Soil–Plant Buffering of Inorganic Nitrogen in Continuous Winter Wheat

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ABSTRACT

The soil-plant system can limit soil profile inorganic N accumulation when N fertilizers are applied at rates greater than needed for maximum yield. Nitrogen rates that maximized grain yield and increased soil profile inorganic N accumulation under continuous dryland winter wheat (*Triticum aestivum* L.) were evaluated in four long-term experiments. Soil cores (0–210 cm) were taken in 1988 and again in 1993 from N rate treatments where wheat had been grown for more than 23 yr. Soil cores were split into 15- to 30-cm increments and analyzed for NH_4-N, NO_3-N, total N, and organic C. Critical N fertilization rates were determined from linear-plateau models of wheat grain yield on annual N applied. Plateau-linear models were established for soil profile inorganic N accumulation (sum of NH_4-N + NO_3-N, converted to kg ha^{-1}) on annual N applied. Maximum yields were observed at N rates less than that required to increase soil profile inorganic N accumulation. Annual N fertilization rates that increased inorganic N accumulation exceeded the N requirement for maximum yields by more than 23.3 kg N ha^{-1} in all experiments. Increased plant N volatilization and grain N uptake have been found when N rates exceed yield maximums. High N rates can also increase straw yield and straw N, subsequently increasing surface soil organic C and N and the potential for denitrification when wheat straw residues are incorporated. In dryland production systems, soil-plant buffering (considering the processes discussed) implies that the system buffers against (resist) soil accumulation of inorganic N, even when N rates exceed that required for maximum grain yield.

ENVIRONMENTALLY SAFE NITROGEN RATES for dryland winter wheat grain production systems require an evaluation of inorganic soil profile N accumulation. Early use of soil testing as a means of refining fertilizer N rates is discussed by Allison and Sterling (1949) and has since evolved into various reliable procedures (Dahnke and Johnson, 1990). More recent work has addressed economic optimum rates of N fertilization using various methods (Nelson et al., 1985; Barreto and Westerman, 1987). It is important to note that refined N fertilizer rate recommendations have also resulted from improved methods of placement (Sharpe et al., 1988), timing of application (Olson et al., 1979), source (Touchton and Hargrove, 1982), and tillage system (Mengel et al., 1982), all of which have received considerable attention in continuous winter wheat and corn (*Zea mays* L.) production systems. Recent work by Cerrato and Blackmer (1990) has focused increased attention on economic and environmental effects of overfertilization.

Early work by Herron et al. (1971) identified the need to test soils for NH_4–N and NO_3–N to a depth of 90 cm to better evaluate fertilizer requirements for irrigated corn. Westerman et al. (1994) used two quadratic equations (grain yield on N rate and soil profile NO_3–N accumulation on N rate) to determine the point where yields are maximized and soil profile NO_3–N accumulation is minimized. Their maximum difference method predicted N rates that optimized grain yield while minimizing the potential for inorganic soil N accumulation. Similar work by Jackson and Sims (1977) used a comprehensive N fertilizer management model for dryland winter wheat that considered soil properties and climatic factors, however, environmentally safe recommendations were not addressed.

Substantial research has been devoted to estimating N fertilizer recovery in continuous cropping systems. Nitrogen fertilizer recovery experiments have attributed unaccounted-for fertilizer N to plant N loss as NH_3 (Hooker et al., 1980; Daigger et al., 1976; O'Deen, 1989; Francis et al., 1993), denitrification (Olson et al., 1979; Olson and Swallow, 1984), surface volatilization of NH_3 when urea-N fertilizers have been used (Christensen and Meints, 1982), and NO_3–N leaching (Jokela and Randall, 1989; Olson and Swallow, 1984).

Present N recommendations in continuous grain production systems do not simultaneously consider N rates required for maximum grain yield while also minimizing N accumulation within the soil profile. Our objective was to establish these fertilizer N rates using linear–plateau and plateau-linear models. The difference between these N rates (N needed for maximum yield and N needed to increase soil profile inorganic N accumulation) is an estimate of the soil-plant buffering capacity for inorganic N when N rates exceed that needed for maximum yield.

MATERIALS AND METHODS

Four continuing long-term winter wheat (*Triticum aestivum* L.) fertility experiments (Table 1) were comprehensively soil sampled in July of 1993. This followed an initial sampling in 1988 to 1990 (Westerman et al., 1994) to further evaluate soil profile accumulation of NH_4–N and NO_3–N. Results from these two sampling periods were evaluated independently. The experiments used a randomized complete block design and are identified as Exp. 222, 406, 502, and 505. Experiments 502 and 505 are separate studies conducted at the same location on a Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll). Experiment 222 was on a Kirkland silt loam (fine, mixed, thermic Udertic Paleustoll), and 406 on a Tillman clay loam (fine, mixed, thermic Typic Paleustoll). Plots were 6.1 by 18.3 m, 5.7 by 18.3 m, 4.9 by 18.3 m, and 4.9 by 12.2 m for Exp. 222, 406, 502, and 505, respectively. Additional site information is provided in Table 1.

