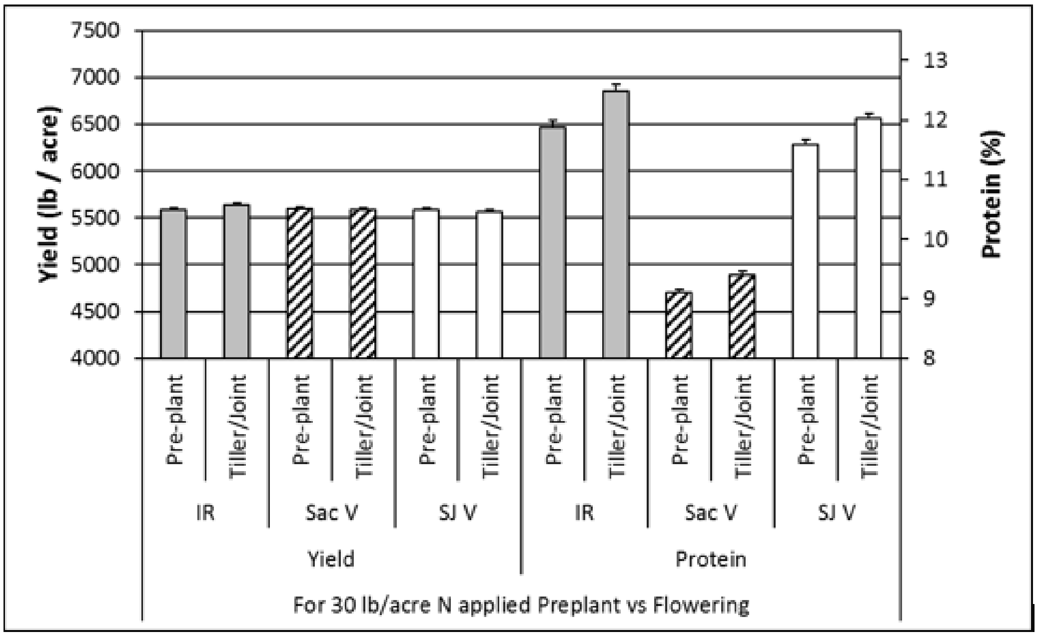

Figure 6. The effect of 30 lb/acre N fertilizer applied either pre-plant or at the flowering (anthesis) stage of growth on wheat grain yield and protein content for 11 site-years of trials conducted in the Intermountain Region (IR—5 site years), the Sacramento Valley (Sac V—3 site years), or the San Joaquin Valley (SJ V—3 site years).

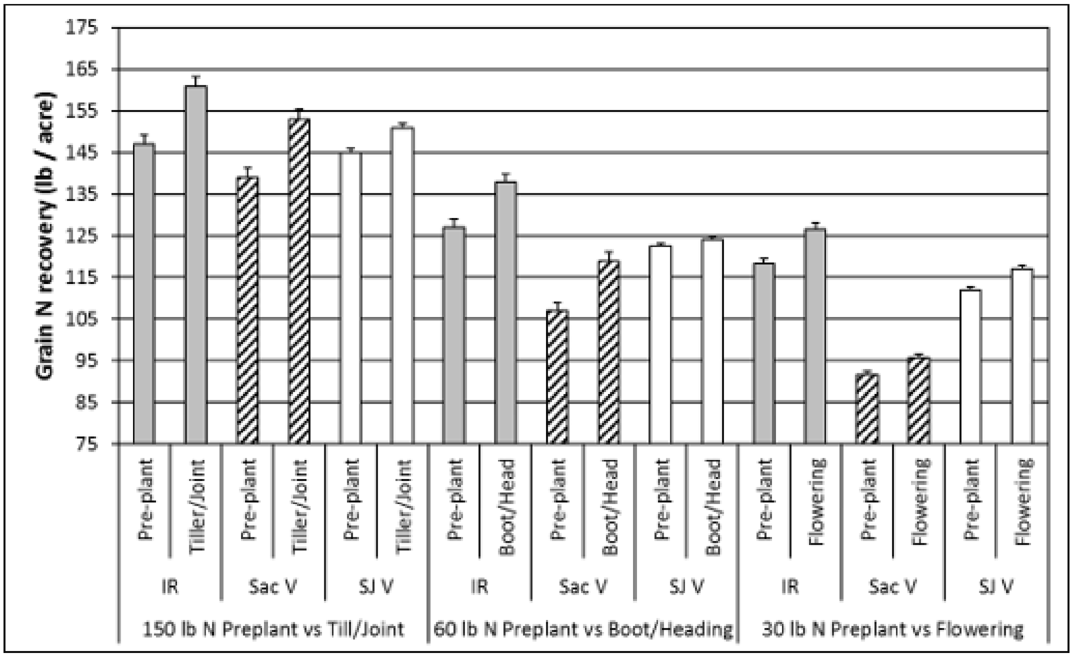

Figure 7. The effect of N fertilizer applied either pre-plant or at the early-vegetative, early-reproductive, or flowering stages of growth at N rates of 150, 60 or 30 lb/acre, respectively, on grain N recovery. Represents 11 site-years of trials conducted in the Intermountain Region (IR—5 site years), the Sacramento Valley (Sac V—3 site years), or the San Joaquin Valley (SJ V—3 site years).

In-field, in-season measurements to predict the degree of crop response to in-season N applications

At the Intermountain Region and Sacramento Valley sites, in-season soil samples were taken from the top 1 foot of soil on a subset of treatments immediately prior to in-season fertilizer application events. Treatments for soil sampling were chosen in order to adequately capture the range of pre-plant N fertilizer rates in a given trial and included the zero N application rate as a control. These samples were analyzed for nitrate-N concentrations via KCl extraction and spectroscopy on four replications per treatment. Subsequently, linear regressions were performed on site-year specific subsets of the data to infer values for N rate treatments for which no soil samples were taken at that site-year. For the subset of treatments that received no fertilizer application subsequent to the soil sampling event, a post-hoc linear plateau regression of the effect of soil nitrate-N concentrations on grain N recovery was used to determine the soil nitrate-N concentration threshold beyond which grain N recovery no longer increased significantly. Figure 8 is included as an example of this method as applied to the soil nitrate-N concentrations measured at the early vegetative stage of growth.

