Fertilizer-Nitrogen Use Efficiency of Irrigated Wheat: I. Uptake Efficiency of Preplant versus Late-Season Application

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ABSTRACT

The addition of N fertilizer late in the growing season to improve grain quality is a potential management option for production of irrigated hard red spring wheat (*Triticum aestivum* L.). This study compared the recovery of fertilizer N applied at planting with that of fertilizer N applied at anthesis, and evaluated the effects on soil N uptake. In a 2-yr field study, N fertilizer rates of 120, 180, or 240 kg N ha^{-1} at planting and 0, 30, or 60 kg N ha^{-1} at anthesis were applied to 'Yecora Rojo' wheat. The experiment utilized a duplicate plot design such that for every N-rate treatment there were two plots, one plot received ^{15}N labeled fertilizer at planting, and the other received ^{15}N labeled fertilizer at anthesis. The recovery of N applied at planting ranged from 30 to 55%, while that of N applied at anthesis ranged from 55 to 80%. The contribution of soil N (non-fertilizer N) to total plant N was not affected by the N rate or timing of application. In another field study 120, 180, or 240 kg N ha^{-1} was applied at planting and 0 or 45 kg N ha^{-1} at anthesis the first year, and 85, 140, 195, and 250 kg N ha^{-1} applied at planting and 0, 25, 45, and 65 kg N ha^{-1} at anthesis the second year. A small dose (<1 kg ha^{-1}) of NH_4-^{15}N was injected 5 cm below the soil surface to follow the effect of N application at anthesis on uptake of existing inorganic soil N. Fertilizer N at anthesis increased the amount of injected ^{15}N taken up by the plants from 38 to 48% the first year, and from 49 to 61% the second year. In both studies, the amount of fertilizer N applied at anthesis had the greatest influence on postanthesis N uptake, which ranged from 17 to 77 kg N ha^{-1}. Without supplemental N applied at anthesis, postanthesis N uptake only provided from 12 to 18% of the total grain N demand, and postanthesis N uptake was not increased by greater preplant N input levels. Likewise, extractable and mineralizable soil N at anthesis were not affected by preplant N treatments. These results indicate that a late N application can be efficiently taken up by plants, and does not decrease soil N uptake. To achieve acceptable grain protein levels for bread wheat in this irrigated cropping system, N should be supplied late in the season to improve N uptake during grain fill.

Despite its relatively low profit margin wheat serves an important role in rotation with high value irrigated crops in the Central Valley of California. High yields and low grain protein concentration are common characteristics of much of California's irrigated hard red wheat. Profit levels could be enhanced if higher protein content grain were produced. Cultivars with good baking qualities and high yield are available, but under current management practices the protein content is often too low to meet bread wheat standards. Thus, producers generally do not expect to receive premiums for quality and have adopted practices designed to maximize yield and minimize costs. These goals are accomplished by providing adequate soil N supply during yield-determining plant growth stages that occur before anthesis.

Studies on the influence of N uptake after anthesis on grain yield and protein content of wheat have focused on the issue of whether significant genotypic variation exists, and if such differences are consistent across environments. In some cases, N uptake after anthesis contributed only 7 to 11% of the total aboveground N yield at maturity (Loffler et al., 1985; Fowler et al., 1990). In other situations, 37 to 43% of total plant N, almost half of the final grain N, was acquired after anthesis (Spiertz and Ellen, 1978; Gregory et al., 1981). Both genotypic differences (Austin et al., 1977; Cox et al., 1985b) and soil-plant water relations (Gregory et al., 1981) contribute to genotype–by–environment interactions affecting postanthesis N acquisition.

Nitrogen availability during grain fill can be increased by addition of N fertilizer in coordination with irrigation. The potential to increase grain protein and grain yield through late-season N application has been demonstrated in a number of studies, both in rain-fed systems (Hucklesby et al., 1971; Spiertz and Ellen, 1978; Ellen and Spiertz, 1980) and irrigated systems (Pushman and Bingham, 1976; Robinson et al., 1979; Strong, 1982). While these studies demonstrate that grain protein levels increase with late-season N applications, the efficacy varies considerably depending upon the native soil N supply, previous N uptake, developmental stage of the plant when supplemental N is applied, and yield potential. Optimizing fertilizer-N use, and at the same time achieving acceptable yield levels and adequate grain protein, requires knowledge of expected N uptake efficiency and utilization within the plant in relation to the rate and timing of N addition.