Winter wheat was planted in 25-cm rows at seeding rates of 67 kg ha^{-1} and grown under conventional tillage (disk incorporation of wheat straw residues following harvest and prior to planting) in all years and at all locations. Ammonium nitrate (34-0-0), triple superphosphate (0-20-0), and potassium chloride (0-0-50) were broadcast and incorporated prior to planting. Annual fertilizer treatments for each experiment are defined in Table 2.

In 1993, three soil cores (4.5 cm diam.) from each plot were taken to a depth of 210 cm and split into increments of 0 to 15, 15 to 30, 30 to 45, 45 to 60, 60 to 90, 90 to 120, 120 to 150, 150 to 180, and 180 to 210 cm. Samples were air-dried at ambient temperature and ground to pass a 20-mesh screen. Samples were extracted using 2 *M* KCl (Bremner, 1965) and analyzed for NH_4–N and NO_3–N using an automated flow injection analysis system (Lachat, 1989, 1990). Total N and organic C

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Table 1. Long-term experiments included in the analysis, year established, soil core sampling date, crop years prior to sampling, annual average rainfall, and range in annual rainfall.

Exp.	Year established	Replications	Dates sampled	Crop years prior to sampling	Rainfall† Annual avg.	Rainfall† Range
		no.			mm	mm
222	1969	4	Sept. 1988	19	894	606–1403
			July 1993	24	922	606–1493
					1057‡	738–1493‡
406	1965	4	Sept. 1988	23	640	295–1141
			July 1993	28	670	295–1141
					806‡	698–1053‡
502	1970	4	Sept. 1988	18	772	503–1314
			July 1993	23	771	503–1314
					765‡	556–1017‡
505	1970	3	July 1990	20	768	503–1314
			July 1993	23	771	503–1314
					780‡	555–1017‡

† Obtained from the years each study was conducted up until soil profile sampling and analyses was performed.

‡ Average rainfall and range for the last 5 yr (Exp. 222, 406, and 502) or the last 3 yr (Exp. 505).

were determined using a Carlo-Erba (Milan, Italy) NA 1500 dry combustion analyzer (Schepers et al., 1989). For Exp. 406, soil organic C was determined via digestion with an acidified dichromate ($K_2Cr_2O_7$–H_2SO_4) solution (Yeomans and Bremner, 1988) due to the presence of free $CaCO_3$ in surface horizons. Inorganic N (NH_4-N + NO_3-N) accumulation was determined on the mean of the three cores after concentration was converted to kg ha^{-1} based on measured bulk density, to a depth of 210 cm. Previously collected soil cores (1 per plot, 0–240 cm) taken in 1988 or 1990 (Westerman et al., 1994) from the same treatments in each of the experiments had been stored at 10°C (over this 3- to 5-yr period). These samples were reanalyzed for NH_4-N and NO_3-N using the same procedures described here to assure analytical consistency. To be consistent with the 1993 sampling depth, only the 0- to 210-cm profile increments were included from the 1988 to 1990 sampling. Separate surface soil (0–30 cm) analyses from a composite sample (20 cores per plot) collected in the summer of 1993 from the same treatments in all experiments is reported in Table 2.

The center 3.0 m, over the entire length of each plot was harvested for grain yield each year using a conventional combine, and wheat straw was uniformly redistributed in all plots each year. Depending on the location, harvest areas ranged between 37.2 and 55.7 m^2. Average grain yields were calculated from the time of initiation of each experiment up to the sampling dates (1988 or 1990 and 1993) when deep soil cores were taken from each long-term experiment.

Yield response to applied N was evaluated using a two-segment linear-plateau model (Anderson and Nelson, 1975). Similarly, soil profile inorganic N accumulation at the two sampling dates was evaluated using a two-segment plateau-linear model. Linear-plateau and plateau-linear programs were adapted using the NLIN procedure (SAS, 1988). Equations for the linear-plateau models were $y = b_0 + b_1$ [min(X,A)] such that b_0 is the intercept, b_1 is the slope of the line up to where X (N rate) = A (point where the combined residuals were at a minimum) (Mahler and McDole, 1987). In each case, model significance was obtained using all replications. Best estimates for b_0, b_1, and the point

Table 2. Treatments and surface soil test characteristics (0–30 cm) in 1993 for Exp. 222, 406, 502, and 505.

