American Society of Agronomy
California Chapter

Co-Sponsored by the California Plant Health Association

2016 Conference Proceedings

California Plant and Soil Conference

California Water – Value to Agriculture, Value to Society

February 2 & 3, 2016

Wyndham Hotel Visalia
9000 W. Airport Drive, Visalia CA

Nitrogen Dynamics in Cropping Systems
-- Why Alfalfa is Important

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ABSTRACT

Alfalfa (*Medicago sativa* L.) as the most important agricultural legume in California cropping systems, has an important role to play in N cycles and mitigation of N risk to the environment. These include 1) it's ability to take up considerable quantities of excess N from soil, and act as a 'buffer' under high N conditions, 2) the production of protein without subsidy from N from fertilizer sources in food-producing systems, and 3) contribution of N to non-legumes in rotation. Based on the wheat N response data, we estimated the legume N credit at the three sites to range from 50 to 125 lbs. N ac^{-1}, which was higher than previous estimates in California of 40 to 80 lbs. N ac^{-1}. The crop's deep-rooted attributes, it's high uptake of water (and thereby soil N), and high N content in the crop indicate that alfalfa is capable of mitigating excess N as well as contribute considerable N to subsequent crops in a rotation, indicate alfalfa's valuable contribution to N management in cropping systems.

INTRODUCTION

Nitrogen is frequently the most limiting plant nutrient for crop growth in cropping systems, critical for the formation of plant proteins as crop products, as well as a potential pollutant in ground and surface waters when applied as fertilizers. Nitrogen is most commonly applied to non-leguminous crops in the form of N fertilizers which mostly originate from the Haber-Bosch process which converts N_2 from the air into ammonia utilizing fossil fuels. Manures are also used to satisfy the N needs of crops, but a portion of manure N similarly originates from crops fertilized with N fertilizer. It is well known that excess N from agricultural sources can result in nitrate contamination of groundwater.

N_2-fixing plants (alfalfa, clovers, beans, vetch, peas, etc.) conduct the same process as Haber-Bosch through biological enzymatic symbiosis with *Rhizobia* spp., providing essentially 'free' N for protein production originating from atmospheric N_2 gas, not fossil fuels. Alfalfa (*Medicago sativa L.*) as California's most important leguminous crop, plays several roles in N management, including:

- The ability to substitute for N fertilizers for protein production in food systems.
- The ability to absorb high quantities of nitrate from the soil or water.
- The ability to contribute biologically-fixed N to subsequent crops in rotation.

The first point is often not appreciated, and not considered in depth here—but (for example), if corn were used to produce the protein currently produced in California's alfalfa crop, nearly 5 million additional acreage of corn grain would be required (as well as the fertilizers and water needed for protein production). The second two points are important in mitigating impacts of N in groundwater, and for N management in general in cropping systems and are considered here.

Does Alfalfa Require N Fertilizers?

Generally the answer to this question is ‘no’ under most conditions, at least from an economic perspective. While some legumes (e.g. some Phaseolus spp.) respond to exogenous N fertilizers, alfalfa generally does not. An extensive review of this issue for either early establishment phase or established phase indicated that when plants are well nodulated and nitrate was above 15 ppm and neutral soil pH (6.2-7.5), seedling alfalfa did not benefit from applications of N fertilizers (Hannaway and Shuler, 1993). In established alfalfa, most studies indicate no positive response to N fertilizers in alfalfa when crops are well-nodulated. Exceptions to this include situations where biological N_2 fixation may be compromised, such as cold temperatures, since nodule formation, root growth and biological N_2 fixation are all affected by temperature (Sprent and Sprent, 1990). Alfalfa under desert conditions may be highly stressed due to moisture limitations or salinity. Shuler and Hannaway (1993) suggested moderate rates of fertilizer only benefits alfalfa growth and yield under low-N, cool conditions.

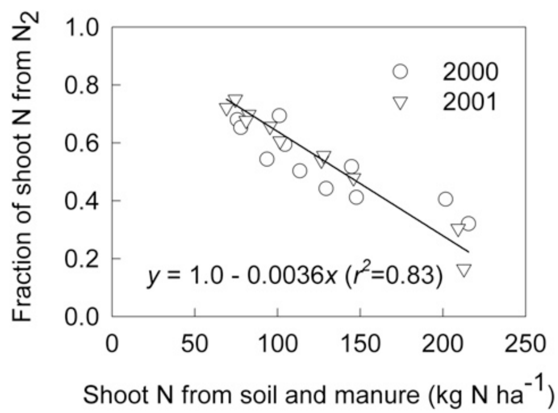

Figure 1. Fraction of N in alfalfa provided by atmospheric N2 at various soil N contributions (M. Russelle, unpublished data).