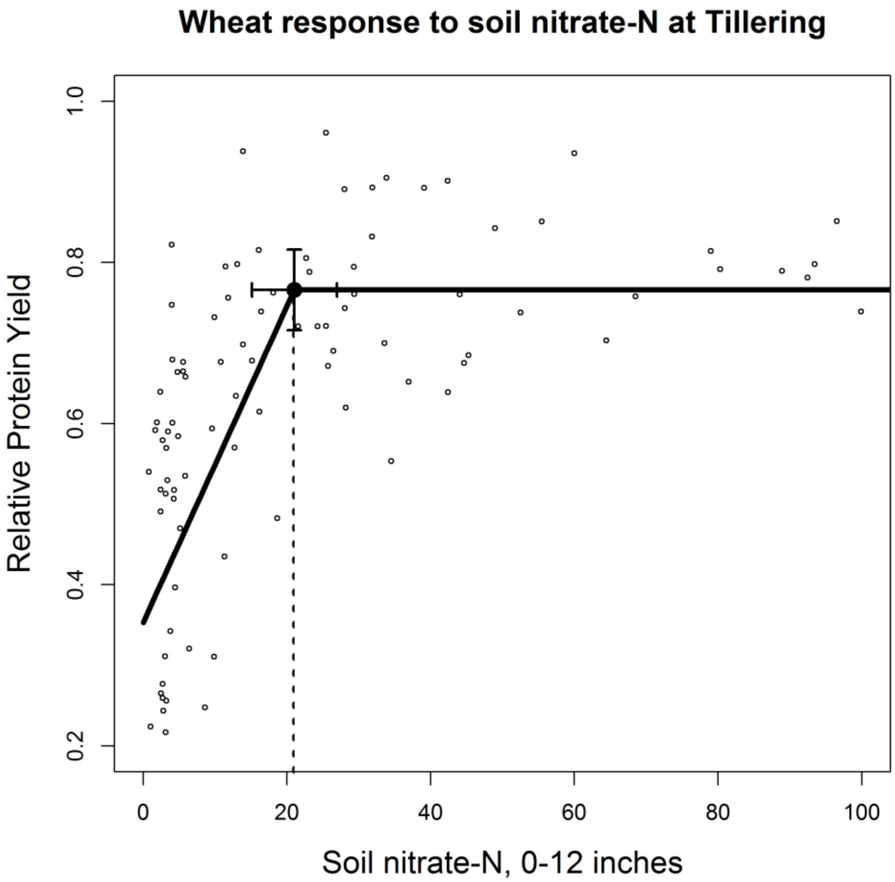

Figure 8. Soil nitrate-N (ppm) in the top 1 foot of soil as the predictor of the site-specific relative grain protein yield in plots where no fertilizer N was added post-measurement. A linear plateau model was used to determine the intercept values (y = 0.77 ± 0.04; x = 20.4 ± 5.0) beyond which increases to relative grain protein yield as a function of increasing soil nitrate-N concentrations are no longer significant.

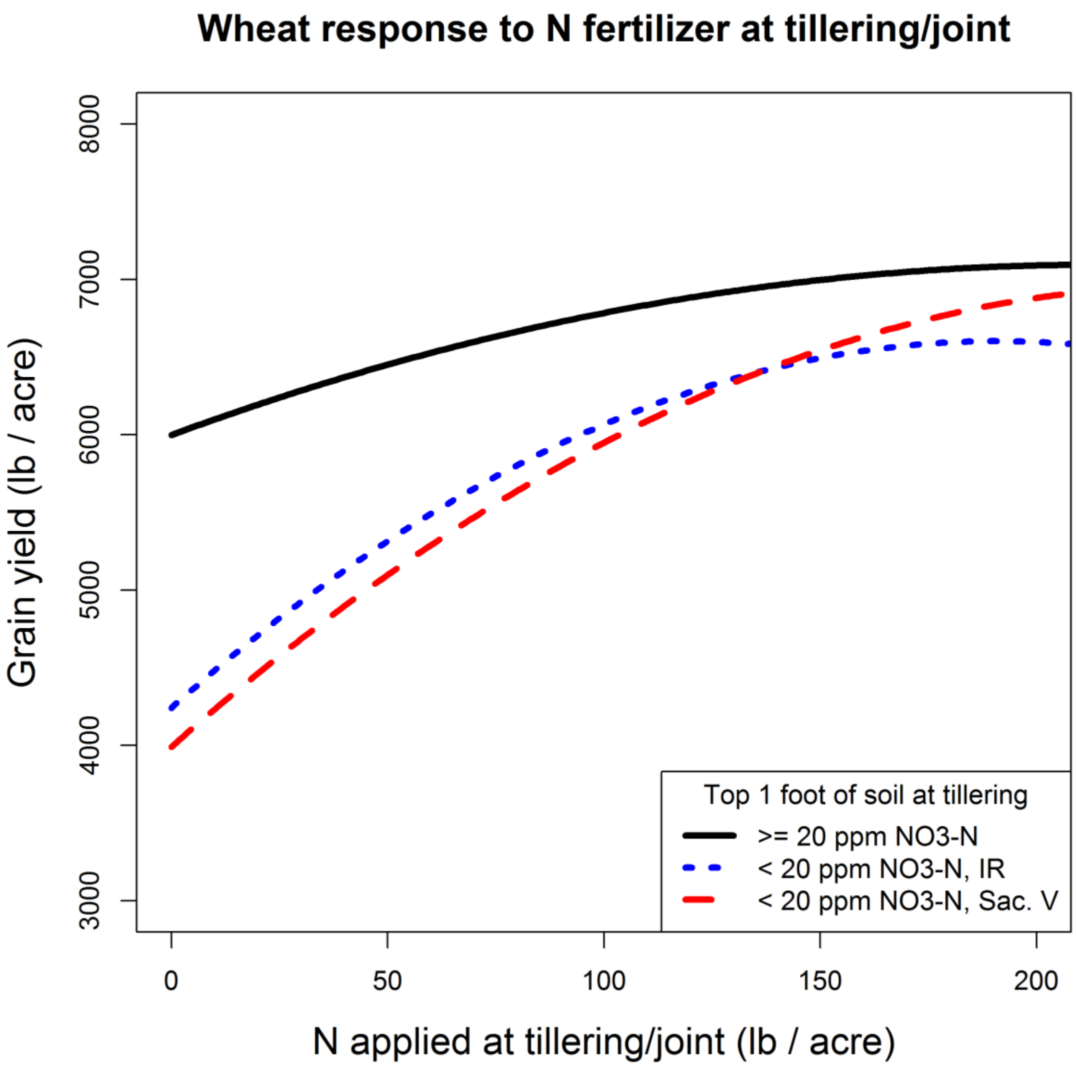

Figure 9. Spring wheat grain yield response (lb acre^{-1}) to applications of N fertilizer (lb acre^{-1}) at the mid-tillering to early jointing stage where soil nitrate-N (ppm) in the top 1 foot of soil was ≥ 20 ppm or < 20 ppm NO_3-N. Figure represents measurements across 3 site-years in the Intermountain Region (IR) and 5 site-years in the Sacramento Valley (Sac. V). Parameter values for response are presented in Table 7.