Exp.	Fertilizer applied N	Fertilizer applied P	Fertilizer applied K	Soil test† pH	Soil test† P	Soil test† K	Soil test† Organic C‡	Soil test† Total N‡
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}		mg kg^{-1}	mg kg^{-1}	g kg^{-1}	g kg^{-1}
222	0	29	38	5.76	81	43	6.15	0.79
	45	29	38	5.49	62	45	6.16	0.75
	90	29	38	5.47	66	32	6.14	0.75
	134	29	38	5.38	56	32	6.48	0.84
SED§				0.12	16	6	0.31	0.05
406	0	0	0	7.15	15	60	7.57	0.68
	45	20	38	7.11	51	66	6.95	0.69
	90	20	38	7.07	45	72	8.11	0.71
	134	20	38	6.63	44	69	8.31	0.71
	179	20	38	6.60	45	68	8.30	0.75
SED				0.18	3	4	0.42	0.05
502	0	20	56	5.67	92	69	5.34	0.70
	22	20	56	5.66	93	65	5.68	0.74
	45	20	56	5.42	91	66	5.88	0.72
	67	20	56	5.41	113	69	5.94	0.80
	90	20	56	5.25	122	70	5.98	0.78
	112	20	56	5.07	94	69	5.76	0.79
SED				0.13	18	5	0.44	0.02
505	0	29	56	5.35	156	56	6.38	0.71
	34	29	56	5.23	150	58	6.46	0.70
	67	29	56	5.00	142	61	6.41	0.70
	134	29	56	4.85	126	56	7.91	0.77
	269	29	56	4.62	140	59	7.18	0.76
SED				0.21	9	3	0.89	0.04

† pH, 1:1 soil/water; K and P, Mehlich III; organic C and total N, dry combustion.

‡ Average of 0–15 and 15–30 cm profiles.

§ SED, standard error of the difference between two equally replicated means.

Table 3. Confidence limits about joint estimates (critical levels) for linear–plateau models of grain yield on N rate and plateau–linear models of soil profile inorganic N accumulation on N rate, and the estimated soil-plant buffer for inorganic N when N rates exceed that required for maximum yield from long-term experiments sampled in the summer of 1988 (Exp. 222, 406, and 502) and the summer of 1990 (Exp. 505).

Exp.	Dependent variable	90% confidence interval Lower	Upper	Joint	r^2	Soil-plant buffer
		kg N ha^{-1}				kg N ha^{-1}
222	Grain yield	40.8	71.4	56.1	0.82***	45.9
	Profile N	91.7	112.4	102.0	0.63***	–
406	Grain yield	39.2	56.9	48.1	0.91***	25.7
	Profile N	52.4	95.2	73.8	0.89***	–
502	Grain yield	45.2	85.7	65.5	0.88***	36.3
	Profile N	95.8	107.8	101.8	0.32*	–
505	Grain yield	35.4	54.8	45.1	0.94***	69.1
	Profile N	80.2	148.2	114.2	0.89***	–

*,*** Model significant at the 0.05 and 0.001 probability levels, respectively.

of intersection (joint for linear and plateau portions, defined here as the critical N rate) were obtained from the model that minimized combined residuals. Combinations of possible values of b_0, b_1, and the point of intersection were evaluated (holding the other two constant), ultimately yielding the highest coefficient of determination (Mahler and McDole, 1987). Similarly, plateau-linear models minimized combined residuals by first establishing the plateau (no effect of N rate). Significant differences in the critical N rate for maximum grain yield that compared the two years included in this work were determined using a t-test that assumes unequal variances (Cochran and Cox, 1957) from independent linear-plateau models. Differences in critical N rates from plateau-linear models for soil profile inorganic N accumulation were determined using this same procedure. Soil-plant buffering capacities were estimated by subtracting the jointing point from plateau-linear models of inorganic N accumulation on N rate from that determined from linear-plateau models of grain yield on N rate (Tables 3 and 4). Lower and upper 90% confidence intervals about the critical N rate (joint) were calculated for both linear-plateau and plateau-linear models, and results from the two time periods were compared (all years up to 1988 for Exp. 222, 406, and 502; all years to 1990 for Exp. 505 compared to all years to 1993; Tables 3 and 4).

The response of average annual grain N uptake (grain yield multiplied times total N in the grain) to applied N was evaluated at each location for all years up to 1993 using a quadratic regression model. Linear-plateau models of average grain N uptake on N applied were evaluated but failed to explain equivalent variation found in quadratic models.

RESULTS

A wide range in annual precipitation (by location) and average precipitation (across locations) was present in these long-term continuous winter wheat experiments. Extended periods occurred where soils were both saturated and extremely dry at each location in different years. A trend for increased soil organic C (0–30 cm) at the higher N rates was found in all experiments (Table 2).

Linear-plateau models of grain yield on N rate were all highly significant ($\text{Pr} < 0.001$) for both time periods (Tables 3 and 4 and Fig. 1 and 2). Nitrogen rates that maximized grain yields (joint from linear-plateau models) were not significantly different between the two time periods (weighted t-test, $\text{Pr} = 0.98$, 0.92, 0.79 and 0.79 for Exp. 222, 406, 502, and 505, respectively). Predicted N rates that maximized grain yields differed by less than 3.5 kg N ha^{-1} when comparing the same experiments over time (Fig. 1 and 2 and Tables 3 and 4).