Alfalfa acts as a ‘buffer’ with soil N uptake .

Most of the N required for alfalfa crop production is provided by N_2 fixation (estimated to be 60-80% under most conditions), with the rest supplied from soil sources. However, when nitrate concentration in the soil is higher, N_2 fixation is reduced, and the crop preferentially takes up N from soil sources (Figure 1). Thus the high uptake of N for protein production is generally satisfied through contributions from biological N_2 fixation, but the crop will preferentially take up soil N when available from the soil. This is unlike high N-requiring crops (like corn) which must satisfy their N requirement from soil residual or exogenous N from fertilizers or manures, and when that supply is depleted, yields are reduced. In the case of alfalfa, yields are rarely reduced under low N soil conditions, but N uptake remains high.

Alfalfa Can Mitigate Excess Nitrogen in Cropping Systems

Alfalfa is a crop which has been shown to mitigate excess N in cropping systems, whether applied as manures, nitrates in water, or from municipal wastes. This is due to several attributes:

- Perenniality and long-season growth--Established alfalfa will remain from 3-7 years, and remains active nearly year-round in warmer climates like the Low Deserts and Southern San Joaquin Valley.
- Deep-Rootedness—Alfalfa Roots commonly reach 4-7 feet and can take up water and nitrates from depth.
- High yields, and high protein content and thereby high N content of the crop, resulting in

high uptake levels.

- Frequent harvest which allow removal of N throughout season, not just one time.
- High seasonal water demand which allows uptake of nitrate if present in water.

Alfalfa produces more harvestable protein per unit area than any other crop plant. This is particularly true in high-yielding environments like California, Arizona and Mexico, where yields can exceed 10 tons/acre.

Quantification of N uptake with alfalfa is a function of two attributes: 1) yield and 2) N concentration in the foliage (which is directly related to Crude Protein concentration). Typical per-year N uptake levels for alfalfa in California's Central Valley are illustrated in Table 1. Average yields in the non-Intermountain regions are about 8 tons/acre and percent nitrogen ranges from about 3.2% to 3.5% (protein can range from about 16% to 26 percent and yields from 5 to 13 tons/acre as shown here). Realistic averages for the CV and desert regions of California are likely to be about 8 tons/acre at about 21% CP, or about 500-600 lbs. N/acre per year in 6-8 cuttings, but can be as much as 700 to nearly 1000 lbs N/acre/year .

Table 1. Annual Estimated Crop removal of Nitrogen at different alfalfa yield and protein levels. Shaded area indicates most likely range for California Central Valley locations.

	Crude Protein of Alfalfa Forage					
	16	18	20	22	24	26
	%Nitrogen in Forage					
Tonnage	2.56%	2.88%	3.20%	3.52%	3.84%	4.16%
(t/a)	Crop Removal of N					
	lbs N/acre					
5	256	288	320	352	384	416
6	307	346	384	422	461	499
7	358	403	448	493	538	582
8	410	461	512	563	614	666
9	461	518	576	634	691	749
10	512	576	640	704	768	832
11	563	634	704	774	845	915
12	614	691	768	845	922	998
13	666	749	832	915	998	1082

Table 2. Estimated per-cut crop removal of Nitrogen at different alfalfa yield and protein levels. Shaded area indicates most likely range for California Central Valley locations.

	Crude Protein of Alfalfa Forage					
	16	18	20	22	24	26
	%Nitrogen in Forage					
Tonnage	2.56%	2.88%	3.20%	3.52%	3.84%	4.16%
(t/a)	Crop Removal of N					
	lbs N/acre					
0.5	26	29	32	35	38	42
0.75	38	43	48	53	58	62
1	51	58	64	70	77	83
1.25	64	72	80	88	96	104
1.5	77	86	96	106	115	125
1.75	90	101	112	123	134	146
2	102	115	128	141	154	166
2.25	115	130	144	158	173	187
2.5	128	144	160	176	192	208
2.75	141	158	176	194	211	229

However, per-cutting yields and uptake differ significantly over the year, so there is likely to be a seasonality to N uptake in alfalfa. Yields are highest in the first 3-4 cuttings of the year and then decline significantly, in a phenomenon known as 'summer slump'. Protein percentages tend to be highest in the early harvests, decline during summer, and go back up during fall harvests. In most environments, late summer and fall harvests are significantly lower than early spring and early summer harvest (April through June), so crop uptake of N is likely to be highest in the spring and decline throughout the summer. Adjustments for stand health and other stresses should be made. Generally, alfalfa has low N uptake rates during cold winter months.

