A Model for Making Field-Based Nitrogen Recommendations For Winter Wheat in Western Oregon

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Summary: A model based on early spring soil and tissue analysis was developed and evaluated for predicting the need for additional nitrogen (N) fertilizer on winter wheat. To develop the model. On-farm trials were established over three years 1994-95 in grower`s fields at three different locations across the Willamette Valley of western Oregon. Two field-scale validation trials were run in 1996-97. Rotations were soft white winter wheat following grass seed, sweet corn or a legume. Four treatments, including a check receiving no nitrogen, were used at each site. At the site where wheat followed corn, the predicted optimum N rate was 168 kg N ha^{-1}; however, the 112 kg N ha^{-1} rate was the optimum rate predicted by the developed model. The 84 kg N ha^{-1} and 140 kg N ha^{-1} rates were selected to bracket the recommended rate (± 28 kg N ha^{-1}).Wheat following grass seed had high soil supplied N which depressed the yield even at moderate fertilizer N rates. The model overall accurately assess field-specific optimum fertilizer N status.

Introduction

The assessment of optimum nitrogen fertilizer rates for winter wheat (*Triticum aestivum* L.) is important for economic and environmental sustainability. In wheat a sub-optimal supply of nitrogen (N) can dramatically reduce dry matter and subsequently grain yield [1, 2]. While oversupply of nitrogen may cause disease, lower grain quality and environmental pollution [3-5]. Establishment of precise N fertilizer rates requires the consideration of realistic yield goals, N requirement of the crop, residual N and the N supplying capacity of the soil [6, 7].

The determination of optimum N fertilizer rates for winter wheat is a major unsolved problem in most humid region of the world [8]. Soil tests for residual nitrogen (N) can improve prediction of crop N fertilizer requirements in humid regions of U.S.A, but incorporation of these test results in fertilizer recommendation depends on the frequency of significant profile NO_3.N carryover [9]. In the humid region of Wisconsin, Vanotti and Bundy [10] found 32 to 106 kg N ha^{-1} of residual N which made soil testing for NO_3 an important tool to optimize N fertilizer use. Despite complications such as mobility, leaching and nitrification, soil tests for residual NO_3 have been found to be useful in determining N fertilizer needs of crops [11]. In western Oregon, a variety of crop rotations create large differences in soil N supplying capacity, which are not reflected in soil tests for inorganic N. In a study carried out in western Oregon, Sebastian [12] measured N recovery by unfertilized winter wheat ranging from 96 to 192 kg h^{-1}. Assessment of mineralizable N at the beginning of the growing season and coupling the results with soil mineral and plant analysis could be helpful in improving fertilizer N recommendations in the region. Plant tissue analysis at early growth stages are another important method of estimating optimum fertilizer N rates and have successfully been used as an indicator of N fertilizer requirements for wheat by many researchers [13]. In regions where soil testing for N is impractical due to heavy precipitation, plant tissue testing could be a promising method of estimating fertilizer N requirements for winter wheat [14].

Incorporating information about crop N requirements, soil testing and plant analysis at early growth stages will be very helpful towards optimizing the fertilizer N recommendations for winter wheat. The objective of this study was to evaluate the suitability of

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an N balance model for predicting the need for additional N fertilizer on winter wheat under western Oregon conditions.

Results and Discussion

Predicted Optimum N Rates

Optimum fertilizer N rates for winter wheat were estimated by the following N balance model.