In this study, uptake of N fertilizer applied at anthesis was compared to uptake from preplant N additions. Both the N difference and isotope recovery methods have been used to quantify uptake from a single N application (Olson and Swallow, 1984; Powlson et al., 1986). Our objective was to measure the N uptake efficiency from two applications of N fertilizer made at different times. A "duplicate plot" experimental design was employed: for every split fertilizer-N treatment, one plot received labeled N with the early application and unlabeled N in the late application, and in another set of plots with identical split N rates, this labeling sequence was reversed. This approach allowed comparison of uptake from the two fertilizer applications, as well as evaluation of their effects on the uptake of soil N. To further study the effect of N fertilizer addition at anthesis on soil N uptake, another experiment followed uptake of a small quantity of labeled NH_4-N (<1 kg ha^{-1}) that was injected into the soil at anthesis.

MATERIALS AND METHODS

General Experimental Conditions

Field experiments were conducted in the Sacramento Valley at the University of California, Davis, CA (38° 32'N, 121° 48'W) on Yolo silt loam (fine-silty, mixed, nonacid, thermic Typic Xerorthent) and Zamora silt loam (Fine-silty, mixed, thermic Mollic Haploxeralf) which are similar except for slight textural differences in the 40- to 80-cm layer. The soil contained about 1120 mg ka^{-1} total N and 12 g kg^{-1} C in the 0- to 30-cm layer; pH was 7.5. In all 3 yr

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the previous crop was unfertilized sudangrass [*Sorghum sudanense* (Piper) Stapf] that was cut and removed before field preparation.

The following crop management operations were common to all of the experiments. Plots were planted at a seeding rate of 125 kg ha^{-1} with 17-cm row spacing using a commercial grain drill. Germination was then initiated with approximately 5 cm of sprinkler irrigation, rainfall providing adequate moisture from germination until anthesis. Adequate weed control was provided by one herbicide application at about the four-leaf stage. Late N fertilizer treatments were applied as each plot reached anthesis, followed by basin irrigation within 24 h, with each plot occupying a separate basin. One additional irrigation followed 21 to 24 d after anthesis. The final plant harvest was taken as individual treatments attained physiological maturity, indicated by a complete loss of green color from glumes (Hanft and Wych, 1982). A plot receiving no N fertilizer was included within each block of all experiments.

Duplicate Plot Experiment

Yecora Rojo wheat was planted on 15 Dec. 1987 and 10 Nov. 1988 in 1.8- by 4-m plots. The experiment was a randomized complete block design with a factorial arrangement of three rates of N applied preplant (120, 180, and 240 kg N ha^{-1}) and three rates of N applied at anthesis (0, 30, and 60 kg N ha^{-1}) with four replicate blocks. Each of the preplant-by-anthesis-N-fertilizer treatments were duplicated in two plots within each block: one plot received labeled preplant N, and the other labeled N at anthesis. In the first year treatments without N application at anthesis received unlabeled preplant N, but in the second yr these treatments received labeled preplant N.

The labeled fertilizer was a solution of ^{15}N-depleted ammonium sulfate with 0.021 atom % ^{15}N (−0.345 atom % excess). A solution with an identical concentration of unlabeled ammonium sulfate was used for unlabeled fertilizer. Preplant fertilizer treatments were sprayed evenly over each plot and the field disked lightly before planting. Anthesis N applications were pipetted onto the ground through acrylic tubes spaced 20 cm apart and lowered into the canopy between each row within a plot, avoiding contact between fertilizer and leaves. Anthesis occurred on 13 Apr. 1988 and 11 Apr. 1989. In 1988–1989, whole plants from 1.20-m sections of two adjacent rows near the center of each plot were sampled before the anthesis N application by cutting stems at the soil surface. In both years, whole plants were taken at physiological maturity from the center rows of each plot. Since physiological maturity was delayed in treatments that received greater levels of N fertilizer, different treatments were harvested on different dates. In 1987–1988, two 0.60-m lengths of row were harvested between 30 May and 6 June 1988. In 1988–1989, 2.00-m lengths of two adjacent rows were harvested between 25 May and 8 June 1989.

Labeled Nitrogen Injection Experiment

Yecora Rojo and 'Anza' wheat were planted on 4 Dec. 1986, and 'Yolo' was planted on 16 Nov. 1987. In 1986–1987, a split-plot design with four complete blocks was used. Mainplots were a factorial combination of the two cultivars and three preplant N rates (120, 180, and 240 kg N ha^{-1}). Split-plot treatments were two levels of N addition at anthesis (0 and 45 kg N ha^{-1}). Split-plot size was 4 by 14 m. In 1987–1988, a factorial of four preplant N fertilizer rates (85, 140, 195, and 250 kg N ha^{-1}) and four rates of N addition at anthesis (0, 25, 45, and 65 kg N ha^{-1}) were combined in five complete blocks. Plot size was 4 by 24 m. In both yr, the preplant N was urea drilled two inches below the seed, and the anthesis N was a broadcast application of ammonium sulfate. In 1986–1987, anthesis occured on 15 Apr. 1987 for Yecora Rojo and 22 Apr. 1987 for Anza,. Yolo reached anthesis on 11 Apr. 1988 in the 1987–1988 study.