Alfalfa Provides Nitrogen Benefits to Subsequent Crops

In order to manage N in a cropping system, the contribution of the legume to a subsequent crop in rotation is important. This is known as the legume N credit. Such N credit values help growers estimate the amount of N fertilizer they can withhold for crops following the legume compared to following a non-legume (Bundy et al., 1997; Kaiser et al., 2011; Leikam et al., 2007). Legume species, stand vigor, soil, climate, and other location-related factors can affect N contributions to a subsequent crop.

The majority of research on the legume N credit for crops following alfalfa has been conducted under rainfed conditions, where hundreds of site-years of data (Yost et al., 2014) have indicated that N contributions can range from 30 to 75 lb ac^{-1} for seeding year stands (Hesterman et al., 1986; Kelner et al., 1997), up to 175 lb ac^{-1} for older stands (Harris and Hesterman, 1990; Hesterman et al., 1987). The majority of studies reviewed by Yost et al. (2014) have indicated that all to partial N needs of corn are satisfied by the rotational contribution of alfalfa (Figure 2). It's striking that in this meta analysis, 10 of 19 studies showed a benefit in year 2 after rotation with alfalfa (data not shown).

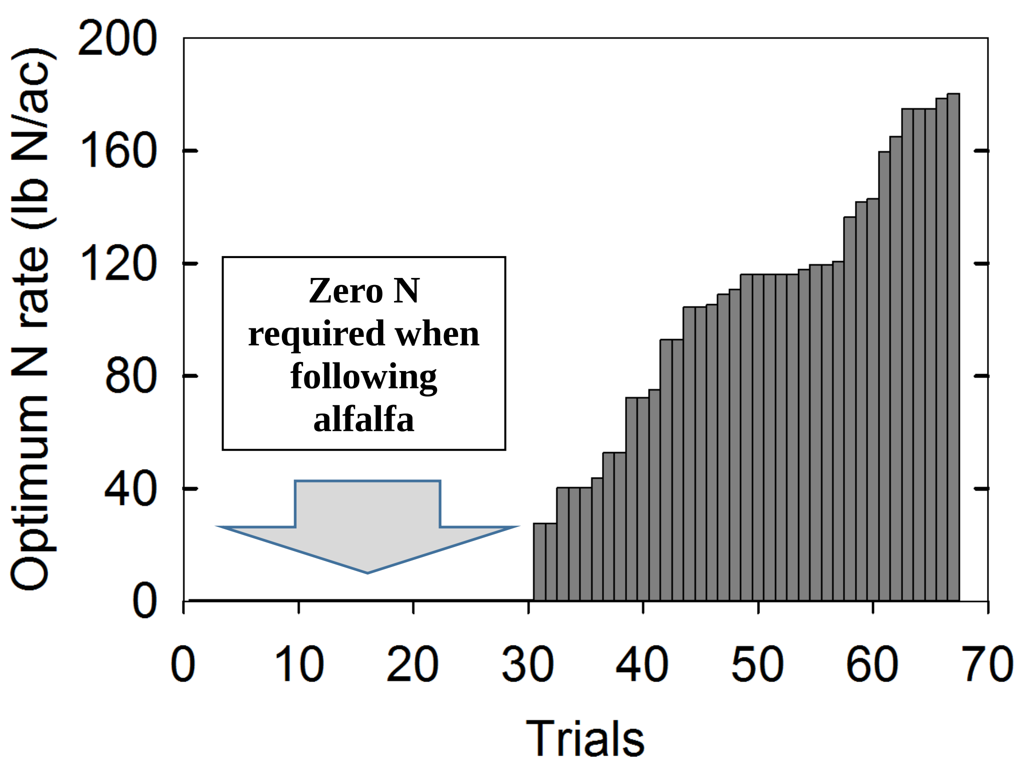

Figure 2. Response of corn to N fertilizers when following alfalfa in rotation – from a meta-analysis of multiple trials, mostly in Midwest, USA. In many of the studies, little or zero N was required and in 10 of 19 studies, zero N was required for two years following alfalfa. (Yost et al., 2014). While it is clear that alfalfa rotation N can supply a majority of the N to a following crop, such benefit is likely to be soil type specific.