The sum of NH_4-N and NO_3-N was used to establish inorganic profile N accumulation, even though significant differences in profile N were largely due to NO_3-N alone in all trials and both years sampled. Including both NH_4-N and NO_3-N was expected to reflect actual differences in soil profile inorganic N when comparing results across locations. Plateau-linear models of inorganic N accumulation on N rate were significant ($\text{Pr} < 0.001$) in all experiments and both time periods, excluding Exp. 502 in 1988 (Fig. 1 and 2 and Tables 3 and 4). For each experiment and time period, annual N application rates that significantly increased soil profile inorganic N were all greater than the N rate needed for maximum grain yields. Predicted N rates that resulted in a significant increase in soil profile inorganic N were not significantly different for the two sampling periods, excluding Exp. 502 (weighted

Table 4. Confidence limits about joint estimates (critical levels) for linear–plateau models of grain yield on N rate and plateau–linear models of soil profile inorganic N accumulation on N rate, and the estimated soil-plant buffer for inorganic N when N rates exceed that required for maximum yield from long-term wheat experiments sampled in the summer of 1993.

Exp.	Dependent variable	90% confidence interval Lower	Upper	Joint	r^2	Soil-plant buffer
		kg N ha^{-1}				kg N ha^{-1}
222	Grain yield	40.7	71.1	55.9	0.88***	48.2
	Profile N	95.8	112.5	104.1	0.76***	–
406	Grain yield	37.8	57.0	47.4	0.90***	27.7
	Profile N	57.1	93.1	75.1	0.92***	–
502	Grain yield	46.9	77.2	62.1	0.87***	23.3
	Profile N	80.2	90.5	85.4	0.89***	–
505	Grain yield	34.7	51.9	43.3	0.91***	55.2
	Profile N	75.9	121.0	98.5	0.96***	–

