A comprehensive nitrogen fertilizer management model for winter wheat (Triticum aestivum L.)
by Grant Dewayne Jackson

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Crop and Soil Science
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Abstract:
Winter wheat at 47 locations in Montana was topdressed with nitrogen (N) in the spring of 1970, 1971, 1972 and 1973.

A stepwise multiple regression technique was utilized to generate a comprehensive N fertilizer management model to predict potential grain yield, N fertilizer requirements, grain protein with additions of N fertilizer, grain yield and grain protein without spring N additions and residual soil NO3-N after harvest.

The data were organized into two groups based on soil NO3-N to 4 ft. Locations having soils which contained less than 120 lbs NOg-N/4 ' were designated as group I and remaining locations as group II. With group I data highly significant equations were generated for the entire N fertilizer management model. Independent variables for potential yield prediction were growing season rain-fall, evaporation rates during the first half of the growing season and soil organic matter. Soil NO3-N, potential yield, evaporation rate during the first half of the growing season and available soil water were the important factors for predicting N fertilizer requirement. The variables useful in predicting grain protein were potential yield, soil NO3-N, N fertilizer rate, soil organic matter and growing season rainfall. For comparison with potential yield, grain yield equations were generated from check plot data; the important independent variables were soil NO3-N, evaporation rate during the first half of the growing season, growing season rainfall and soil organic matter. Similarly grain protein was predicted; important factors were soil NO3-N, growing season rainfall, grain yield and soil temperature at 50 cm. Equations for the group II data were eractic because of insufficient data for analysis and response to added N was uncertain. Data from groups I and II were combined and equations developed similar to group I; only the protein functions were nonsignificant.

A modeling system to predict residual soil NO3-N after harvest was generated. The equations developed from the check plots were highly significant; the important variables include soil NO3-N, soil water, soil temperature at 50 cm, evaporation rate and grain protein. Equations generated from 80 to 180 - N treatments were nonsignificant.

The modeling system applies to winter wheat producing areas of Montana where excellent stands of recommended varieties are present, an alternate' crop-fallow management system is practiced and P fertilizer is drilled with the seed.

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Approved:

Kurt C Feltner
Head, Major Department

James R. Sims
Chairman, Examining Committee

Henry L Parsons
Graduate Dean

MONTANA STATE UNIVERSITY
Bozeman, Montana

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ABSTRACT

Winter wheat at 47 locations in Montana was topdressed with nitrogen (N) in the spring of 1970, 1971, 1972 and 1973.

A stepwise multiple regression technique was utilized to generate a comprehensive N fertilizer management model to predict potential grain yield, N fertilizer requirements, grain protein with additions of N fertilizer, grain yield and grain protein without spring N additions and residual soil NO_3-N after harvest.

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A modeling system to predict residual soil NO_3-N after harvest was generated. The equations developed from the check plots were highly significant; the important variables include soil NO_3-N, soil water, soil temperature at 50 cm, evaporation rate and grain protein. Equations generated from 80 to 180 - N treatments were nonsignificant.

The modeling system applies to winter wheat producing areas of Montana where excellent stands of recommended varieties are present, an alternate crop-fallow management system is practiced and P fertilizer is drilled with the seed.

INTRODUCTION

A basic objective of any natural resource management scheme is to maximize sustained outputs, minimize inputs, and maintain a high quality product with a minimum pollution hazard. This idea is especially true of small grain production in which nitrogen (N) fertilization plays an important role as an input. In the past N fertilizer was applied haphazardly or according to single factor soil tests with little consideration of grain quality, potential yield and pollution potential. Furthermore in this day and age it is vitally important to manage N fertilizer additions intelligently since N is in limited supply, and our society has become more aware of food quality and environmental hazards.

Obviously, models to predict N fertilizer needs and the fate of applied N are necessary to produce optimum yields of high quality winter wheat while minimizing undesirable side effects. This dissertation is one attempt to develop such models.

LITERATURE REVIEW

Winter wheat production research has received considerable attention since the organization of agricultural experiment stations in the late 1800's and early 1900's. The data published are so immense that one could say "there is no such thing as a complete literature review of winter wheat research".

Certainly the conclusions of Collis-George and Davey (8) are pertinent to this study. They stated "until complete descriptions of experiments are available, the quantitative importance of environment and its interaction with fertilizer and cultivation practices cannot be determined". Their main criticism of recent field fertilizer experiments was the failure of investigators to include a sufficient number of soil properties and climatic factors as variables.

Thompson (50) and Schlehuber and Tucker (34) attribute recent increases in wheat production to increased nitrogen fertilization. However, the development of higher yielding varieties, phosphorus fertilization and more efficient summer fallowing techniques are also responsible for increased production (4).