Immediately before the anthesis fertilizer application and irrigation in both yr, a solution containing 0.93 kg N ha^{-1} ammonium sulfate enriched to 99% ^{15}N was injected 5 cm below the soil surface in 0.40-m^2 microplots. This was accomplished by inserting a 1-cm diameter probe to 5-cm depth, withdrawing the probe approximately 1 cm, and injecting 2.9 ml of ^{15}N solution. Six injections were made at 15-cm intervals midway between each of three adjacent rows of wheat. At physiological maturity, whole plants were harvested from adjacent 0.6-m sections of the two rows that had received ^{15}N injection on both sides. This sample was used to determine ^{15}N concentration in the grain and straw. A separate plant sample was taken at anthesis and physiological maturity from four adjacent 2-m lengths of row for grain and straw yield and N analysis.

Soil and Plant Analysis

In two of the 3 yr, soil samples were taken 4 d after the anthesis irrigation from plots that did not receive fertilizer-N addition at anthesis. In 1986–1987, samples were taken from plots receiving 120 and 180 kg N ha^{-1} preplant, and in 1988–1989 from plots receiving 120, 180, and 240 kg N ha^{-1} preplant. Soil samples were taken in 10-cm increments from 0 to 30 cm. Eight 2.5-cm diam. cores per plot were pooled by depth and thoroughly mixed. A subsample equal to approximately 5 g dry soil was immediately placed in 50 mL of 2 *M* KCl. The maximum time from soil sampling to mixing in KCl was 10 min. After filtering, the extracts were analyzed for NH_4-N by the indole-phenol blue method (Mitchell, 1972) and for NO_3-N by the cadmium reduction method (American Public Health Assoc., 1975; p. 423–427). Dry weight of the extracted soil was determined after rinsing to remove excess KCl and drying at 105 °C. The remainder of each soil sample was air-dried and passed through a 2-mm sieve. Nitrogen mineralization under anaerobic conditions (Waring and Bremner, 1964) was measured to provide an estimation of mineralizable N present in soil at anthesis.

Grain was separated from samples taken at maturity. All samples were oven dried at 55 °C, weighed, and ground. Oven-dry sub-samples of 1 g were analyzed for N by the Kjeldahl method. Kjeldahl distillates were used for analysis of N isotope ratios on a VG Micromass 602E mass spectrometer (Vacuum Generators Ltd., Hastings, England).

Calculation of N uptake after anthesis was made by subtracting total plant N determined at anthesis from total plant N at maturity. For each preplant-by-anthesis-N rate treatment in the duplicate plot experiment, plant recovery of labeled N from fertilizer applied preplant or at anthesis was determined in respective duplicate treatment plots. The sum of recovered labeled N was subtracted from the mean total N of the two duplicate plots in each block to estimate N uptake from soil. Analysis of variance was performed on means of the duplicate plots for dry matter and N yield parameters. Analysis of variance for treatment effects on N uptake from labeled preplant or anthesis fertilizer N were based on the values obtained from the individual duplicate plots.

For the injection experiment, the recovery efficiency of injected ^{15}N was calculated as the percentage of ^{15}N applied to the harvested area that was found in the plant at maturity. Analysis of variance was used to evaluate treatment effects.

RESULTS

Yield and Grain Nitrogen Concentration

Anza and Yolo are closely related high yielding, low protein cultivars [Yolo = Bluebird (sib) × Anza].

Table 1. Grain yield, grain N concentration, and total aboveground N of wheat receiving no N fertilizer. Values in parenthesis are the standard error of the mean.

Growing season	Experiment	Cultivar	Grain yield	Grain N concentration	Total N yield
			kg ha^{-1}	g kg^{-1}	kg ha^{-1}
1986-1987	^{15}N Injection	Yecora Rojo	1920 (73)	23.1 (1.37)	53 (5.2)
	^{15}N Injection	Anza	3020 (136)	14.8 (0.22)	53 (2.3)
1987-1988	^{15}N Injection	Yolo	3450 (218)	14.1 (0.62)	57 (2.7)
	Duplicate plot	Yecora Rojo	3130 (196)	17.1 (0.33)	65 (3.9)
1988-1989	Duplicate plot	Yecora Rojo	4640 (332)	18.3 (0.49)	110 (10.4)

Yecora Rojo has slightly lower yields, but is a bread quality wheat with higher grain protein levels than Anza or Yolo (Jackson et al., 1990). Yecora Rojo is an earlier maturing cultivar and reaches anthesis about 6 d before Anza and Yolo when planted in December.