$$\text{Recommended N} = 300 - (N_r + N_{min} + N_{up}) \quad (1)$$

where N_r and N_{min} are the soil inorganic N ($NH_4 + NO_3$) and soil mineralizable N kg ha^{-1} at Feekes 5 before fertilizer application, respectively and N_{up} is the total N (kg ha^{-1}) taken up by the crop at Feekes 5 prior to fertilization. The 300 N kg ha^{-1} is the total N (residual N + mineralizable N + fertilizer N) assumed to be needed for maximum yield in Willamette Valley of western Oregon. The parameters used in the model were determined at the time of spring fertilization in order to assess optimum N rates. Parameter values and predicted fertilizer N need for the various trials conducted as part of this study are shown in Table-1. At on-farm sites, the amount of soil inorganic N in the top 30 cm of soil at the time of spring fertilizer application was low through all rotations over years. The average inorganic N across all rotations over years was only 27 kg N ha^{-1} (Table-1). This is likely because of leaching and/or denitrification losses due to heavy precipitation during winter months [12]. Soil mineralizable N in the top 30 cm of soil varied greatly among rotation over years. Amount measured prior to spring fertilization ranged from 53 kg N ha^{-1} in the wheat following corn in 1995 to 116 kg N ha^{-1} in the wheat following grass seed in 1996. In 1995 and 1996, wheat following grass had relatively high soil mineralizable N. The amount of N taken up by the crop at the point of fertilization was also comparatively high in wheat following grass in 1995 and 1996 which indicates high N availability in grass rotation (Table-1). In small plots for 1996 and 1997, the soil inorganic N in the top 10 cm of soil at Feekes 5 was similar in oat and clover rotations (Table-1). In 1996, the soil mineralizable N in the top 10 cm of soil was also same for two rotations with average of 57 kg N ha^{-1}. In 1997; however, wheat following clover had a higher soil mineralizable N compared to wheat following oat. A similar pattern was found for plant N uptake at Feekes 5 where in 1996 the N uptake was not significantly different between rotations but in 1997, clover-wheat had a significantly higher N uptake of 32 kg N ha^{-1} compare to 6 kg N ha^{-1} for wheat following oat (Table-1). Based on the proposed model recommended-N rates ranged from 114 to 217 kg N ha^{-1}

Table-1: Assessment of optimum N rates for each rotation using the N balance model.

Rotation	Mineralizable N*	Soil N**	Plant N Uptake***	Recommended N rate****
		On-farm Trials		
		1994		
Clover - wheat	94.9	22.9	19.0	163
Corn - wheat	106.5	18.4	18.0	157
Grass - wheat	84.4	38.8	20.0	157
		1995		
Clover - wheat	72.2	36.1	25.6	166
Corn - wheat	53.2	25.8	31.1	190
Grass - wheat	91.6	24.9	38.6	145
		1996		
Clover - wheat	60.4	26.6	26.1	187
Corn - wheat	74.4	33.3	15.1	177
Grass - wheat	116.0	26.7	42.8	114
		Small Plot Trials		
1996				
Oat - wheat	55.1	33.7	17.6	193
Clover - wheat	59.7	43.1	14.3	179
1997				
Oat - wheat	63.2	13.1	6.5	217
Clover - wheat	85.3	14.4	31.7	168

* Soil mineralizable N kg ha^{-1} at Feekes 5 before fertilizer application

** Residual N (NH_4-N + NO_3-N) kg ha^{-1} at Feekes 5 before fertilizer application

*** Whole plant N uptake kg ha^{-1} at Feekes 5 before fertilizer application

**** Recommended N rate obtained by using model: $N = 300 - (N_r + N_{min} + N_{up})$ (1)

Grain Yield Response

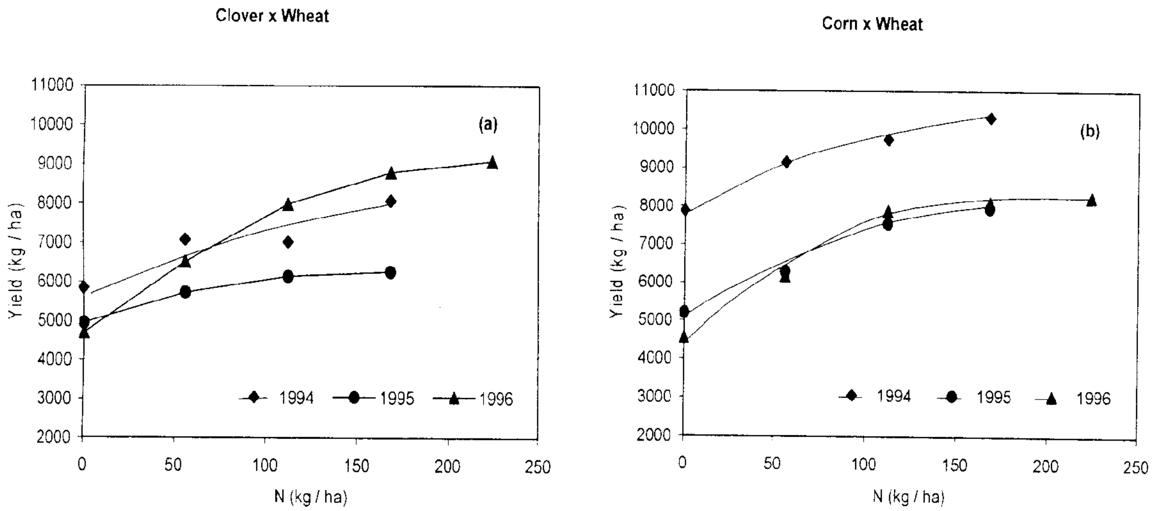
The grain yields for each site-year are summarized in Table-2. There was a significant yield response to fertilizer N in every trial. In all rotations, a significant yield increase occurred with the first increment of N fertilizer. The effects of additional N varied among rotations and years. This variation in yield response to added fertilizer N among rotations and years may have been due to the factors such as soil type, soil texture, water availability, soil nutrient levels and weather. Grain yield responded curvilinearly to applied N fertilizer as illustrated in Figs. 1a-1c. The regression equations that best described grain yield response to N fertilizer at each site are given in Table-3.