Table 7. Parameter values and associated standard error (SE) estimates for quadratic response [y= a*(N rate)^2 + b*(N rate) + c] of wheat grain yield to fertilizer N applications across 3 site-years in the Intermountain Region (IR) and 5 site-years in the Sacramento Valley (Sac. V) where soil nitrate-N (ppm) in the top 1 foot of soil was ≥ 20 ppm or < 20 ppm NO_3-N.

Grain Yield (lb /acre) Parameter Values									
	intercept ± SE			slope ± SE			quadratic ± SE		
>= 20 ppm NO3-N	5998	±	759	10.25	±	4.49	-0.024	±	0.011
< 20 ppm NO3-N, IR	4241	±	1885	24.71	±	2.47	-0.065	±	0.027
< 20 ppm NO3-N, Sac. V	3990	±	1124	24.73	±	1.34	-0.051	±	0.016

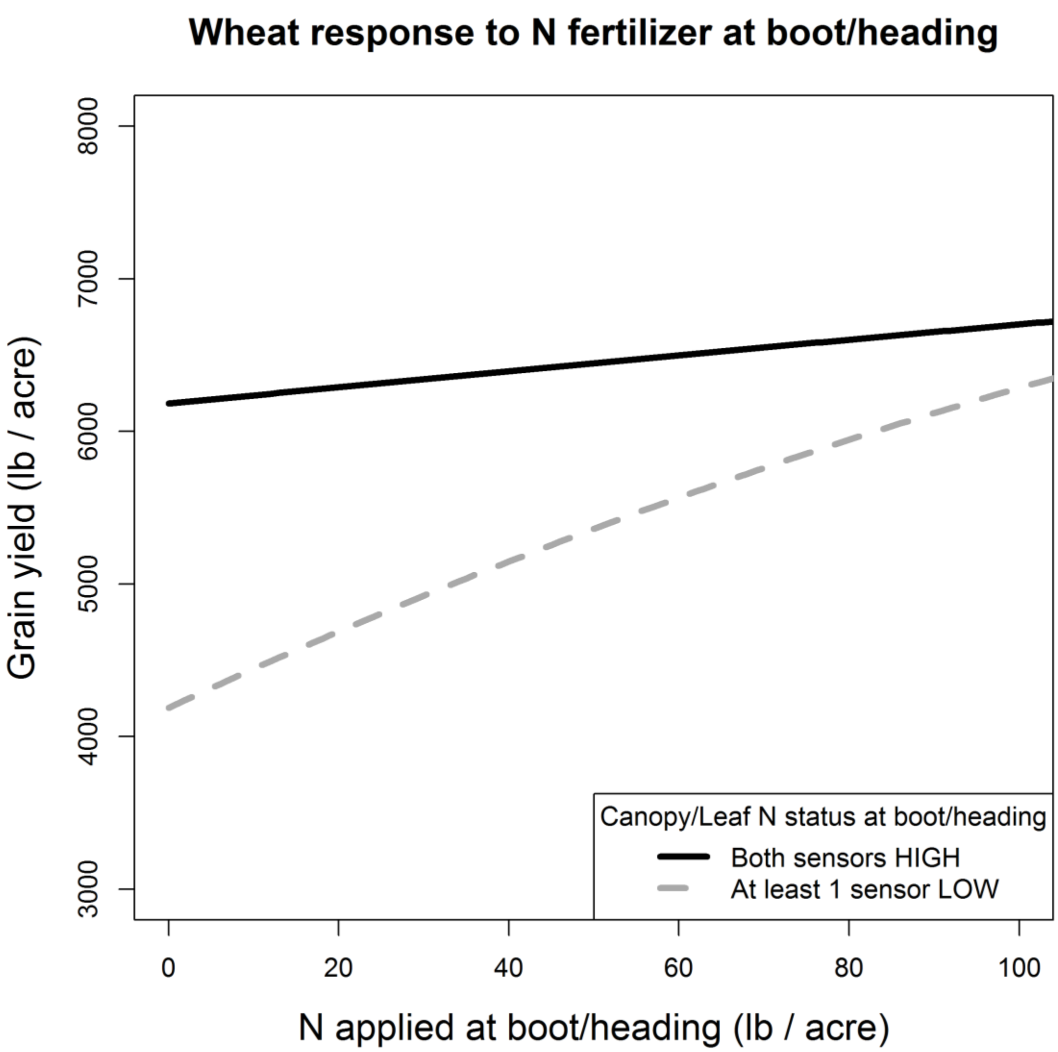

Figure 10. Spring wheat grain yield response (lb acre^{-1}) to applications of N fertilizer (lb acre^{-1}) at the late-boot to early-heading stage where relative canopy NDVI and leaf chlorophyll measurements were ≥ or < sufficiency/deficiency thresholds (0.97 for Greenseeker NDVI meter and 0.96 for atLEAF chlorophyll meter). Figure represents measurements across 3 site-years in the Intermountain Region (IR) and 5 site-years in the Sacramento Valley (Sac. V). Parameter values for response are presented in Table 8.

Table 8. Parameter values and associated standard error (SE) estimates for quadratic response [y= a*(N rate)^2 + b*(N rate) + c] of wheat grain yield to fertilizer N applications across 3 site-years in the Intermountain Region (IR) and 5 site-years in the Sacramento Valley (Sac. V) where relative canopy NDVI and leaf chlorophyll measurements were ≥ or < sufficiency/deficiency thresholds.

Grain Yield (lb /acre) Parameter Values									
	intercept ± SE			slope ± SE			quadratic ± SE		
Both sensors HIGH	6182	±	824	5.41	±	2.08	-0.002	±	0.012
At least 1 sensor LOW	4190	±	742	25.93	±	1.85	-0.050	±	0.017

Similar methods were used to develop thresholds related to canopy NDVI and leaf chlorophyll measurements taken at the various in-season fertilizer N application timings. For these measurements, sampling from a broad range of treatments was more feasible than with the soil samples, and no regression-inferred values were used. Because of site-year differences in abiotic conditions (e.g. water status) and the potential for differences between measurement devices or within a single device over time, all sensor values were expressed as a proportion of the site-year-day specific maxima for the measurement. These relative measurements were then regressed against the post-hoc grain N recovery values on the subset of treatments receiving no further fertilizer subsequent to the measurement event, and threshold values beyond which crop responses were unlikely were determined for each device and application timing. The threshold values were used to divide the dataset into populations that were either greater than/equal to the threshold or less than the threshold. For each subdivision of the dataset, crop response to N applied subsequent to the measurement event was modeled as a quadratic response using a mixed linear model, and the potential for regional interactions was tested.