Grain yield and N accumulation by wheat grown without fertilizer-N addition reflect the seasonal N supply from soil under the conditions of these experiments (Table 1). Mean soil N uptake without added N fertilizer was 57 kg ha^{-1} in 1986–1987 and 1987–1988 with similar values for the three cultivars. In 1988–1989, soil N supply was nearly two-fold greater.

Preplant N rates were chosen to produce moderately deficient, adequate, and excessive N supply in terms of maximizing yield, and, except in the year of high soil N, this objective was achieved (Tables 2, 3, and 4). In 1988–1989 the lowest rate, 120 kg N ha^{-1}, was sufficient to obtain maximum yield. In each experiment, grain N concentration increased gradually as the preplant N rate was increased. Larger increases in grain N concentration resulted from the addition of N at anthesis. The rise in grain N concentration per unit of N applied was much greater from increased fertilizer-N at anthesis compared with increased preplant N. In the injection experiment, late N application also resulted in a significant increase in yield (Tables 2 and 3).

Assuming a desired minimum protein concentration of 120 mg g^{-1} in grain containing 120 g kg^{-1} moisture, grain N concentration on an oven-dry basis must be 23.6 g N kg^{-1} or greater (grain protein equals 5.7 times grain N concentration). This grain N concentration was met or exceeded in several treatments by the high protein cultivar, Yecora Rojo, but only when N was applied at anthesis (Table 2 and 4). Grain N concentration of Anza and Yolo were well below this threshold even with high preplant N rates and N addition at anthesis (Tables 2 and 3).

Nitrogen Uptake from Soil and Fertilizer

The level of preplant N addition had little influence on postanthesis N uptake (Fig. 1a). In 1986–1987, mean postanthesis N uptake by Anza and Yecora Rojo without N addition at anthesis was 22 kg N ha^{-1}. Mean postanthesis N uptake by Yolo in 1987–1988 was 24 kg N ha^{-1} without late N addition. Even in 1988–1989, when the total season soil N supply was almost twice that of the other years (Table 1), mean postanthesis N uptake by Yecora Rojo was only 30 kg N ha^{-1} for treatments without a late N application. In contrast to the small effect preplant N had on N uptake after anthesis, N applied at anthesis increased N uptake markedly (Fig. 1b). The uptake response appeared to be linear from 0 to 65 kg N ha^{-1}, which was the highest anthesis N rate applied.

Soil N levels measured at anthesis in two of the 3 yr indicated no significant differences in extractable soil N among preplant N fertilizer treatments, ranging from 120 to 240 kg N ha^{-1}. In 1986–1987, mean ammonium plus nitrate soil N levels (extracted immediately after sample collection) were 1.0, 1.0, and 0.8 mg N kg^{-1} soil (C.V. = 12%) at 0 to 10, 10 to 20, and 20 to 30 cm, respectively. In 1988–89, mean

Table 2. Grain yield, grain N concentration, and total aboveground N of two wheat cultivars in the 1986–1987 ^{15}N injection experiment.

N fertilizer		Yecora Rojo			Anza		
Preplant	Anthesis	Yield	N conc.	Total N	Yield	N conc.	Total N
kg ha^{-1}		kg ha^{-1}	g kg^{-1}	kg ha^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}
120	0	5030	18.3	120	6650	14.5	127
	45	5650	21.9	160	7010	19.1	173
180	0	6470	19.9	173	7080	17.4	167
	45	6890	22.9	210	7580	19.5	200
240	0	6650	19.9	184	6750	18.3	183
	45	6790	24.5	231	7120	20.9	229

ANOVA	Yield	N concentration	Total N
Cultivar	***	***	NS
Preplant N rate	***	***	***
Anthesis N rate	***	***	***
Preplant × anthesis	NS	*	NS
CV	4.7	3.5	6.4

*,*** Significance at $P = 0.05$ and 0.001, respectively; NS, not significant at $P > 0.05$.

Table 3. Grain yield, grain N concentration and total aboveground N of Yolo wheat as influenced by preplant and anthesis N fertilizer in the 1987-1988 injection experiment.