In irrigated semiarid and arid regions, however, experimental evidence has been comparatively lacking. Some recent work in semiarid Spain has produced estimates of approximately 140 lb ac^{-1} (Ballesta and Lloveras, 2010; Cela et al., 2011). In Idaho, crop rotation research conducted under irrigation found that alfalfa could often supply all the N needs of subsequent crops (Carter et al., 1991). Compared to rainfed regions, high yielding irrigated regions could have higher N credits due to higher total N_2 fixation, higher yields, and longer growing seasons. Alternatively, they could have lower N credits due to greater N removal or higher temperatures promoting mineralization and losses.

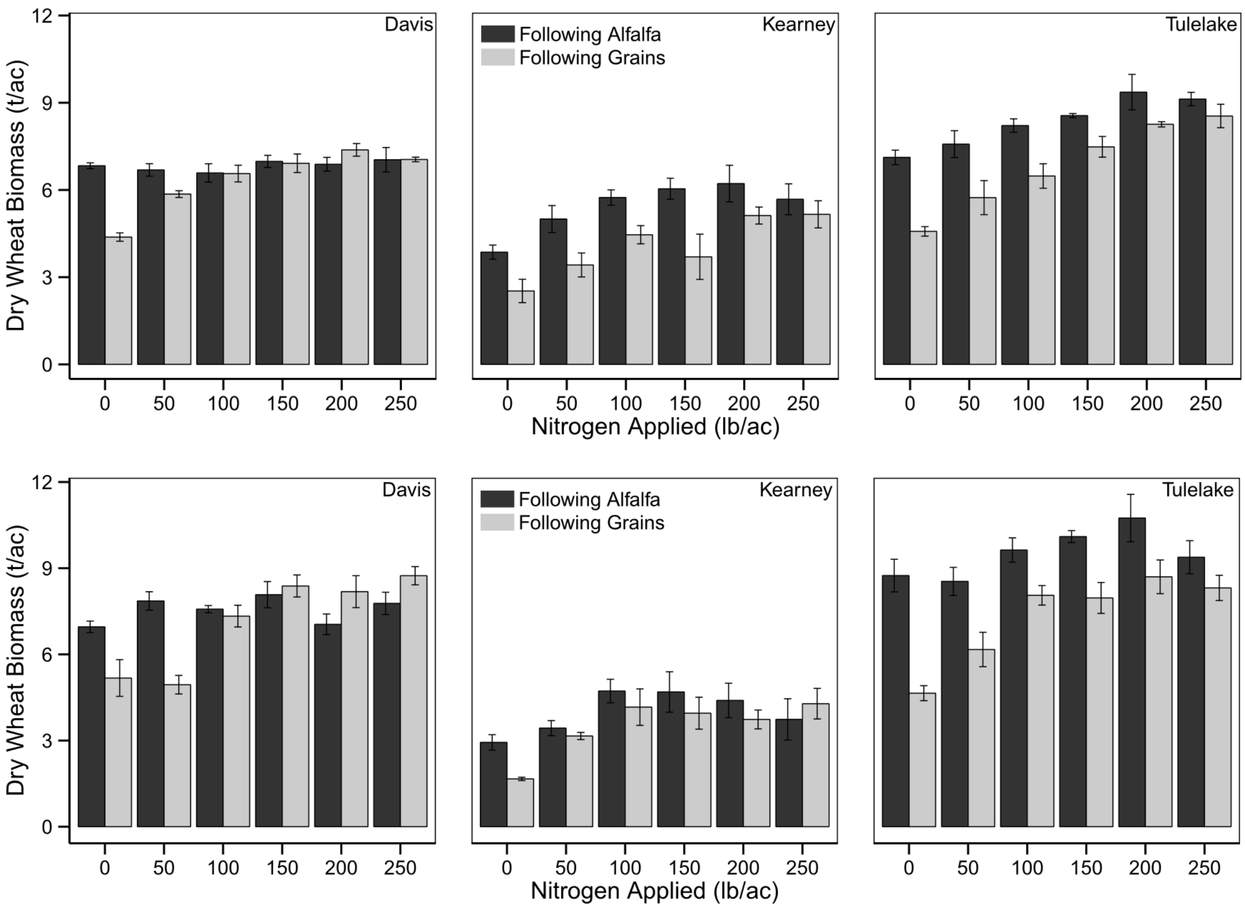

Figure 3. Response of wheat to N rate as affected by previous crop in rotation. Data from fields planted to wheat in 2013 (top) and 2014 (bottom). Wheat yield expressed as above-ground plant biomass (dry weight) at soft dough stage. Error bars represent standard errors of the mean.