Regardless of the soil nitrate-N concentration, crop yield responded positively to N fertilizer applied at the early vegetative growth stage (Figure 9). However, the rate of response was significantly higher for crops where soil nitrate-N concentrations in the top 1 foot of the soil profile was < 20 ppm (Figure 9; Table 7). For 100 lb acre^{-1} N applied at the mid-tillering to early-jointing stage, crops where soil nitrate-N in the top 1 foot of soil was ≥ 20 ppm added 780 lb acre^{-1} of grain yield; whereas when soil nitrate-N in the top

1 foot of soil was < 20 ppm, crops in the Sacramento Valley and Intermountain Region added 1944 and 1813 lb acre^{-1} of grain yield, respectively. For the same rate of N application (100 lb acre^{-1}) at the early-vegetative stage, when soil nitrate-N concentrations in the top 1 foot of soil were < 20 ppm, fertilizer use efficiency was 31% and 15% higher in the Sacramento Valley and Intermountain Region, respectively, compared to applications of N fertilizer made when soil nitrate-N in the top 1 foot of soil was ≥ 20 ppm. Of note is that for observations where soil nitrate-N was < 20 ppm at the early-vegetative growth stage, crops in the Intermountain Region were responsive to a smaller range of rates (0 - 194 lb acre^{1} N) than crops in the Sacramento Valley trials (0 - 263 lb acre^{1} N).

At the early reproductive stage of growth (late-boot to early-heading) canopy NDVI and leaf chlorophyll were effective predictors of the magnitude and probability of grain yield response to applications of fertilizer N. The thresholds for sufficiency/deficiency relative to a site-year-field specific reference point for sufficiency were 0.97 for the Greenseeker NDVI meter and 0.96 for the atLEAF chlorophyll meter at the late-boot to early-heading stage of development. When the canopy and penultimate leaves of crops measured at or above these thresholds, there was little grain yield response to subsequent applications of N fertilizer (Figure 10; Table 8). However, when either the canopy NDVI and/or leaf chlorophyll measurements were below these thresholds, the grain yield responded strongly to subsequent N applications (Figure 10; Table 8). For the average N fertilizer rates applied at the late-boot to early-heading stage for this subset of the dataset (56 lb acre^{-1} N) yields increased 1276 lb acre^{-1}and grain N recovery increased 36 lb acre^{-1} compared to increases in grain yield of 291 lb acre^{-1} and increases in grain N recovery of 21 lb acre^{-1} in plots where sensor measurements were above sufficiency/deficiency thresholds. This resulted in a fertilizer use efficiency increase of 27% when sensors indicated deficiency compared to when there was no sensor indication of deficiency and 56 lb acre^{-1} fertilizer N was applied at the late-boot to early-heading stage.

Soil nitrate quick-test development

On a subset of the soil samples collected during the experiment, a simplified version of the nitrate quick test method detailed by Hartz (2010) was applied to dry soil samples that were also tested for nitrate-N by KCl extraction and spectroscopy. This version of the quick test eliminated calcium chloride as a flocculent and wicked liquid onto the colorimetric pad directly from the disturbed solution without waiting for the soil particles to settle (more details of this test can be found at http://smallgrains.ucanr.edu/files/256250.pdf). Across the range of nitrate-N values (0 - 50 ppm), there was a significant log-linear relationship between the test strip reading from the soil nitrate quick-test and the nitrate-N values obtained via KCl extraction ($P<0.001$, $R^2=0.84$) (Figure 11). In addition, the log-linear relationship varied significantly between the mineral soils sampled in the Sacramento Valley and San Joaquin Valley and those in the Intermountain Region ($P < 0.01$). As a result, two separate equations were developed to translate the strip reading obtained from the quick test to a laboratory-equivalent value for the Intermountain Region and the Sacramento and San Joaquin Valleys. For the Intermountain Region, the equation for this is $y = e^{[(\ln(\text{Strip reading (ppm NO3-N)}) * 0.685) + 1.60]}$ while in the Sacramento and San Joaquin Valleys the equation is $y = e^{[(\ln(\text{Strip reading (ppm NO3-N)}) * 0.759) + 1.18]}$.

Effect of slow release fertilizer on grain yield and protein compared to urea

Broadcast applications at the mid-tillering stage of Super U were compared to applications of urea at 2 locations in the 2014-15 season at rates of 150 lb/acre N and 225 lb/acre N. No significant differences were found in grain yield (P = 0.17), grain N recovery (P = 0.45), or grain protein content (P = 0.50) between plots top-dressed with SuperU versus urea. Pre-plant applications of ESN were also compared to pre-plant applications of urea at 3 rates (150, 225, and 300 lb/acre N) at a single site (UCD) across two seasons (2013-14 and 2014-15). Applications were incorporated into the soil via light tillage. There were not significant differences in grain yield (P = 0.99), grain N recovery (P = 0.99), or grain protein content (P = 0.95) among comparisons of ESN and urea.