*** Model significant at the 0.001 probability level.

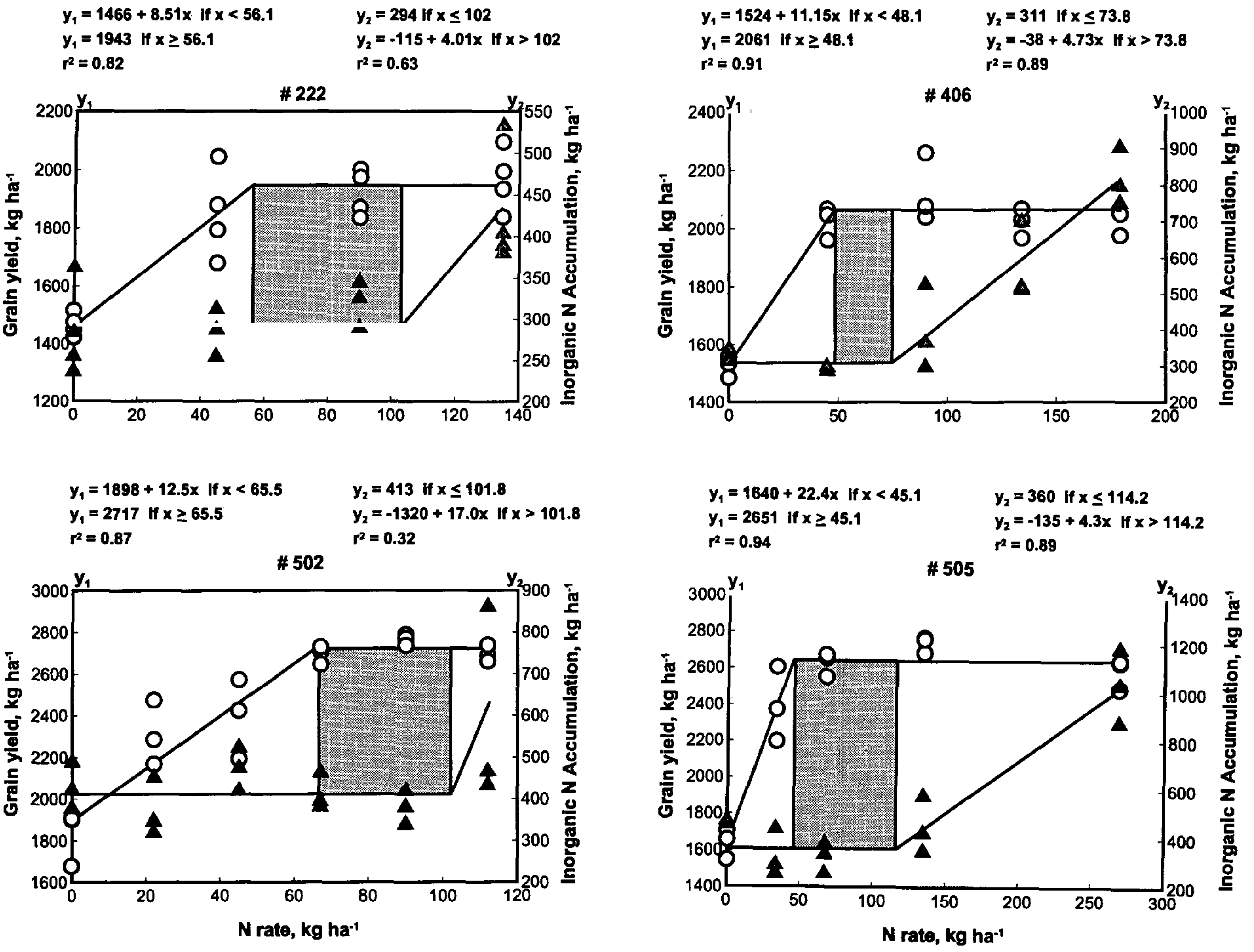

Fig. 1. Linear-plateau models of grain yield (open circles) on annual N applied and plateau-linear models of inorganic N accumulation (shaded triangles) on annual N applied and the estimated soil-plant buffer for inorganic N (shaded area) from Exp. 222, 406, 502 (1988), and 505 (1990).

t-test, Pr = 0.78, 0.93, 0.002 and 0.50 for Exp. 222, 406, 502, and 505, respectively; Fig. 1 and 2 and Tables 3 and 4). The poor correlation of soil profile inorganic N accumulation on N rate in Exp. 502 in 1988 was limited by the range of N rates, which failed to produce a highly significant cause-effect relationship (Fig. 1 and Table 3). Following five additional years of fertilizing and cropping (1993), small but significant increases in soil profile inorganic N at the high N rate were observed (Fig. 2 and Table 4).

Soil profile inorganic N accumulation increased at only one observed N rate above the joint estimate in three of eight plateau-linear models (Exp. 222, Fig. 1 and 2; Exp. 502, Fig. 1). In these cases, the joint (critical N rate) would be ≥90 and <135 kg N ha^{-1} (Exp. 222) and ≥90 and <112 kg N ha^{-1} (Exp. 502), since the joint could fall anywhere within these ranges without affecting residuals. However, the confidence limits about the joint estimate envelop this problem (significant increase in soil profile inorganic N accumulation observed only at the highest N rate) in terms of where to expect soil profile inorganic N accumulation to become significant.

Regression analysis of soil profile inorganic N accumulation on N rate, at N rates less than the jointing point is reported in Table 5. This analysis was performed to verify the presence of a plateau (no cause-effect relationship) prior to the estimated joint. For all experiments and sampling periods the slope was not significantly different from zero, excluding Exp. 406 in 1988, where a slightly negative slope was found (Table 5).

DISCUSSION

Differences between 1988 to 1990 and 1993 Sampling

Critical N rates for maximum grain yield did not differ between the first (1988 or 1990) or second (1993) time periods for any of the long-term field experiments (Tables 3 and 4). Furthermore, critical N rates for inorganic soil profile N accumulation were also not different for the same contrasting time periods. An exception was Exp. 502, where a significant increase in soil profile inorganic N could not be established in 1988, which restricted this comparison.

Soil profile inorganic N (kg ha^{-1}) was similar when comparing the same locations for the two independent sam-