Field Studies in California

To determine the alfalfa N credit, we conducted field trials at UC field stations in three locations: Tulelake near the California-Oregon border, Davis in the southern Sacramento Valley, and Kearney in the San Joaquin Valley. At each location, we grew irrigated wheat in small plots within larger replicated strips that previously had either (1) alfalfa for 2.5+ years or (2)

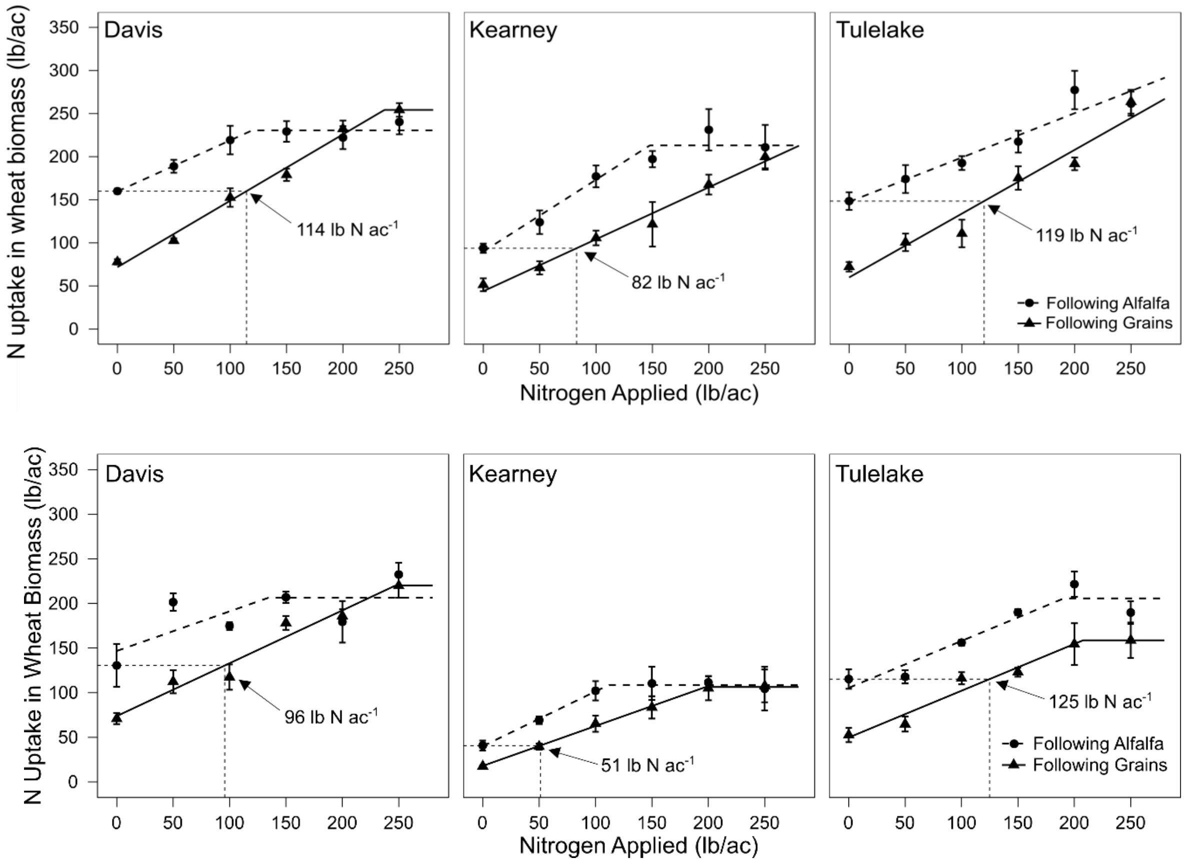

Figure 4. Total nitrogen uptake of wheat grown with 6 N rates after alfalfa and following sudangrass-wheat (grains) at the three locations from fields planted to wheat in 2013 (top) and 2014 (bottom). Error bars represent standard errors of the mean. Regression curves (dashed and solid lines) represent linear-plateau models. Dotted lines and arrows indicate the amount of fertilizer N required for wheat following sudangrass-wheat to take up the same amount of N as unfertilized wheat following alfalfa.