In the 1994, yields were high across all rotations compare to the average long term yield for the region (Table-2). The average yield across all rotations with no fertilizer was 6824 kg ha^{-1}-. The USDA Agriculture Statistics Service reported yields 15 % above the long term average in western Oregon during 1994 [15]. In the wheat following corn rotation, each increment of N fertilizer significantly increased yields

Table-2: Mean grain yield and protein content of on-farm trials for the 1994-96 growing season.

Total N * applied	**Previous crop**								
	Clover			**Corn**			**Grass**		
	1994	**1995**	**1996**	**1994**	**1995**	**1996**	**1994**	**1995**	**1996**
kg ha^{-1}					-------------- kg ha^{-1} --------------				
0	5842a	4950a	4697a	7880a	5207a	4559a	6752a	3191a	4520a
56	7082b	5731b	6518b	9147b	6295b	6178b	9165b	5499b	5704b
112	7020bc	6138bc	7987c	9742c	7549c	7897c	9180bc	5853bc	6331bc
168	8076d	6258cd	8794d	10315d	7957cd	8111cd	10272d	6288cd	5915bcd
224			9082de			8251cde			5551bcde
PLSD	949	517	513	493	975	690	935	925	720
CV %	6	4	3	2	7	6	5	9	5
P-value	0.008	0.004	0.000	0.008	0.009	0.003	0.001	0.000	0.00

*In 1995 and 1996 wheat following grass fertilizer N rates were used as 0, 67, 134, 201 kg N ha^{-1}



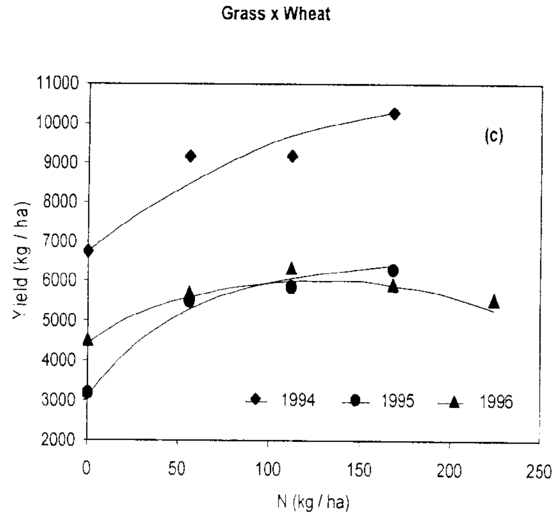


Fig. 1: Yield response of (a) Clover - wheat (b) Corn - what (c) Grass - wheat rotations to fertilizer N rate of on-farm trial for the 1994-96 growing season.

Table- 3: Regression equations for nitrogen response curves of On-farm trials for the 1994-1996 growing season.