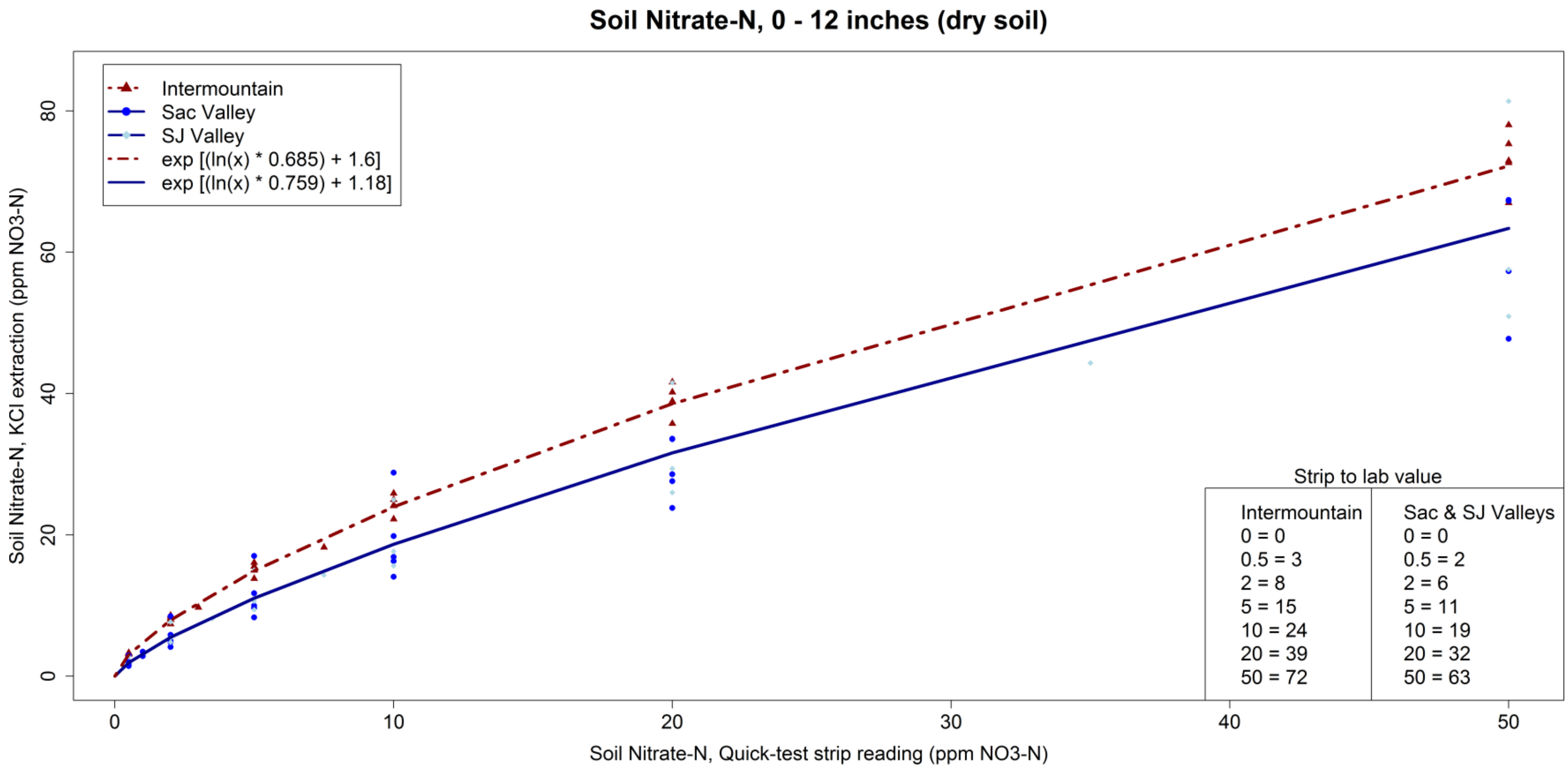

Figure 11. Depicts the log-linear relationship between soil nitrate-N in air-dried soil as measured via KCl extraction and spectrometry versus shaken water extraction and nitrate test strip pads wicked directly into soil-water solution. More details of this procedure can be found at http://smallgrains.ucanr.edu/files/256250.pdf.

Discussion and Conclusions

Overall spring wheat response to N

Of note in the data was the wide range of crop yield responses to N fertilizer applications across site-years as depicted in Figure 1. In spite of this variability, the quadratic response was highly significant for all terms ($P < 0.001$) and there was little evidence of regional interactions except for the slope of the response in the San Joaquin Valley. This was due to the 2015-2016 site-year, where yields were 64% of average and little response to N fertilizer was observed. This crop was limited by a non-nitrogen component (improper herbicide application is suspected), which uniformly and greatly reduced overall yield potential, reducing the ability to measure the relative N response.

The differences in grain protein response between trials in the Intermountain Region and those in the in the Sacramento Valley and San Joaquin Valley (Figure 2; Table 5), were consistent across years and are more likely explained by differences in soil type rather than the particular details of a single trial. The trials in the Intermountain Region were grown on Tulebasin mucky silty clay loam soils with > 6% soil organic matter. Whereas the trials in the Sacramento Valley were grown on either Yolo silty clay loam or Rincon silty clay loam with < 2% soil organic matter; and the trials in the San Joaquin Valley were grown on Panoche clay loam with < 1% soil organic matter. The higher soil organic matter in the Intermountain Region trials likely resulted in relatively more mineralized N available to the crop during the growing season, which would help to explain its lower rate of protein response to applied N and the overall higher grain protein in these crops.

The higher overall rate of response to N fertilizer application in the Sacramento Valley as compared to the trials in the Intermountain Region and the San Joaquin Valley (Table 6) may be explained both by differences in pre-plant soil N status, cropping season precipitation patterns and associated irrigation practices. In terms of pre-plant soil N status, the measurements of pre-plant soil nitrate-N in Sacramento Valley were lower on average than in either the Intermountain Region or the San Joaquin Valley. The lower available N from the soil likely made these crops more responsive to applications of fertilizer N than those in the other regions of the study. In addition, trials in the Sacramento Valley received approximately double the average cumulative precipitation during the growing season as those in the San Joaquin Valley (11.5 inches versus 5.5 inches), and trials in the Intermountain Region were spring sown and received little precipitation during the growing season. Because of this, for both the Intermountain Region and the San Joaquin Valley, early-season irrigation was critical for crop productivity; whereas early season irrigation was not required in the Sacramento Valley.

As a result, for crops in the Intermountain Region and the San Joaquin Valley early-season irrigation timing was more in line with overall crop evapotranspiration and soil moisture depletion. In contrast, crops in the Sacramento Valley were much more likely to have experienced precipitation events that supplied water to the soil profile in excess of overall crop demand, creating more opportunities for leaching and other N loss pathways. Across all treatments included in the quadratic response models, a majority (54%) of the N total was applied in-season. Therefore, the higher overall rate of response to fertilizer N applications in the Sacramento Valley may partly be the result of a treatment structure that interacted with the higher rainfall totals at the Sacramento Valley sites to produce the proportionately greater rate of response to N in this region.

The same explanation likely applies to the higher fertilizer use efficiency in the Sacramento Valley (61%) as compared the Intermountain Region (44%) and the San Joaquin Valley (41%). On the topic of fertilizer use efficiency, it should be noted that the overall estimates produced from the model are different from those taken from a simple mean of the trial data in Table 3. The reason for this is that the model incorporates many factors that influence the crop’s response to N and more appropriately weights these factors than do simple calculations on a site-year basis (e.g. Table 3). The modeled estimates of fertilizer use efficiency are more reliable and, in this case, higher than a simple mean calculated from the raw data.

Effect of N application timing on wheat yield and quality

The timing of N application was in important factor influencing grain yield and protein. To quantify the timing effects presented in Figures 4-7, only trials where applications of N fertilizer were made at each of the four stages of crop growth (pre-plant, early vegetative, early-reproductive, and flowering) were analyzed (11 of 13 trials). In addition, observations in treatments that received rates of N fertilizer beyond the overall N response range measured in the trial (264 lb acre^{-1}) were excluded in order to focus the analysis of timing effects within the N response region.