Preplant N fertilizer	Anthesis N fertilizer ($kg\ N\ ha^{-1}$) 0			25			45			65		
	Yield	N conc.	Total N	Yield	N conc.	Total N	Yield	N conc.	Total N	Yield	N conc.	Total N
$kg\ ha^{-1}$	$kg\ ha^{-1}$	$g\ kg^{-1}$	$kg\ ha^{-1}$	$kg\ ha^{-1}$	$g\ kg^{-1}$	$kg\ ha^{-1}$	$kg\ ha^{-1}$	$g\ kg^{-1}$	$kg\ ha^{-1}$	$kg\ ha^{-1}$	$g\ kg^{-1}$	$kg\ ha^{-1}$
85	6250	13.5	110	7120	15.2	138	6630	17.5	145	7130	19.0	166
140	7420	13.6	136	7670	16.1	164	8080	16.5	175	7960	17.9	186
195	7630	15.0	163	8360	16.1	190	8290	17.4	212	8440	18.9	229
250	8220	16.5	212	7980	17.4	215	8550	17.7	245	7680	19.6	249

ANOVA	Yield	N concentration	Total N
Preplant N rate	***	***	***
Anthesis N rate	**	***	***
Preplant × Anthesis	*	**	NS
CV	6.3	4.5	7.0

*,**,*** Significance at $P = 0.05$, 0.01, and 0.001, respectively; NS, not significant at $P > 0.05$.

extractable soil N levels at anthesis were 1.6, 1.0 and 0.9 mg N kg^{-1} soil (C.V. = 18%) at the same depths. Likewise, mineralizable N estimated by anaerobic incubation ranged only from 19.4 to 20.9 mg N kg^{-1} soil (0- to 20-cm depth) for the three preplant N treatments, indicating little difference among preplant N rates. Strong (1982) reported a similar finding, where 50 to 200 kg N ha^{-1} at planting produced no significant soil N difference at the boot stage of irrigated wheat, even though maximum plant N accumulation at that stage was only 80 kg N ha^{-1}.

The duplicate plot experiment was designed to quantify acquisition of N from three potential sources: preplant fertilizer, anthesis fertilizer, and N supplied

Table 4. Wheat grain and straw yields, N concentrations, N yields, and contributions of fertilizer and soil N to total aboveground plant N at maturity as determined by labeled fertilizer. Yecora Rojo, 1987–1988 and 1988–1989 duplicate plot experiments.

N fertilizer		Grain			Straw				Source of plant N		
								Total	Fertilizer-N		
Preplant	Anthesis	Yield	N conc.	N yield	Yield	N conc.	N yield	Plant N yield	Preplant	Anthesis	Soil N
$kg\ ha^{-1}$		$kg\ ha^{-1}$	$g\ kg^{-1}$	$kg\ ha^{-1}$	$kg\ ha^{-1}$	$g\ kg^{-1}$	$kg\ ha^{-1}$		$kg\ ha^{-1}$ (% of applied)		
1987–1988											
120	0	5850	18.0	105	9110	3.8	35	140	—	—	
	30	6020	20.3	122	9170	4.1	37	159	55 (46)	22 (73)	82
	60	6250	23.2	145	9100	4.5	41	186	57 (48)	48 (80)	81
180	0	7060	19.7	139	10410	5.4	56	196	—	—	
	30	7070	21.8	154	10540	5.9	62	216	97 (54)	24 (80)	95
	60	6870	23.6	162	10100	6.7	68	230	99 (55)	44 (73)	87
240	0	6990	21.5	150	10950	7.0	77	226	—	—	
	30	7090	22.8	161	10530	7.4	78	239	131 (55)	18 (60)	90
	60	6980	24.0	167	10490	7.7	81	248	133 (55)	33 (55)	83
ANOVA											
Preplant N rate		***	***	***	***	***	***	***	***	***	NS
Anthesis N rate		NS	***	***	NS	***	NS	**	NS	***	NS
Pre. N × Ant. N		NS	**	NS	NS	**	NS	NS	NS	**	NS
CV		10.0	3.7	10.0	8.0	12.4	16.1	10.4	14.8	12.7	16.7
1988–1989											
120	0	6520	19.6	128	9430	4.3	41	169	41 (34)	—	128
	30	7190	22.1	159	9490	4.7	45	204	43 (36)	20 (67)	141
	60	6980	24.4	170	9150	4.9	45	215	38 (32)	40 (67)	138
180	0	7460	20.4	151	9860	4.8	47	199	63 (35)	—	136
	30	7260	23.0	167	9560	5.5	53	220	60 (33)	19 (63)	141
	60	7220	25.6	185	9770	6.1	60	245	59 (33)	43 (72)	143
240	0	7050	22.5	159	9710	6.0	58	216	84 (35)	—	132
	30	6730	24.6	165	9640	6.6	64	229	76 (32)	15 (50)	138
	60	7310	26.2	192	9690	6.5	63	255	71 (30)	46 (77)	138
ANOVA											
Preplant N rate		NS	***	***	NS	***	***	***	***	NS	NS
Anthesis N rate		NS	***	***	NS	***	**	***	NS	***	NS
Pre. N × Ant. N		NS	NS	NS	NS	NS	NS	NS	NS	*	NS
CV		6.5	2.9	7.0	7.1	9.2	10.6	7.2	12.9	12.2	7.9

*,**,*** Significance at the 0.05, 0.01, and 0.001 probability levels, respectively; NS, not significant at $P > 0.05$.