Rotation	Regression equation	R^2
	On-farm Trials	
	1994	
Clover-wheat	$G = 5963 + 14.34 * N - 0.11 * N^2$	.66
Corn -wheat	$G = 7913 + 23.40 * N - 0.05 * N^2$	.78
Grass - wheat	$G = 6925 + 30.50 * N - 0.73 * N^2$	.98
	1995	
Clover - wheat	$G = 4955 + 16.59 * N - 0.53 * N^2$	.77
Corn - wheat	$G = 5156 + 26.07 * N - 0.05 * N^2$	.84
Grass - wheat	$G = 3324 + 35.61 * N - 0.10 * N^2$	.92
	1996	
Clover - wheat	$G = 4674 + 38.75 * N - 0.85 * N^2$	.82
Corn -wheat	$G = 4499 + 39.40 * N - 0.10 * N^2$	.77
Grass - wheat	$G = 4359 + 24.08 * N - 0.09 * N^2$	.67
	Small Plot Trials	
	1996	
Oat - wheat	$G = 2193 + 40.77 * N - 0.06 * N^2$	.97
Clover - wheat	$G = 4027 +36.80 * N - 0.07 * N^2$	.89
	1997	
Oat - wheat	$G = 1171 + 43.38 * N - 0.06 * N^2$	.97
Clover -wheat	$G = 3566 + 51.61 * N - 0.14 * N^2$	.94

($p < 0.05$). The high response to N fertilizer for wheat following corn could be because corn provided a large quantity of a residue with a high C:N ratio. Echeverria *et al.*, [16] also found that wheat after corn responded most to N fertilizer as compared to wheat following soybean or sunflower.

Wheat following clover in 1994 had lowest overall mean yields ranging from 5842 kg ha with no fertilizer to 8076 kg ha^{-1} with 168 N kg ha^{-1}. No significant difference was observed between 56 and 112 kg N ha^{-1} treatments (Table-2). A current western Oregon fertilizer recommendation for wheat following clover are less than for wheat following row crops, but varies depending on how vigorous the clover crop was. A less than average stand of clover would result in less available N for the subsequent wheat crop. The check yield for wheat following grass was 6752 kg ha^{-1}. As was observed for wheat following clover rotation, there were no significant difference between treatments of 56 and 112 N kg ha^{-1} (Table-2).

In 1995, response to N fertilizer for wheat following corn was similar to 1994 observations. Yield increased significantly with each increment of N fertilizer except at the highest N rate (168 N kg ha^{-1}). Mean grain yields were, in general, greater in wheat following corn compared to wheat following clover or grass. The wheat following grass rotation had the lowest check yield (3191 kg ha^{-1}) and the largest response to initial N increment (5499 kg ha^{-1}). Adding 56 N kg ha^{-1} increased the yield by over 2300 kg ha^{-1}. At the highest N fertilizer rate, the mean yield of wheat following clover and grass were the same, 6258 kg ha^{-1} and 6288 kg ha^{-1}, respectively. In addition, the yield increased from 56 to 112 N kg ha^{-1} was not significant for clover-wheat and grass-wheat rotations.

As 1994-95 data suggested there may be a response to a higher N rate, a 224 N kg ha^{-1} rate was included in 1995-96 experiments. No additional yield response was obtained for this higher rate in any rotation. Interestingly, the check yield for all three rotations was similar with an average value of 4592 kg ha^{-1}. At higher N rates, mean yields of wheat following clover and corn were about the same, while yields of wheat following grass were less. In fact, the highest yield of wheat following grass was achieved with 112 N kg ha^{-1}. Yield dropped when the fertilizer N was applied at the rates of 168 and 224 N kg ha^{-1} (Fig. 1 c). This reduction in yield at high N rates may be due to increase in disease incidence, water stress, or to physiological reactions by the plant itself [17]. No lodging occurred in any rotation. It was observed throughout the study that wheat following grass had relatively higher soil N availability (Table-1) and higher N uptake (data not shown) as compared to wheat following clover and wheat following corn.