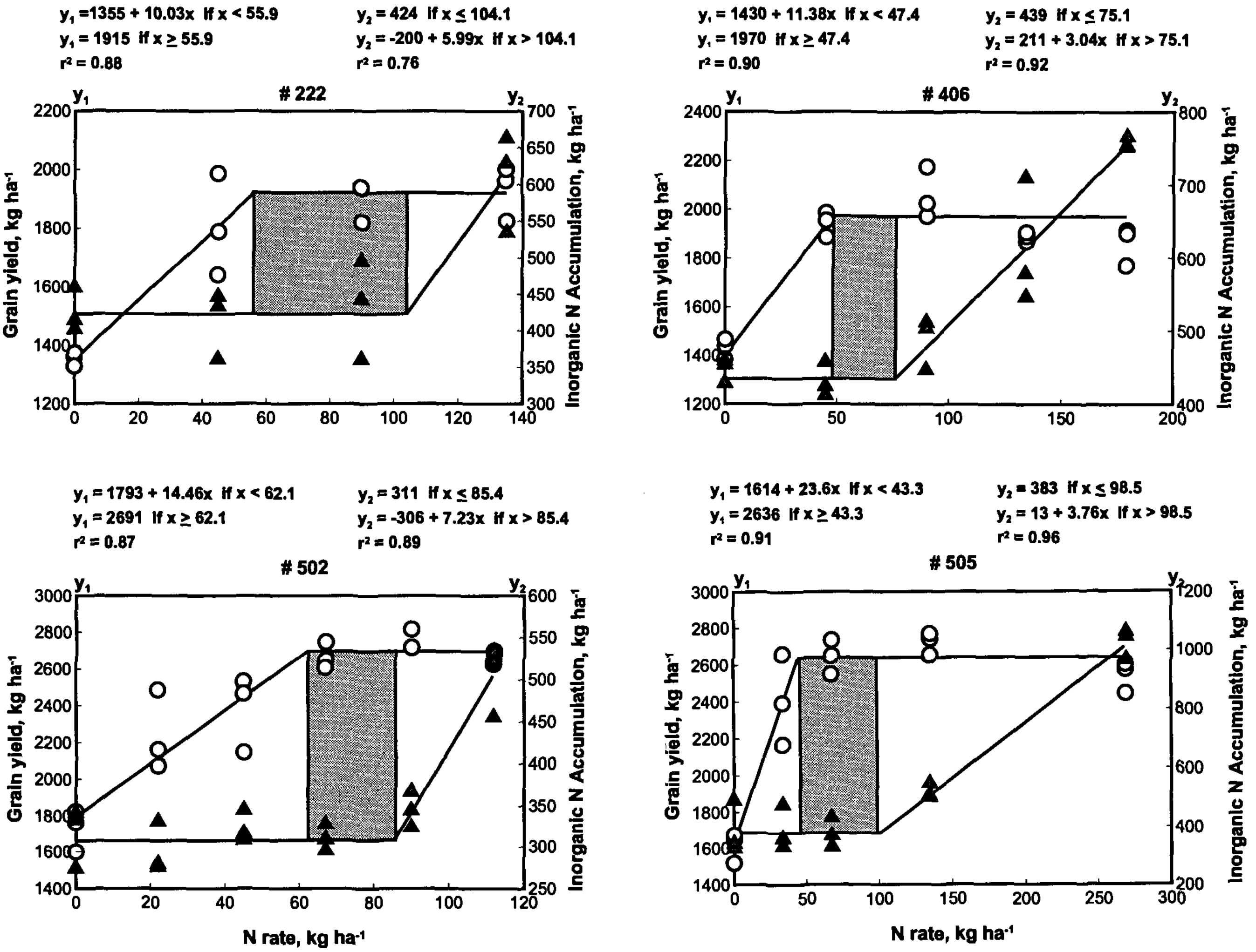

Fig. 2. Linear-plateau models of grain yield (open circles) on annual N applied and plateau-linear models of inorganic N accumulation (shaded triangles) on annual N applied and the estimated soil-plant buffer for inorganic N (shaded area) from Exp. 222, 406, 502, and 505 (1993).

pling dates (Fig. 1 and 2). Given the large amount of inorganic N found (>500 kg ha^{-1} in high-N treatments in all experiments and years), and considering that rainfall was above average during the time period separating sampling dates, it was interesting to find no significant differences in soil profile inorganic N over this time period (analysis of variance over time not reported). These results indicate that, if leaching of N occurred, it was no different in the check (0-N) or fertilized plots (up to rates where accumulation was significant), since the N rate where accumulation became significant was the same for both time periods (sampling dates).

Once maximum grain yields have been achieved at a given N rate, one might expect that excess fertilizer N would immediately result in increased inorganic soil profile N accumulation. However, this was not observed at any of the four locations or years sampled. The estimated N rate (joint) where soil profile inorganic N accumulation increased was considerably higher than the optimum N rate for maximum grain yields at all locations and for both time periods. In addition, the upper confidence limit for the estimated N rate required to achieve maximum grain yields was less than the lower confidence limit for the estimated N rate needed to increase soil profile inorganic N accumulation for both time periods, excluding Exp. 406 in 1988 (Tables 3 and 4). The N rates required to significantly increase soil profile inorganic N exceeded the N requirement for maximum yields by > 23.3 kg N ha^{-1} (all experiments and both time periods, Tables 3 and 4). Given the significance of each model, these results show

Table 5. Test for the significance of slope components (different from zero) for the regression of soil profile inorganic N accumulation on N rate, when N rates were less than the joint determined from plateau-linear models, for both sampling periods and all experiments.

Exp.	Year	Slope (b_1)	Pr > |t|†
222	1988	0.37	0.27
	1993	0.08	0.84
406	1988	−0.73	0.03*
	1993	−0.36	0.38
502	1988	0.63	0.35
	1993	0.06	0.85
505	1988	−1.96	0.10
	1993	−0.17	0.87

* Significant at the 0.05 probability level.
† Pr > |t|, probability of a greater absolute value of t.

a resistance to change in inorganic soil profile N accumulation (buffering) when fertilizer N is applied at rates greater than that needed for maximum yield.

Nitrogen Buffering Mechanisms

Mechanisms that would limit soil profile N accumulation when N rates exceeded that required for maximum yield were considered to explain the presence of soil-plant buffering of inorganic N. In several other wheat experiments, increased N rates resulted in increased grain protein without a subsequent increase in grain yield (Wuest and Cassman, 1992; Rasmussen and Rohde, 1991; Fowler and Brydon, 1989). Similar results were found in these experiments (Fig. 3). Average grain N uptake beyond the N rate required for maximum yield but less than the N rate required to increase soil profile inorganic N, was 9.4, 5.3, 3.2, and 14.9 kg N ha^{-1} yr^{-1} (Exp. 222, 406, 502, and 505, respectively). Based on the 1993 joint estimates for maximum yield and increased soil profile inorganic N accumulation, this increased grain N uptake represented 19, 19, 14, and 27% of the soil-plant buffer at the same respective locations (Table 4 and Fig. 3). Furthermore, increased grain N uptake was observed at all locations when N rates exceeded that required to increase soil profile inorganic N accumulation (Fig. 3). Although this was found to level off soon after N rates exceeded that required to increase soil profile inorganic N accumulation, it enhances the importance of increased grain N uptake as a buffering mechanism against accumulation.