sudangrass-wheat rotation for 1.5+ years before being terminated in the fall and planted to wheat shortly after. Neither the alfalfa nor the sudangrass-wheat strips received N fertilizer, but were otherwise grown using standard farming practices. At Kearney and Tulelake, strips of alfalfa were removed from existing stands and planted to sudangrass to establish sudangrass-wheat rotations. Remaining strips of alfalfa were used for plots of alfalfa for 2.5+ years. At Davis, the sudangrass-wheat rotation was established in a separate field. Alfalfa and sudangrass were both terminated by tillage before establishment of wheat. To determine the effect of the preceding crop (alfalfa vs. sudangrass/wheat) on wheat N requirement, we applied N fertilizer rates to the wheat ranging from 0 to 250 lb N ac^{-1}. Besides N fertilization, the wheat was grown using standard farming practices for the region. When the wheat reached the soft dough stage, plots were harvested to determine aboveground biomass. Subsamples were taken for determination of plant moisture and N content. At maturity, wheat was harvested, and grain yields, grain moisture content, and grain protein content were determined. The experiment was repeated in 2014 in different plots at the same locations.

Soil nitrate-N levels (0-12 inch depth) in the fall of 2013 were 5-7 ppm NO_3-N in plots that had just been in alfalfa and 0.5-4 ppm in plots following the sudangrass-wheat rotation. Similar levels were observed in 2014. This soil nitrate difference between the two rotations was consistent across the three locations.

Wheat aboveground whole plant biomass and N Uptake

In plots receiving no N fertilizer, wheat whole-plant above-ground biomass was higher following alfalfa than following sudangrass-wheat for all location-years (Figure 3), indicating that, as expected, the alfalfa contributed more plant-available soil N than did the sudangrass-wheat rotation. At Davis, Tulelake, and Kearney, wheat following sudangrass-wheat required 100-150 lb N ac^{-1}, 100-150 lb N ac^{-1}, and 50-100 lb N ac^{-1}, respectively, to produce the same amount of biomass as wheat grown without N fertilizer following alfalfa. Additionally, at Davis, wheat biomass following alfalfa was the same regardless of N fertilization levels for both years, indicating that alfalfa likely satisfied a high proportion of the wheat's N needs there.

Indeed, nitrogen uptake data from the wheat biomass suggest that, in plots at Davis receiving no N fertilizer, wheat following alfalfa assimilated 80-100 lb ac^{-1} more N than wheat following sudangrass-wheat (Figure 4). In order to sequester this additional 80-100 lb N ac^{-1}, the wheat following sudangrass-wheat needed about 114 lb N ac^{-1} and 96 lb N ac^{-1} fertilizer in plots planted to wheat in 2013 (Figure 3, top) and 2014 (Figure 3, bottom), respectively. Similarly, for 0 N plots following alfalfa in plots planted to wheat in 2013 and 2014, 119 lb N ac^{-1} and 125 lb N ac^{-1}, respectively, were required for wheat following sudangrass-wheat at Tulelake to achieve similar levels of N uptake, and at Kearney, 82 lb N ac^{-1} and 51 lb N ac^{-1} were required.

From these N uptake data, alfalfa's N contribution to irrigated wheat in a semiarid climate might range from 50 lb N ac^{-1}, as observed at Kearney, up to 125 lb N ac^{-1}, as observed at Tulelake.

CONCLUSIONS

Alfalfa's N contribution ranged from about 50 lb N ac^{-1} at Kearney to about 125 lb N ac^{-1} at Davis and Tulelake, but there was evidence of contributions above 120 lb N ac^{-1} at Tulelake. Calculations using different metrics or different methods could yield slightly different results. These results were higher than expected, but correspond well with results from research in Spain for irrigated plots in a climate similar to California's (Ballesta and Lloveras, 2010; Cela et al., 2011). Wheat grain protein was also significantly improved in rotation with alfalfa at most location/years, indicating a benefit for quality as well as yield.

ACKNOWLEDGMENTS

We thank staff at UC Davis, UC Kearney Research and Extension Center in Parlier, CA, and UC Intermountain Research and Extension Center in Tulelake, CA for their help with field operations. We also thank Chris van Kessel and Girma Getachew for their helpful comments and insightful discussions, and Chris DeBen and student staff for field assistance. This research was funded by grants from the California Department of Food and Agriculture's Fertilizer Research and Extension Program and from the California Wheat Commission.

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