Determination of Nitrogen Rates for Optimum Grain Yield

Fig. 1 shows yield as a function of applied fertilizer for wheat following clover, corn and grasses. The yield data fit a quadratic model using applied N as an independent variable. Regression equations for yield response curves and their corresponding correlation coefficient (R^2) are given in Table-3. The amount of N fertilizer required at Feekes 5 to produce maximum yield (MPY) in each rotation and years was determined by using the N balance model. The MPY rates predicted by this model were compared with actual N rates required to obtain maximum economic yields (MEY). The amount of fertilizer N required for maximum economic yield were calculated from each response curve at each rotation site. The MEY for any given response curve is the fertilizer rate where the first derivative of the response function equals the price ratio of N fertilizer to wheat (eq. 3). Two N fertilizer / wheat price ratios were used in this study to calculate MEY. The difference between the MEY values (N_1 and N_2) was not significant ($p > 0.8$), consequently N_1 is used in comparisons. In 1994, the MEY rates for wheat following clover and wheat following corn exceeded the largest N fertilizer rate used in the study; therefore, the highest N rate of 168 N kg ha^{-1} was considered as MEY rate (Table-4). The comparison of MPY and MEY values are given in Table-4. At on-farm sites in 1994, the model underestimated MEY by 5 N kg ha^{-1}, 11 N kg ha^{-1} and 18 N kg ha^{-1} for wheat following clover, corn and grass, respectively. In 1995, the model overestimated N need in the clover rotation by 54 N kg ha^{-1}. This was the largest difference observed in this study. In 1995, corn and grass rotation MPY and MEY rates were very close. In 1996, good agreement was found between MPY and MEY values for all three rotations with the largest difference only = 7 N kg ha^{-1} Average MPY and MEY rates, 174 and 178 N kg ha^{-1}, respectively, were highest for wheat following corn. Due to high soil N, low average MPY and MEY rates (141 and 143 N kg ha^{-1}) were observed for wheat following grasses. A good correlation between MPY and MEY ($r = 0.77$) was observed across rotations and years.

Table-4: Comparison of calculated and observed N rates.

Rotation	Yield at recommended N rate	N [*] rate recommended by model	N [**] rate for Max. Econ. Yield N1	N [**] rate for Max. Econ. Yield N2
		kg ha^{-1}		
On-farm Trials				
		1994		
Clover - wheat	7994	163	168	168
Corn - wheat	10216	157	168	168
Grass - wheat	9908	157	175	182
		1995		
Clover - wheat	6258	166	112	121
Corn - wheat	8007	190	196	200
Grass - wheat	6287	145	147	152
		1996		
Clover - wheat	8951	187	190	196
Corn - wheat	8290	177	170	175
Grass - wheat	5956	114	107	112
		Small Plot Trials		
		1996		
Oat - wheat	7953	193	200	200
Clover - wheat	9154	189	179	200
		1997		
Oat - wheat	7915	217	200	200
Clover - wheat	8145	168	162	165

[*] Recommended N rate calculated by using equation (1)

[**] N rate to obtain maximum economic yield. N1 and N2 are the rates where the price of wheat
was set equal to \$3.5 and \$4 per bushel, respectively and price of N fertilizer was \$0.25.

In small plot trials the N fertilizer rates predicted by the model were also fairly close to the N rates required to obtain maximum economic yields rates. In 1996, due to high response of grain yield to N fertilizer (Fig. 2), the MEY yields rates for wheat following oat and wheat following clover exceeded the largest N fertilizer rate; therefore, high rate of 200 was considered as MEY rates. In 1997, MPY and MEY rates were very similar. However, wheat following oat had higher MPY and MEY rates compare to the clover-oat rotation, 38 kg N ha^{-1} 49 kg N ha^{-1}, respectively.

Model Validation

In 1996-97, N rate trials were conducted to further check the validity of the proposed model. Recommended N rates and subsequent yield and grain protein concentration are given in Table-5. The recommended fertilizer N rates were 112 N kg ha^{-1} and 168 N kg ha^{-1} for wheat following grass and corn, respectively. Cooperating growers selected other N treatments in these trials. Bracketing treatments were chosen at the grass site and lower rates at the corn site.