Increased plant loss of NH_3 (and other volatile N forms) at high N rates has been observed in wheat (Parton et al., 1988; Harper et al., 1987), and similar results have also been found in corn (Francis et al., 1993). Harper et al. (1987), in an experiment that also reported no NO_3-N leaching, estimated that 21% of the applied N fertilizer lost from the wheat plant and soil was lost as volatilized NH_3. Olson et al. (1979) noted that denitrification losses assisted in explaining unaccounted-for N, which may have been greater at the higher N rates evaluated. Burford and Bremner (1975) found that denitrification losses increased under anaerobic conditions with increasing soil organic C from surface (0-15 cm) soils with a wide range in pH, texture, and organic C. Their work supports the action of denitrification as a buffering mechanism (during wet periods of the year) that could decrease the amount of NO_3-N leaching when N rates exceed that required for maximum yields. The necessary substrate for denitrification, soil organic C, tended to be higher with increasing applied N in all four long-term experiments reported here (Table 2). Although soils were saturated only for limited periods of time in our dryland trials, work by Burford and Bremner (1975) aids in explaining added N loss (at high N rates) other than via NO_3-N leaching. Similar work by Havlin et al. (1990) found that high rates of applied N can result in increased soil organic C and N. This is attributed to increased biomass production at the higher N rates over a long period of time. Increased wheat straw N uptake and straw dry matter yields at high N rates (Ras-