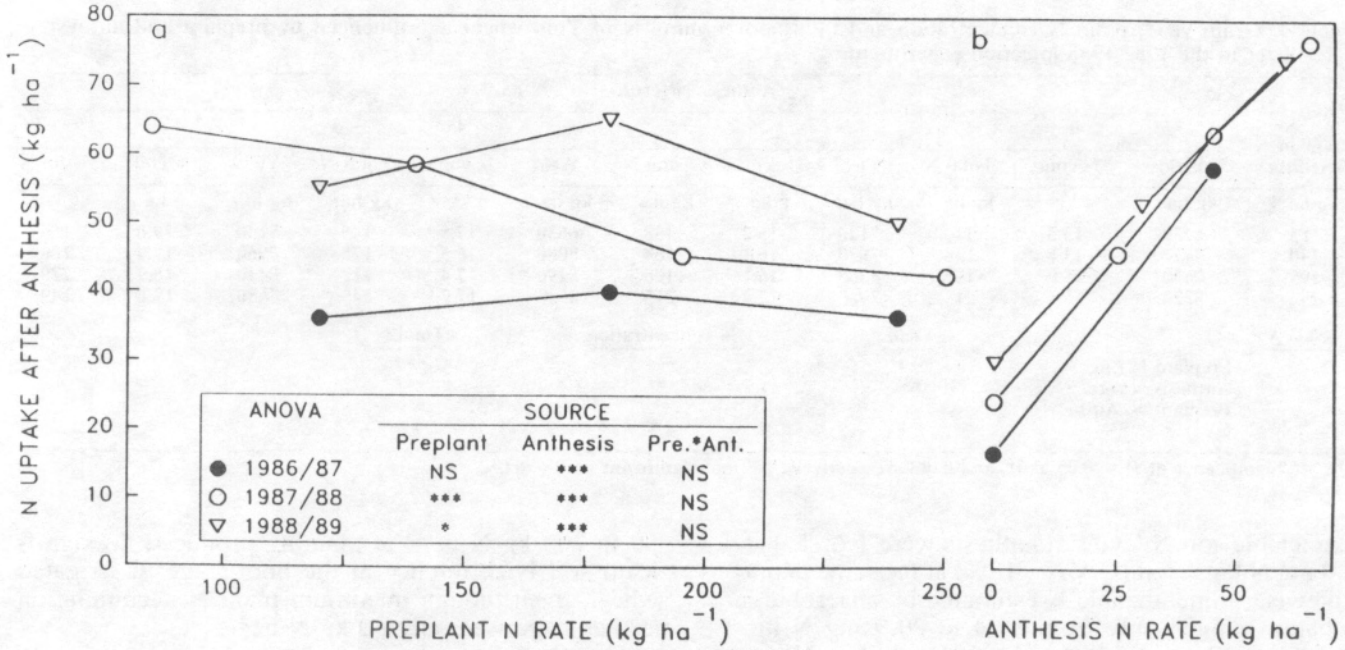

Fig. 1. The influence of N rate applied to wheat just before planting (a), or at anthesis (b), on postanthesis N uptake. Values in (a) are means of all N rates applied at anthesis, and values in (b) are means of all preplant N rates. In 1986–1987, Yecora Rojo and Anza did not differ significantly and are shown pooled. Also shown are the 1987–1988 (Yolo) ^{15}N injection experiment, and 1988–1989 (Yecora Rojo) duplicate plot experiment. Significance at 0.05 and 0.001 denoted by * and *.**

by soil. The proportion of N applied at anthesis recovered in aboveground plant biomass at maturity was always greater than that of N applied at planting (Table 4). The mean fertilizer-N uptake efficiency over yr and N rates was 68% for N added at anthesis versus 41% for N added preplant. In 1988–1989 (the high soil N year), recovery of both preplant and anthesis fertilizer-N was reduced compared to 1987–1988. In 1987–1988, there was a significant yield response when preplant N increased from 120 to 180 kg ha^{-1}, and recovery of fertilizer N applied at anthesis was greatest at these preplant N rates. Recovery of labeled N decreased considerably when preplant fertilizer N was increased to 240 kg ha^{-1}. The recovery of labeled preplant fertilizer measured in this study was comparable to that of Campbell and Paul (1978) and Abshahi et al. (1984), but higher than that of Powlson et al. (1986), where only 11 to 34% of the preplant fertilizer application was recovered.