Of the three stages of crop growth when in-season N fertilizer was applied, applications at the early-vegetative stage were most effective at increasing overall grain N recovery (Figure 7). With the exception of the San Joaquin Valley site, mid-tillering to early-jointing applications increased both the grain yield and grain protein per unit of fertilizer N applied (Figure 4). It is important to point out that at the site where the exception existed (San Joaquin Valley site) crop response to fertilizer N was poor in one of the three seasons (Table 3). In addition, this site had, on average, the highest residual soil nitrate-N concentrations at the start of the season. Therefore, the smaller protein response to mid-tillering to early-jointing applications of N measured at this site might not hold in cases with lower residual soil nitrate-N and higher yield potential.

Fertilizer N applications at the late-boot to early-heading stage of growth were also used more efficiently than pre-plant applications. However, there was more variation as to whether the N applied at this stage of growth benefitted yield, protein or both. Crops in the Sacramento Valley consistently demonstrated both yield and protein benefits from N applications at this stage; whereas, crops in the Intermountain Region and the San Joaquin Valley only demonstrated a consistent protein benefit across all trials (Figure 5). The reasons for this may be related to the above explanations of higher fertilizer use efficiency and rates of response to N in the Sacramento Valley compared to the Intermountain Region and San Joaquin Valley (i.e. lower residual soil nitrate-N concentrations and higher in-season precipitation unsynchronized to crop demand). Regardless, grain N recovery was significantly higher in all regions when N was applied at the late-boot to early-heading stage versus pre-plant (Figure 7), indicating that whether filling unmet demand for grain yield potential or grain protein potential, fertilizer applications applied at this stage of crop growth were used productively. The benefit of applications at flowering versus pre-plant was also consistent across all regions, but was confined to an increase in grain protein, rather than grain yield (Figure 6).

To interpret the results related to N application timing appropriately, it is important to note that the rate structure did not include fully equivalent rates of N fertilizer comparing the rates applied pre-plant to the rates applied at the early-reproductive and flowering stages of growth. Because of this, the increased efficiency of fertilizer use at these in-season timings should only be applied to the range of rates applied at each stage of growth within the trial structure, or, more conservatively, to the approximate average rates applied at each of the growth stages in these trials (as has been done in Figures 5-7). After considering such, the 23% increase in grain N recovery and the 10% increase in fertilizer use efficiency associated with in-season applications of N fertilizer compared to pre-plant applications argues strongly for more in-season applications of N and less pre-season N applications in California wheat crops.

In-field, in-season measurements to predict the degree of crop response to in-season N applications

In spite of the spatiotemporal variability of crop response to applied N measured in this study (Figure 3), the in-field measurements of the soil and plant environment taken within the trial demonstrate that crop responses to in-season applications of fertilizer N can be predicted across heterogeneous seasonal and regional environments. At the early-vegetative stage of growth, when little biomass accumulation had occurred, the soil nitrate-N concentration in the top 1 foot of the soil profile proved to be an effective predictor of the magnitude of crop response to subsequent N fertilizer applications (Figure 9). Which of the differential response curves reported in Figure 9 may apply to a given crop is something that a grower or consultant could determine in real-time with simple, low-cost tools and the information presented in Figure 11. Although the precision of the soil nitrate quick-test is not equivalent to the laboratory-based test, the test does appear to effectively differentiate between values greater/less than the 20 ppm nitrate-N threshold. Since this is the approximate threshold determined in Figure 8 and the cutoff for the sufficient/deficient regressions in Figure 9, the quick-test has the capacity to deliver actionable information. However, efforts are still in process to test for potential interactions between wet and dry soil and to further validate the regression relationship reported here.

The laboratory to quick-test ratio in the Intermountain Region soils was higher than in the soils from the Sacramento Valley and the San Joaquin Valley (Figure 11). This is likely the result of the much lower bulk density of this high organic matter soil (0.9 – 1 g cm^{-3}) compared to bulk densities in the 1.30 - 1.45 g cm^{-3} range for the soils sampled in the Sacramento Valley and the San Joaquin Valley. Because of this decrease in bulk density, there was less soil reacting with the same volume of water, thereby reducing the overall concentration of nitrate-N in solution for the Intermountain Region soils by a factor similar to the difference in correction values in Figure 11. These differences highlight the limitations of this empirical data and suggest that the interpretations of the quick-test be informed by some broader knowledge of the characteristics of the soil being tested.

By the early reproductive stage of growth, the crop was in its peak period of N demand and had substantially more biomass than the early vegetative stage of growth. Because of this, the crop itself became an effective predictor of deficiency, independent of the soil N status (Figure 10). Of note is that the regional interaction present in the response to mid-tillering to early-jointing stage applications was no longer measurable at the early reproductive stage of growth.

One reason for this is that there was less overall crop demand for N remaining past the late-boot to early-heading stage. As a result, any regional interaction present would have had less time to manifest itself during the period measured. Beyond that, as discussed previously, the higher organic matter in the Intermountain Region soil is likely to have resulted in a higher proportion of mineralizable-N accruing across the season. This may have contributed to the interactions between the regions of the study in the broader dataset at the reproductive stages of growth. The soil test that measured nitrate-N at the early-vegetative stage would not have effectively captured differences in future mineralizable-N. Therefore, the difference in the range of N response between the Intermountain Region and Sacramento Valley trials in Figure 9 may also be related to the accruing mineralizable-N later in the season. Because the plant canopy NDVI and leaf chlorophyll measurements were always expressed as proportion of a field- and day-specific N-rich reference region, some of the soil-related mechanism for regional interactions were likely to have been integrated into the plant measurements themselves. As a result, there were no significant regional interactions for the plant-sensor-differentiated N response depicted in Figure 10. Similar results to these late-boot to early-heading stage measurements were found at the flowering stage of growth. However, because these represented an even smaller subset of the data and a narrower range of N rates for which a crop response could be expected, the results included in Figure 10 serve to represent a similar dynamic at point in the season where applications are more impactful to grain N recovery, overall.

Taken together, the ability for in-season measurements to deliver actionable crop management information argue for further development and extension of in-season sampling protocols. Further work is needed to quantify the relative contributions of each of the measures used in this study as well as the potential for other in-season measurements to produce similar information.

Effect of slow release fertilizer on grain yield and protein compared to urea

The slow-release N fertilizers used in this study did not show a benefit to grain yield or protein content as compared to urea. However, this result should be interpreted with some caution. First, the experimental setting in which these products were used ensured that urea was always applied in a manner that minimized the potential for volatilization losses. At the farm scale, the precision of timing of the experimental treatments with respect to soil tillage management (pre-plant) and water availability (in-season) may not be typical. In addition, the two years during which slow-release materials were tested were abnormally low precipitation years. For ESN, which is designed to be used as a pre-plant product, in particular, the relatively small amount of precipitation may not have highlighted the potential value of the product in high rainfall years. With that being said, the irrigation supplied to these crops was at or above typical rainfall amounts in the Sacramento Valley, so the lack of benefit may indeed represent the relative value of these products in this agroecosystem.