Published models for predicting nitrogen fertilizer requirements of winter wheat are quite variable in their approach and in their utility. Simple linear regression analysis with soil nitrate nitrogen (NO_3-N) has been successful in some locals (36). However Smika et al. (42) reported no relationship whatsoever. Leggett (22) reported one of the first systems which included climatic variables to predict nitrogen fertilizer needs for winter wheat in Washington state. He used available soil water plus expected rainfall to determine maximum yield (Ym). Then the yield (Yn) one would expect from the initial soil NO_3-N content to the depth of six feet was calculated. The yield expected from nitrogen (N) mineralization (recrop yield) was added to Yn also. If Ym > Yn, then additional N was added at the rate of 3 lb N/bu ((Ym-Yn)/3 = additional N). In North Dakota, Young et al. (54), correlated (R=.70) available soil water at seeding to the depth of 122 cm, stored soil NO_3-N to 61 cm at seeding, precipitation from seeding to five days before harvest, and number of degree days above 21^{o}C from five to sixty days before harvest with response to spring wheat to N fertilizer. In Oklahoma Eck and Tucker (15) attempted, with little success, to correlate available soil water in the spring, growing season precipitation, soil organic matter and temperature at maturity with winter wheat response to N fertilizer. Currently in Montana (36) nomograms are used for N fertilizer recommendation. Available soil water and soil NO_3-N to four feet and expected rainfall are the variables that comprise the system. Kloster and Whittlesey (21) and Geist et al. (16) both published small grain yield predictions based on nitrogen fertilizer rates and other soil and climatic factors. Recently Read and Warder (32) utilized a stepwise multiple regression program to determine the soil and climatic variables important to response of spring wheat to fertilizer on stubble land. They concluded that an NH_4-N soil test was more important than NO_3-N; however, R^2 was increased only by 1 or 2% with the inclusion of either NH_4-N or NO_3-N. Growing season rainfall was more important than stored soil water on yield and protein content of unfertilized plots, but stored soil water had a greater influence than rainfall on the response of spring wheat to fertilizer.

Several attempts to quantify the relationships between winter wheat yield and several components of the environment are documented in the literature. Eck and Tucker (15) concluded that rainfall distribution was more important than total rainfall. Legget (22) used expected growing season rainfall as a factor in his fertilizer prediction equation. Lehane and Staple (23) correlated available soil water and rainfall received during the growing season with yield. In another paper (24) they recorded the relationship of spring wheat yield with rainfall and soil water. Based on research in Colorado, Nebraska and Montana, Smika et al. (42) reported grain yields to be positively correlated with stored soil water at seeding. Baier and Robertson (3) related yield components with available soil water.

Other researchers have shown (31, 44, 46) the effects of soil temperature, wind reduction, or shelter belts on the yields of wheat.

Grain protein content is a very important quality factor to be considered in the formulation of fertilizer management systems for wheat. This area has received considerable attention in recent times (16, 19, 37, 40) since the average protein level of Montana's wheat has declined considerably during the last 12 years.

McGuire et al. (28) and Sims and Jackson (41) published data that shows positive relationships between grain protein and N fertilizer and between grain protein and soil NO_3-N. They did not include least square analyses in their reports. In Australia Taylor and Gilmore (47) successfully predicted wheat grain protein from rainfall and air temperature variables. Alkier et al. (1) related protein content to soil NO_3-N and N fertilizer rate; however, no climatic variables were included. Johnson et al. (19) reported a positive relationship between grain protein and N fertilizer. Smika and Greb (43) used multiple linear regression analysis to relate grain protein with soil NO_3-N to 6 feet, available soil water to 6 feet and total precipitation 40-55 days before maturity. The relationship was positive with soil NO_3-N and negative with soil water and rainfall.

Nutrient losses in runoff, particularly N, have been studied for years. Daniel et al. (10) in 1938 evaluated NO_3-N losses from different cropping systems and concluded NO_3-N in rainfall was significantly larger than the NO_3-N lost via surface runoff from unfertilized plots. In 1945 Midgley and Dunklee (29) reported that volitalization and runoff are responsible for large losses of N when manure was spread on frozen soil. Some early data on nutrient losses from erosion was published by Massey et al. (27) also. So the problem is not new but was recognized many years ago when the Great Plains Program was legislated to reduce erosion and farm production.

During the last decade renewed interest in nutrient losses was created by continued use of high fertilizer rates in some areas of the United States, and the disposal of enormous quantities of animal and municipal wastes on land (25). Of course, attacks by Commoner (9) blaming agriculture and chemical fertilizers for pollution of lakes and streams certainly had their effect also.

Recent literature has placed nutrient losses from runoff in perspective. White and Williams (53) compared nutrient losses from prairie and cultivated soils and concluded that "losses of plant nutrients in soil eroded from cultivated land may be similar to average losses that would occur naturally if the area were in pristine prairie that was periodically subjected to fire". This conclusion agrees with the data of Timmons et al. (48); their vegetation leaching experiments indicate that vegetation is a potential source of nutrients.