Based on uptake of labeled fertilizer N, estimates of soil N taken up during the growing season were not significantly influenced by preplant or anthesis N rates. All N fertilizer treatments produced a similar increase in the estimated soil N contribution compared with N uptake by wheat grown without N fertilizer (Table 4 vs Table 1). This comparison, however, is confounded by potential "added N interactions" that may result from apparent (pool substitution) and real (increased root exploration) effects as discussed by Jenkinson et al. (1985). The potential for apparent added N interactions makes it difficult to quantify the effect of a labeled N addition on soil N uptake with certainty. Nevertheless, the comparable estimates of soil N uptake for all preplant and anthesis N fertilizer treatments within years indicates that the amount of fertilizer N added had little, if any, effect on soil N uptake. The lack of difference in soil N uptake when

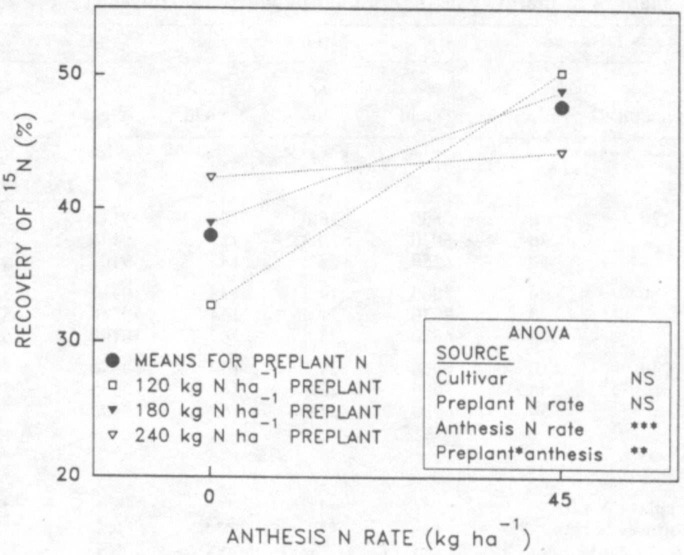

Fig. 2. Interaction of preplant and anthesis N fertilizer rate on recovery of NH_4-^{15}N (<1 kg ha^{-1}) injected into soil at wheat anthesis in the 1986–1987 ^{15}N injection experiment. Values shown are means for both Yecora Rojo and Anza because cultivar effects were not significant. Significance at 0.01 and 0.001 are denoted by * and *.**

various rates of labeled fertilizer N are applied has been noted in other field studies (Neilsen and Jensen, 1986; Olson and Swallow, 1984).

The injection of a small amount of ^{15}N (< 1 kg N ha^{-1}) below the soil surface allowed a more direct evaluation of the effect of late-season N addition on uptake of existing inorganic soil N. The addition of 45 kg ha^{-1} unlabeled fertilizer N at anthesis increased the recovery of injected ^{15}N from 38 to 48% in 1986–1987 (Fig. 2). In 1987–1988, recovery of injected ^{15}N without an anthesis N addition was 49% compared to 61% for the mean of the three anthesis N addition levels ranging from 25 to 65 kg ha^{-1} (Fig. 3). In 1986–1987, the interaction between preplant and anthesis treatments was significant. The magnitude of the effect of anthesis N addition on uptake of NH_4-^{15}N uptake decreased as the preplant N rate increased. This same trend was observed between the 0 and 25 kg ha^{-1} N additions in 1987–1988, but the interaction was not significant.

DISCUSSION

The Mediterranean climate of the Central Valley of California provides a favorable environment for growth of spring wheat between the months of October and June. With irrigation, yields commonly range from 6000 to 8000 kg ha^{-1} in commercial fields. To achieve desirable grain protein levels in this high yield environment, large quantities of N must be supplied and acquired by the crop.