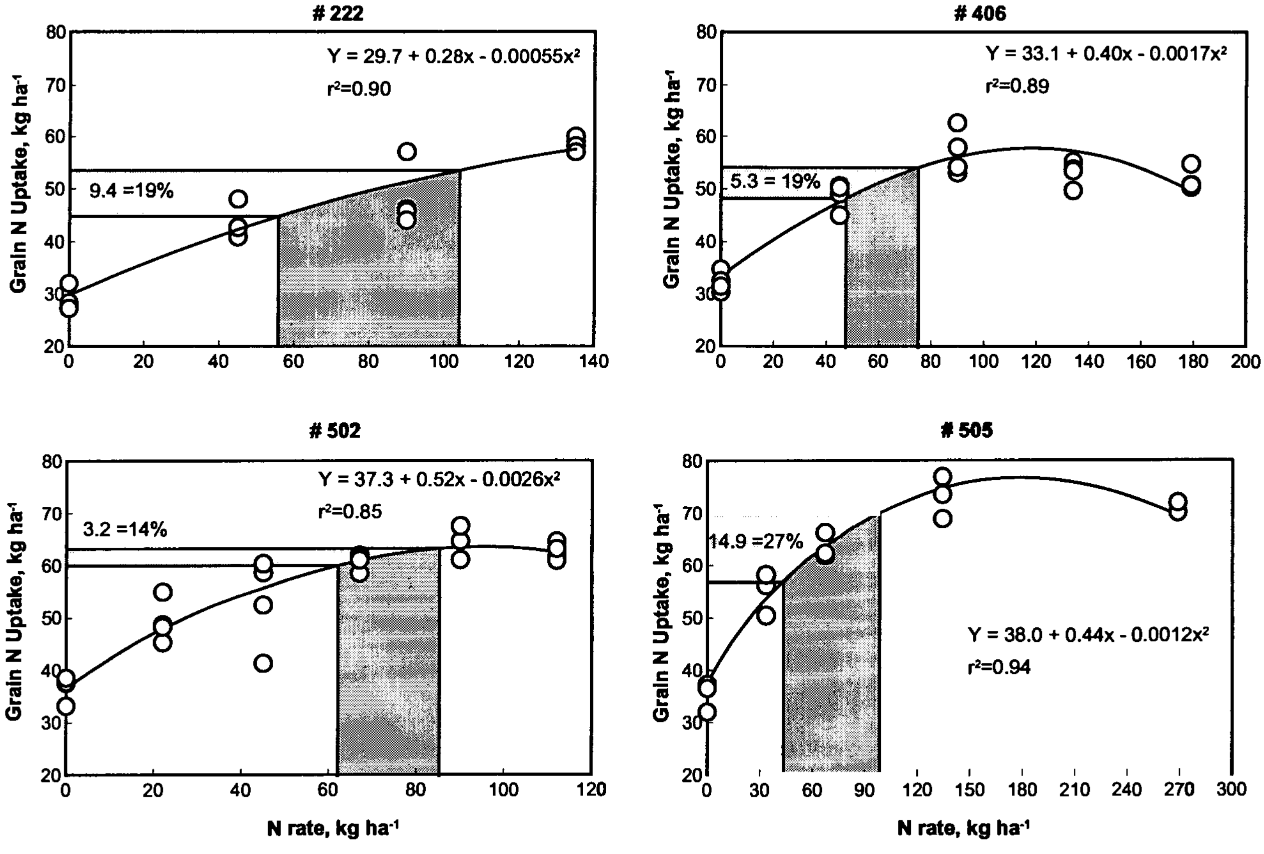

Fig. 3. Quadratic regression models of grain N uptake on annual N applied, superimposed critical levels for maximum grain yield and soil profile inorganic N accumulation (difference between the two vertical lines represents the estimated soil-plant buffer in Fig. 2) and percent of the soil-plant buffer explained by increased N uptake, Exp. 222, 406, 502, and 505 (all years up to 1993).

mussen and Rohde, 1988) can account for increased soil organic C and total N when N fertilization rates exceed requirements for maximum grain yield.

Soil-Plant Buffering of Inorganic Nitrogen

Although not specifically investigated in this work, each of the previously mentioned mechanisms aids in understanding why immediate increases in soil profile inorganic N were not observed when N rates exceeded that required for maximum yields. Furthermore, each of these mechanisms aids in understanding why plateau-linear models would be appropriate to evaluate soil profile inorganic N accumulation as a function of N applied. Two distinct relationships between soil profile inorganic N and N rate are implied: no cause and effect up to a critical N rate (plateau, slope = 0), and a significant cause and effect (linear, slope significantly different from zero) beyond the critical N rate. Excess N fertilizer can continue to be assimilated by the plant, resulting in increased grain protein, straw N removal, and plant N loss, each of which could act as a compensating factor or buffering mechanism. Harper et al. (1987) found no evidence to suggest large amounts of N translocated from vegetative plant parts to the roots and subsequent N loss by the roots to the soil. Even if this were a significant pathway for plant N loss, soil profile inorganic N accumulation from these long-term trials would reflect these possible differences.

This work supports the hypothesis that applied inorganic N and/or inorganic N coming from organic pools are subject to various fates that can diminish the likelihood of NO_3-N leaching. Westerman et al. (1994) reported soil profile NO_3-N accumulation within specific profile increments (e.g., Exp. 505, 180-210 cm) at levels exceeding the annual amount of N applied when extremely high rates were used. For this to occur, leaching below the depth sampled could not have been a major pathway for N loss. Excluding freely drained deep sandy soils, inorganic N accumulation reported here was expected to reveal if and where excessive N rates contributed to the potential for NO_3-N leaching in dryland wheat production systems.

An illustration of the buffer concept is shown in Fig. 1 and 2 whereby an inorganic N buffer zone is calculated based on the differences between the N rate where significant soil profile inorganic N accumulation took place and the N rate where maximum yields were achieved. Use of the maximum difference method proposed by Westerman et al. (1994) did not identify this inorganic N buffer zone, since two quadratic equations (grain yield on N rate and soil profile NO_3-N accumulation on N rate) were used that resulted in one specific N rate when simultaneously solving for X. While their approach optimizes the difference between yield and inorganic soil N accumulation, it is limited to identifying a single rate for both dependent variables. Alternatively, the combined use of linear-plateau and plateau-linear models are useful in identifying factor or factors controlling response following an observed maximum with one variable (Y_1), but prior to an increase in another variable (Y_2) when both are regressed on X.

Grain yield maximums were obtained at markedly different N rates at all locations, which was expected to be a function of the native N supplying power of each soil, percent organic matter, rainfall, and a combination of other biological factors. Although limited by the number of sites reported, the soil-plant buffer tended to be positively correlated with surface soil (0-30 cm) organic C. It is possible that the soil-plant buffer could be greater in soils with high soil organic matter, however, this is expected to be dependent on the cropping system, climatic conditions influencing plant and soil gaseous N loss, variety, and the possible combination of several other factors. It is important to note that these relationships could not have been studied in short-term experiments where changes in soil organic C levels would not have been expressed in three to five year studies, and when N rates were only slightly above the requirement for maximum yield.

Differences in the size of the soil-plant buffer at the locations studied here could not be attributed to differences in plant type since the same varieties were used. However, in all instances the N rate required for inorganic N accumulation to become significant was greater than that required for maximum yield and that the confidence intervals about each estimate (maximum yield and inorganic N accumulation) did not overlap (an exception was Exp. 406, 1988). While the soil-plant buffer zone has been emphasized, we recognize that buffering exists over the entire range of fertilizer N rates used in these studies. Long-term N rate experiments with other continuous cropping systems should reveal similar results when the same common, fundamental chemical and biological processes are active. Where inorganic soil profile N accumulation directly reflects the potential for NO_3-N leaching, this evaluation method should be useful in establishing safe N rates in dryland crop production systems. Future work will focus on identifying the specific variables that characterize differences in soil-plant buffering.

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