In both rotations, the model predicted mean yield for the recommended rate was significantly higher than the other two treatments used in the experiment

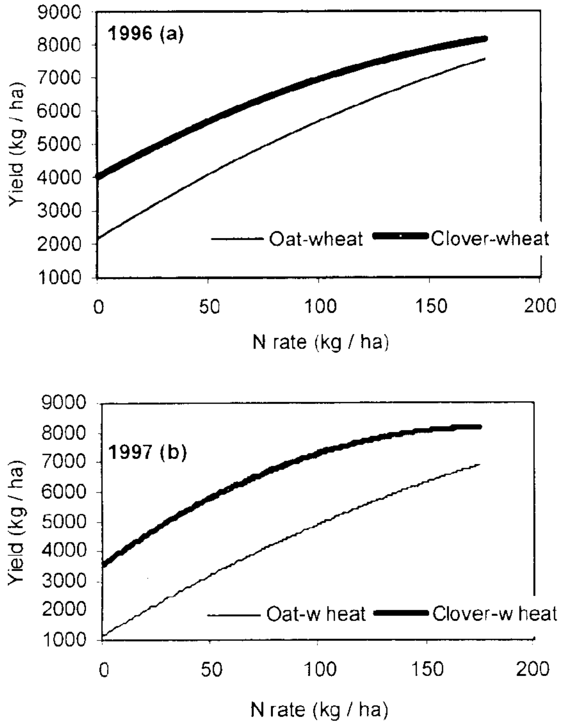


Fig. 2: Yield response of clover - wheat and oat - wheat rotations to fertilizer N rates (a) 1996 and (b) 1997 of small research plots trials.

Table-5: Mean yield and protein content for model validation trials conducted during 1996-97 winter wheat growing season.

*N rate (Kg ha^{-1})	Yield (Kg ha^{-1})	Protein content %
Grass - wheat rotation		
84	4651a	9.8a
112	5168b	9.7ab
140	4875ab	10.5c
PLSD	381	0.15
CV	2	1
P-value	.004	.000
Corn - wheat rotation		
84	6476a	8.0a
132	7237b	8.7b
168	7946c	9.5c
PLSD	577	0.56
CV (%)	3	3
P-value	.005	0.01

*Recommended N rate by using model (1)

(Table-2). In the grass rotation, model predicted mean yield dropped at the higher fertilizer N rate and there was no significant difference in yield between the high and low fertilizer N rate treatments. Soil analyses also revealed high residual N (NH_4 and NO_3) at the end of the season (data not shown). The plant N uptake at the end of the season was also higher for wheat following grass compared to wheat following corn (data not shown). Similar results were observed for wheat following grass of on-farm trials in 1996 where mean yield dropped considerably at higher fertilizer N rates, while total biomass and grain protein content increased significantly as higher fertilizer N was added (Fig. 2). Costa and Kronstad [18] reported that the redistribution of N from vegetative plant growth accounted for at least 50 % of grain protein N. Higher levels of biomass observed in the study due to higher levels of N could potentially increase the amount of N to be redistributed which contributes to a higher grain protein N concentration. In the wheat following corn rotation each increment of N fertilizer significantly increased grain yield. These results are similar to observations for wheat following corn in 1994-96 in on-farm trials (Table-1) which shows that model effectively predicted the N-management practices for the area.

Experimental

Nitrogen Balance Model

A model similar to that proposed by Rice and Havlin [19] was developed to calculate optimum fertilizer N rates. Recommended nitrogen rates were determined by this model:

$$\text{Recommended N} = 300 - (N_r + N_{min} + N_{up}) \quad (1)$$

where,

N_r = Residual inorganic N (NH_4-N + NO_3-N) kg ha^{-1} at Feekes 5

N_{min} = Soil mineralizable N kg ha^{-1} at Feekes 5
N_{up} = Plant N uptake kg ha^{-1} at Feekes 5

The 300 kg N ha^{-1} is the total N (residual N + mineralizable N + fertilizer N) estimated to be required for maximum yield in Willamette Valley of western Oregon. Analysis of nitrogen response data for soft white winter wheat by Neil Christensen and John Hart, Soil Scientists, Department of Crop and Soil Science, Oregon State University, suggested that this total quantity of N maximized yield over an array of environmental and production conditions. Data from over twenty years and dozens of trials were analyzed.

Total N requirement was estimated by adding the amount of N recovered in unfertilized plots (an estimate of mineralized N) to the amount of applied fertilizer N that gave maximum yield in each trial. The average total N requirement was about 300 kg N ha^{-1} (unpublished data) and showed little variation across an approximately 2X range in grain yield. This uniformity in N needed to optimize yield under an array of environmental conditions suggested that it may be possible to model N need. Nitrogen response trials were established in three years to develop model and two validation field-scale trials were run in one year. Each type of trial is discussed below.