Overall Conclusions

The results reported here are broadly in-line with studies in other wheat growing regions and suggest that N fertilizer management in California wheat can be made most efficient by shifting larger proportions of N fertilizer application totals from pre-season to in-season. In addition, in-season applications can be guided in real-time by site-specific measurements of the plant-soil environment using relatively low-cost tools and methods. The use of these tools would allow N applications to be more pinpointed across sites and years that differ in soil N supply and crop N demand. Taken together, management approaches that utilize in-season applications informed by site-specific measurements can increase fertilizer use efficiency alongside high yields and high protein content in California's wheat cropping systems.

H. Project Impacts

Throughout the duration of this project, results have been presented to growers and consultants in the state of California in a variety of forums and formats. Presentations related to the effects of N fertilizer application timing on wheat yield and quality have been made at over 20 public field days and grower meetings to audiences that have ranged from 20 to 250 individuals and, in aggregate, more than 1500 individuals have been in attendance at these forums. In addition, information derived from this research was presented at three CDFA training workshops related to N management regulations within the state. There have been four blog posts related to the results presented here posted between 2014 and 2017 dates. The blog membership where these posts reside are comprised of individuals who are primarily involved in crop production or research in the state of California. As of the April of 2017, these posts have been viewed directly more than 7700 times.

While there has been no direct measurement of the effects of the research and outreach efforts documented in this report, the project leaders have had scores of individual conversations related to the application of these results. Anecdotally, at least 25 individual producers have reported changing or intending to change their N management practices as a result of this research and extension effort. In a recent survey of 49 California wheat growers and consultants working on wheat around the state, 80% reported that they value and incorporate management-related research produced by UC Cooperative Extension. Within this group the distribution of N fertilizer application by timing through the season was 51% pre-plant, 18% early-vegetative stage, 15% early-reproductive stage, and 16% at flowering, which indicates that there are still improvements in N use efficiency to be had by further communication and extension of the study results.

The results of this work have produced a valuable dataset that will be useful for continuing to communicate best N fertilizer management practices for wheat grown under heterogeneous cropping system conditions. Because of the timing/rate structure used in the experimental work and the wide array of productivity outcomes measured alongside plant and soil indicators of N availability, the ability to quantify and communicate variations in probable responses to in-season N fertilizer applications (as depicted in Figures 9 and 10), can and will be expanded. Plans for extending the information include incorporating spatially and temporally specific temperature and rainfall data into an online interface housed on small grains portion of the UC Agronomy Research and Information Center. Here, an overview of the results produced from this study will be combined with a dynamic, interactive tool that enables growers to gain context for an in-season N topdress decision based on climatic variables and in-field methods.

The main results of the research on the effect of N application timing represent a win-win from both productivity and environmental perspectives. Increasing N fertilizer use efficiency will improve net profits for growers while minimizing the amount of applied fertilizer lost to the environment. The empirical data gathered throughout the course of this project has already enabled this concept to be communicated to relevant audiences. More work is planned to tailor these results to regional and seasonal conditions so that they can be effectively and broadly applied in the future.

I. Outreach Activities Summary

Limited Distribution Publications

Lundy, M. (2014) Timing of nitrogen (N) demand for wheat. UC Sacramento Valley Field Crops Blog, 3 October 2014. Available: http://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=15484

Lundy, M. (2015). The value of pre-plant soil nitrate testing. UC Sacramento Valley Field Crops Blog, 26 January, 2015. Available: http://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=16592

Lundy, M., Orloff, S., Wright, S., Hutmacher, R. (2015) In-season applications of N fertilizer improve the yield and protein content of irrigated hard spring wheats. Nutrient Digest: Nutrient Management Newsletter for the Western U.S: Volume 7, Issue 3 (Fall): pp 1, 4, 5: http://extension.colostate.edu/docs/pubs/ag/nutrientdigest/2015-fall.pdf

Lundy, M., Orloff, S., Wright, S., Hutmacher, R., Clark, N. (2017) Topdress of nitrogen at tillering stage is something to seriously consider over the coming weeks. UC Small Grains Blog, 27 January 2017. Available: http://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=23096

Lundy, M., Orloff, S., Wright, S., Hutmacher, R., Clark, N. (2017) Is it too late to topdress fall-planted heat with N fertilizer? UC Small Grains Blog, 22 March 2017. Available: http://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=23610

Presentations

Orloff, S. (2013) “Nitrogen Management Practices in Wheat to Maximize Yield and Profitability.” 2013 IREC Field Day. Tulelake, CA, 1 August 2013. *Approximately 60 growers, researchers and industry professionals in attendance.*

Lundy, M. E., Wright, S., Orloff, S., Hutmacher, R. (2014) “Calibrating in-field diagnostic tools for improved nitrogen management” CAPCA ED continuing education seminar. Colusa, California, 17 January 2014 (oral). *Approximately 60 growers and crop consultants in attendance.*

Hutmacher, R. (2014). “Nitrogen management for wheat.” CCA Nitrogen Management Training Meeting. Woodland, CA 18 March 2014. *Approximately 40 growers and industry professionals in attendance.*

Lundy, M., Orloff, S., Wright, S., Hutmacher, R. (2014) “Calibrating in-field diagnostic tools for improved N management in wheat.” 2014 Russell Ranch Sustainable Agriculture Field Day, Winters, California, 28 May 2014 (oral). *Approximately 250 growers, researchers and policy makers in attendance.*

Lundy, M., Orloff, S., Wright, S., Hutmacher, R. (2014) “In field diagnostic tools for improved nitrogen management.” Small Grains/Alfalfa Field Day, Davis, California, 7 May 2014 (oral). *Approximately 150 growers, researchers and industry professionals in attendance.*

Lundy, M., Orloff, S., Wright, S., Hutmacher, R. (2014) “Managing N fertilizer to optimize protein and yield in California wheat.” Wheat Field Day, Visalia, California, 1 May, 2014 (oral). *Approximately 30 growers, researchers and industry professionals in attendance.*

Orloff, S. (2014) “Nitrogen Management Practices in Wheat to Maximize Yield and Profitability.” 2014 IREC Field Day. Tulelake, CA, 13 August 2014. *Approximately 60 growers, researchers and industry professionals in attendance.*

Lundy, M. (2014) “Calibrating In-field Diagnostic Tools to Improve Nitrogen Management for High Yield and High Protein Wheat in the Sacramento Valley.” Report submitted to the California Wheat Commission 30 September, 2014: http://californiawheat.org/uploads/resources/717/lundy_13l14annual_report_9l30l14.pdf.