Yields produced by the preplant N treatments in this study were comparable to those reported by other researchers at this location (Abshahi et al., 1984; Cox 1985a). These preplant N treatments had a relatively small effect on grain N concentration. In 1988–1989, when the highest preplant N treatment of 240 kg N ha^{-1} was 120 kg N ha^{-1} greater than required to maximize yield and the total season soil N supply was relatively large, grain N concentration remained below the 12% protein threshold when N was not applied at anthesis. It is clear that attempting to maximize grain protein by increasing early season N rates is not an effective or efficient use of N in these production systems. The fate of preplant N fertilizer not accounted for by plant uptake at the time of anthesis was not determined. Preplant N treatments, however, had no measurable effect on soil N levels at anthesis or on N uptake by plants after anthesis, suggesting loss through leaching, conversion to gaseous forms, or immobilization. Leaching was not considered likely because of the low amounts of rainfall received during the experiments.

In these studies, the postanthesis soil N supply was not sufficient to meet the N uptake capacity of the crop, regardless of the preplant N rate, unless additonal fertilizer N was applied at anthesis. Although the duration of active grain filling lasts less than 30 d after anthesis in this environment, two irrigations were supplied, one at anthesis and another 21 to 24 d later. Despite adequate soil moisture, only 20 to 30 kg N ha^{-1}, representing 12 to 18% of total N accumulation, was acquired postanthesis without additional late-season N fertilizer. This is comparable to values reported in other studies (Austin et al., 1977; Van Sanford and MacKown, 1987; Waldren and Flowerday, 1979). With the application of N at anthesis, N acquisition from flowering to maturity ranged from 30 to 50% of total N accumulation, depending on the early season N supply and the rate of N addition at anthesis. An upper limit to the N uptake capacity of wheat between anthesis and maturity was not detected in these experiments, even when 65 kg N ha^{-1} was applied and 77 kg N ha^{-1} acquired after anthesis.

In some years the addition of N at anthesis produced a significant increase in yield. When a yield increase was measured it was due to greater kernel weight (data not shown). Net CO_2 assimilation rates are correlated with total leaf N (Evans 1983), and longer duration of green leaf area with greater late season N supply was found to increase kernel weight in other studies (Spiertz and Ellen, 1978; Spiertz and van de Haar, 1978).

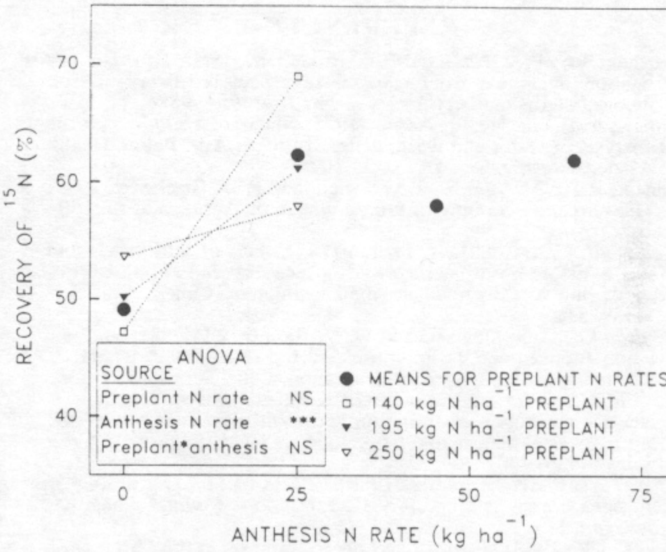

Fig. 3. Recovery by wheat of a small dose of NH_4-^{15}N (< 1 kg ha^{-1}) injected into soil at anthesis as influenced by anthesis N rate, and recovery at the three highest preplant rates for 0 and 25 kg N ha^{-1} anthesis rates. 1987–1988 (Yolo) ^{15}N injection experiment. Significance at 0.001 denoted by *.**

The greater efficiency of late-season versus preplant fertilizer N may reflect the more extensive root system, better photosynthate supply, and larger sink capacity of the fully established plant community at anthesis. All three of the cultivars tested responded similarly to late N treatments. The results of this study, in which late N fertilization combined with irrigation greatly increased N supply when the plant could best assimilate it, suggest that the often observed inverse relationship between grain yield and grain protein (McNeal et al., 1972; Terman et al., 1969) may in part result from a limited late-season N supply as opposed to a genetic or physiological barrier.

The late N application made at anthesis was always followed by an irrigation because rainfall rarely occurs during grain fill in the Central Valley. This coordination of the late season N application with an irrigation is likely to have contributed to the efficient uptake of the late N fertilizer. In rainfed systems, uptake from a late season N application would be more dependent on rainfall patterns.

This study examined only one of many possible N application schemes. It is likely that other split fertilizer arrangements can be devised which provide for postanthesis N uptake. Our comparison of preplant versus late season N application in irrigated wheat suggests that early season N management should be targeted to optimize grain yield, and late season fertilizer-N applications provided to optimize grain protein levels.

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