On-farm Trials

On-farm trials were conducted in growers fields at three different locations across the Willamette Valley of western Oregon during the 1994-1996 growing seasons. Each site of these experiments represented a crop rotation system that is commonly used in the Valley. Rotations were soft white winter wheat following grass seed, sweet corn or a legume. The experimental design was a randomized complete block with three replications on each site. Plot size varied site-to-site depending on size of machinery used by the grower. An average plot size of 90 m × 10 m was used. Nitrogen fertilizer was applied as urea (46-0-0) at approximately Feekes 5 in one application with drop or spinner spreader. Four treatments, including a check receiving no nitrogen, were used at each site during the 1993-94 and 1994-95 growing seasons. Soil samples were collected at approximately one-month intervals from each site during the 1993-94 and 1994-95 growing seasons. Samples were taken at four depths- 0-30, 30-60, 60-90 and 90-120 cm. Intensive soil sampling was performed just after harvesting at each site on each plot in all years to three depths- 0-30, 30-60 and 60-90 cm. To calculate total N uptake, plant tissue samples were taken at growth stage Feekes 5 (prior to fertilizer application) and at maturity. Plant N uptake (kg N h^{-1}) was calculated by multiplying the N concentration in the tissue by dry matter production per hector (kg DM h^{-1}).

Small Plot Research Station Trials

Fertility trials were established during the 1993-94 growing season at the Hyslop Experimental Station of the Department of Crop and Soil Science, Oregon State University, Corvallis, Oregon. The experiment was arranged as a spilt plot design with four replications having rotation (clover or oat) as main plots and fertilizer treatments as sub-plots. Rotation treatment (main plots) size was 12 m × 45 m, while fertilizer treatment (sub plots) size was 12 m × 10 m. Five fertilizer treatments - 0, 50, 100,150 and 200 kg N ha^{-1} were used. Rotations include winter wheat following clover and winter wheat following oat. Soil samples were collected pre-plant and post-harvest. An intensive pre-plant soil sampling was done in fall 1995 by taking samples at 30 cm increments to a depth of 150 cm from individual plots. Post-harvest sampling was performed on 0, 150 and 200 kg N ha^{-1} treatment plots with each rotation from all the plots. Plant tissue samples were taken at growth stage Feekes 5 and at maturity for dry mater yield and nitrogen uptake. Four above ground plant samples of 1.5 meter of row were cut from drill strips in each sub-plot. Plant N uptake (kg N ha^{-1}) was calculated by multiplying the N concentration in the tissue by dry matter (DM) production (kg ha^{-1}).

Model Validation Trial

In 1996-97, two trials were conducted to further check the validity of the proposed model. Trials were conducted in grower's fields at two locations in the Willamette Valley. Rotations were soft white winter wheat following grass seed and sweet corn. The experimental design was a randomized complete block with three replications at each site. Plot size varied depending on size of machinery used by the grower. An average 90m × 10m plot size was used. Nitrogen fertilizer was applied as urea (46-0-0) at approximately Feekes 5. Three treatments were used at each site. At the wheat following grass seed rotation site, N was applied at the rate of 84, 112 and 140 kg N ha^{-1}. The 112 kg N ha^{-1} rate was the recommended rate from our model. The 84 kg N ha^{-1} and 140 kg N ha^{-1} rate were selected to bracket the recommended rate (± 28 kg N ha^{-1}). Soil samples were collected before fertilizer application and after harvest. At pre-fertilization, soil samples were taken from 0-30 cm depth while after-harvest samples were taken at three depths- 0-30, 30-60 and 60-90 cm from individual plots. Plant tissue samples were taken at Feekes GS 5 (prior to fertilizer application) and at maturity to calculate total N uptake.