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Lundy, M., Orloff, S., Wright, S., Hutmacher, R. (2016) “Tools for assessing in-season N needs in wheat.” Agronomic Crops and Water Conservation Field Day, UCANR Desert Research and Extension Center, Holtville, CA, 13 April 2016 (oral). *Approximately 120 growers and industry professionals in attendance.* Handout: http://agric.ucdavis.edu/files/241284.pdf

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J. Factsheet/Database Template

1. Project Title: Developing Nitrogen Management Strategies to Optimize Grain Yield and Protein Content while Minimizing Leaching Losses in California Wheat

2. Grant Agreement Number: #13-0267-SA

3. Project Leaders:

Robert Hutmacher, Extension Specialist
UCD Plant Sci. Dept., UC West Side REC
P.O. Box 158, Five Points, CA 93624-0158
(559) 884-2411; cell: (559) 260-8957
rbhutmacher@ucdavis.edu

Steve Orloff, Farm Advisor, County Director
UCCE Siskiyou County
1655 S. Main St. Yreka, CA 96097
(530) 842-2711; Fax: (530) 842-6431
sborloff@ucdavis.edu

Steve Wright, Farm Advisor
UCCE Tulare County
4437 S. Laspina, Ste. B. Tulare, CA 93274; (559) 685-3309 Ext. 215 Fax: (559) 685-3319; sdwright@ucdavis.edu

Mark Lundy, Extension Specialist
UCD Plant Sci. Dept., UC Davis
One Shields Avenue, Davis, CA 95616
Phone: (530) 458-0570 Fax: (530) 458-4625
melundy@ucdavis.edu

4. Start Year/End Year: 2014 – 2017

5. Location: Tulelake, California (UC ANR Intermountain Research and Extension Center); Yolo County, California (UC Davis Agronomy Research Fields and UC Davis Russell Ranch Sustainable Agricultural Facility); Five Points, California (UC ANR Westside Research and Extension Center)

6. County: Siskiyou County, Yolo County, Fresno County

7. Highlights

- There is a wide range of productivity and N use outcomes across highly variable growing environments for wheat in California.
- Timing N fertilizer applications to match crop demand can significantly improve yield, protein, and fertilizer use efficiency outcomes.

- Real-time, in-field measurement of the crop-soil environment can indicate the likelihood and magnitude of crop N response across heterogeneous cropping system environments.

8. Introduction

Nitrogen (N) fertilizer management is a key determinant of the productivity and profitability of spring wheat. Wheat growers are paid not only for crop yield, but also for grain protein content, and achieving acceptable protein content is a continual challenge for California wheat producers. Grain yield and protein content are often inversely related and influenced by the rate and application timing of N fertilizer and its interaction with the timing and quantity of water moving through the soil profile. High rates of pre-season N fertilization can be attractive to growers due to the reduced cost of the pre-season forms of N and the ease of application. However, applying high rates of N pre-plant can also result in reduced grain protein content because average root-zone soil N levels available for plant N uptake may have declined once the crop reaches the grain filling stage, which is a critical time in determining grain protein. Additionally, very high early rates of N fertilization may contribute to lodging and increase N losses to the environment through pathways such as nitrate leaching. The goal of this work is to equip growers and crop consultants with a better understanding of the need for N at various stages of crop growth and to provide guidelines as to appropriate rates based on the use of in-field tests of the plant-soil environment.

9. Methods/Management

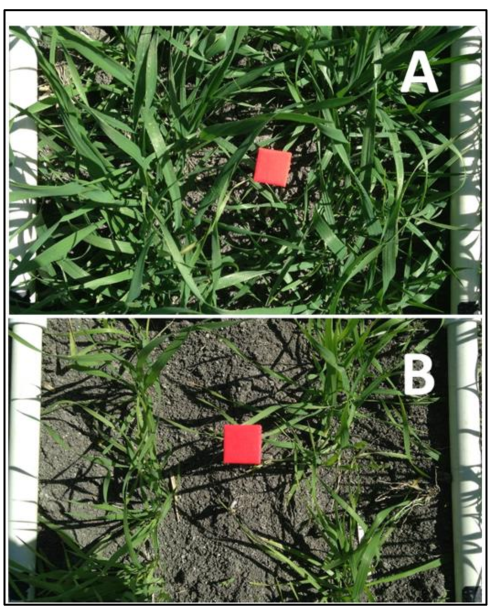

Figure 1. Yecora Rojo at mid-tillering in Tulelake, CA. Crop A received 100% of seasonal N application pre-plant. Crop B received 80% at tillering and 20% at flowering. Grain yield for crop B was 16% higher and grain protein was > 1% higher.

Over four locations and five seasons, the effects of N application timing and rate on the yield and protein content of hard spring wheats grown in diverse California environments were evaluated across a total of 13 site-years. Quantitative assessments of the relative contribution of N fertilizers applied either pre-plant, at the early vegetative growth stages (late-tillering/early jointing), at the transition from the vegetative to reproductive growth stage (late-boot/early heading) or at anthesis were made. In order to account for the spatial and temporal variability of crop responses to N fertilizer application, and to develop diagnostic thresholds for soil and plant indicators of N deficiency/sufficiency, in-season plant-soil measurements were made at a subset of the trials corresponding to in-season application timings.

10. Findings

In-season applications of N fertilizer increased grain yield, grain protein content and apparent fertilizer recovery compared to pre-plant applications. Overall, in-season applications increased rates of N recovery in grain by 23% compared to equivalent quantities applied pre-plant, with applications at the early-vegetative stages increasing both grain yield and grain protein content and applications during the reproductive stages primarily increasing grain protein content. While the degree of crop response to N fertilizer applications varied considerably among site-years, the overall effect of N timing was generally consistent across all regions and varieties in the study.

Soil nitrate-N concentrations in the top 1 foot of the soil profile, relative canopy NDVI, and relative leaf chlorophyll concentrations each provided unique information about the likelihood of crop response to in-season N fertilizer application. During the early vegetative stages of growth, soil nitrate-N in the top 1 foot of soil was the best predictor of crop response to N fertilization; whereas, during the reproductive growth stages, canopy and leaf measurements were better predictors of crop response to N fertilization. Overall, these findings suggest that N fertilizer management in California wheat can be optimized by shifting more of the total N fertilizer application from pre-season to in-season. In addition, in-season applications can be guided in real-time by site-specific measurements of the plant-soil environment using relatively low-cost tools and methods.

K. Copy of the Product/Result:

All current products resulting from this work are provided as web links in section I. Outreach Activities Summary. Articles in preparation for submission to peer-reviewed journals will be submitted to CDFA-FREP once published.