Maximum Economic Yield Equations

The validity of the N balance model was checked by comparing the recommended N rates determined by the model with N rates assessed in 1996-97 trials for maximum economic yield. To calculate the fertilizer rate required for maximum economic yield, regression equations were developed to describe the wheat grain yield response to N fertilizer applied at Feekes 5 [1]. The relationship between grain yield and fertilizer was quadratic in shape for each rotation. The quadratic equation used is as follow:

$$Y = a + b_1N - b_2N^2 \quad (2)$$

where,
Y = Grain yield (kg ha^{-1})
a = Intercept
b_1 = Linear regression coefficient
b_2 = Quadratic regression coefficient
N = Fertilizer N rate (kg ha^{-1})

The maximum economic N rate for any given response curve is the N fertilizer rate value that makes the first derivative of the response function equal to the price ratio of N fertilizer to wheat ($ kg N to $ kg wheat). The fertilizer rate for maximum economic was calculated as follows:

$$Y = a + b_1N - b_2N^2 \quad (2)$$

By setting the first derivative equal to N price/wheat price

$$dY/dN = b_1 - 2\,b_2\,N \qquad N = P_N/P_Y = r$$
$$r = b_1 - 2\,b_2N \qquad 2\,b_2N = b_1 - r$$

$$N = (b_1 - r)/\,2b_2 \quad (3)$$

where,
r = ratio price ratio of N fertilizer to wheat ($kg N to $ kg wheat)
b_1 and b_2 are regression coefficients.
P_N and P_Y are the price of nitrogen and wheat, respectively

Soil Analyses

Soil and plant tissue samples were analyzed in the Central Analytical Lab (CAL) at Oregon State University, Corvallis, Oregon. To determine total N in the aerial portion of the plant, the entire aboveground portion of the plant is excised at the soil surface. Plant samples were dried at 70 °C in a forced air oven, weighed and ground in Wiley mill to pass 1 mm mesh. The N content of wheat grain and straw was determined by Leco CNS 2000 (Leco corporation, St. Joseph, MI) combustion analyzer. Soil inorganic N (NH_4-N and NO_3-N) was determined using the modified potassium chloride KCl extraction method described by Keeney and Nelson [20]. Twenty-gram soil samples were placed in 250 mL bottles and 75 mL of 2 N KCL extracting solution was added. The NH_4-N and NO_3-N content of the extract was determined with an ALPKEM (Auto Analyzer Instrument) rapid flow analyzer (RF-300) which complexes NH_4^+-N with salicylate to form indophenol blue. This color was intensified with sodium nitroprusside and measured at a wavelength of 660 nm. The NO_3-N concentration were determined with the same equipment used for NH_4-N analysis by reducing nitrate via a cadmium reactor and complexing the NO_3-N with sulfanilamide and N-(1-Napthyl)- ethylenediamine dihydorchloride to form a red-purple color. The color intensity was measured at a wavelength of 540 nm.

Anaerobic Incubation

Soil mineralizable N was determined using a short-term anaerobic incubation method described by Keeney [11] slightly modified by increasing the sample size. Through use of a sample splitter, a 20 g soil sample was obtained and placed in a 250 mL extraction bottle. Fifty mL of distilled water was added to each bottle so that the soil became completely saturated. Bottles were made air tight by putting a plastic cover under their lids. Samples were placed in an incubator for 7 days (168 h) at 40 °C ± 0.5 °C. After incubation, samples were carefully removed from the incubator and 50.0 mL of KCl was added. Vessels were shaken on a mechanical shaker for one hour. The extracting solution was filtered through Whatman No. 42 filter paper. Final NH_4^+ content of the extract solution was determined from incubated samples. Initial NH_4^+ values were subtracted from the final values to obtain the amount of N mineralized.

Conclusions

The results showed that the optimum N rates predicted by the developed model were closely related to the N rates required to obtain maximum economic yield. In 1996-97, the model validation experiment also gave promising results. Overall, this study shows that the model appears to accurately assess field-specific optimum fertilizer N status and it can be used to recommend the N application rates for the region. It was also observed that the response of winter wheat to fertilizer N varied greatly among rotations and years in this study. Wheat following corn rotation was highly responsive to added fertilizer N while wheat following grass was less responsive. Wheat following grasses had high soil supplied N which depressed the yield even at moderately high fertilizer N rates. This finding contradicts conventional wisdom that suggests higher N rates are needed following grasses. This study documents a difference between perennial grasses and cereals grain crops in rotation. Also, the average yield with no fertilizer for wheat following corn and wheat following legumes was about the same.

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