Klausner et al. (20) reported with the exception of heavy fertilized, poorly managed soils, the total yearly accumulative N discharge in surface runoff did not exceed the amount of N received in rainfall measured in a 10 month period. Other researchers (33, 52) have shown no significant differences in total N loss from fertilized and unfertilized soils; however, NO_3-N was significantly higher in the sediment from fertilized soils. Thomas and Crutchfield (49) studied NO_3-N and P in streams that drain predominately cultivated and forested watersheds. Their data showed very little change in NO_3-N and P concentrations regardless of land use. Moe et al. (30) stated that erosion losses of organic N are much more severe than fertilizer loss from fallow soils.

Obviously nutrient losses via surface runoff are highly variable (52) and are related to soil conditions and plant cover (13, 14, 26). Furthermore, models to predict nutrient losses are lacking. Models to predict erosion losses from rainfall are available (51). However, modifications are apparently required before any erosion prediction equation can be adapted to predict erosion losses related to snow melt and spring runoff.[1]

Although many experiments on the response of wheat to N fertilizer have been conducted, only a few have resulted in useful predictive models. Furthermore, virtually none of the previous studies produced a comprehensive model for managing N fertilizer on small grain crops. Most published models relate grain yield response or protein response to N fertilizer with soil and climatic variables. To be of maximum utility a model should predict grain yield potential, grain yield and protein responses to N fertilization, and the fate of applied N as it related to a pollution potential. The primary objective of this study was to develop such a comprehensive model.

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1 Jerry Waller, U.S.D.A. Soil Conservation Service, Bozeman, Montana. Personal communication.

METHODS AND MATERIALS

Plot Location and Design

Data for this dissertation were gathered from winter wheat fertility plots which were located throughout Montana's winter wheat producing area. These data represent 19, 14, 8 and 6 locations for the growing season's of 1970, 1971, 1972 and 1973, respectively. Geographic locations, investigators and soils classification are included in the Appendix Table 1. The field plots were organized in randomized complete blocks with individual plots running across the rows. Individual plot sizes were uniform at a locations but ranged from 150 ft^2 to 300 ft^2. The following criteria were established for site location:

A. Field should have:

1. Received P fertilizer with the seed or prior to seeding and worked in.
2. Good stand.
3. Limited weed problem, particularly regarding cheat grass, wild oats and wild buckwheat.
4. Recommended variety of winter wheat.

B. Actual plot size should be:

1. Uniform in all visual aspects.
2. No less than 20 ft. from west side of strip.
3. No less than 150 ft. from end of strip.

C. Soil Should be:

1. Montana benchmark soil or a representative soil of an extensive dryland grain acreage for the particular area.

Climate Measurements

Open pan evaporation and rainfall were measured according to the methods described by Sims and Jackson (39). Pan evaporation was measured in this study to integrate humidity, wind velocity and air temperature variables. This approach was necessary because funds were unavailable for the equipment to continuously monitor the climatic variables.

Soil temperature was measured at 50 cm with a dial thermometer during the growing season's of 1970, 1971 and 1972. Indoor-outdoor thermometers were employed in 1973 by placing the outdoor sensor at a depth of 50 cm in a hole made with an oakfield tube and backfilling the hole with the soil cores. The soil depth of 50 cm was chosen so the diurnal effects would not be measured and cold soils can be delineated from warmer ones. Since the Soil Conservation Service (SCS) uses soil temperature at 50 cm in their soil classification system, then soil survey information can be utilized to estimate soil temperatures when the proposed model is applied. Climate measurements were taken at 7 to 14 day intervals throughout the growing season (1 May - 15 August).

Soil Analysis

Soil water was determined by conventional gravimetric analysis using a forced draft oven at 60-65°C for 48 hours. Available soil water was estimated by the method described by Cole and Mathews (7). Basically this method uses soil water content at harvest as the limit of available water rather than soil water at 15-bar tension. This proved to be more significantly related to winter wheat yield.

Soil nitrate-nitrogen (NO_3-N) was estimated by phenoldisulfonic acid procedure as described by Bremner (4).

Soil organic matter was measured by the colorimetric method published by Sims and Haby (38).

Grain Analysis

The grain was harvested from 80 ft^2 or more near the center of each plot. Sickle mowers and Vogel threshers were predominately utilized for cutting and threshing; however, at the Northern Research Center a combine was used in 1970 and 1971, and a Chain combine was employed on all 1973 plots.

Grain yields and test weights were determined at about 12% moisture with gravimetric and volumetric equipment. Grain protein was measured by the Udy dye method 46-16 (2).

Statistical Procedures

The multiple regression analysis was accomplished by a stepwise regression computer program developed at UCLA (12). Computations were made on a XDS Sigma 7 computer. The regression analysis and partial regression coefficients were tested by the methods of Steel and Torrie (45). The partial regression coefficients were tested using a single df F against error df; a standard F test was used for the regression equation.

Methods unique to specific analyses will be discussed in the Results and Discussion section.

RESULTS AND DISCUSSION

The following pages contain multiple regression models which deal with the major phases of N fertilizer management relative to winter wheat. Equations are proposed to predict potential yields based on soil properties and climatic factors. The predicted potential yields are then entered into N fertilizer requirement prediction models along with soil NO_3-N and other variables. These models generate the N fertilizer rates required to achieve the potential yields predicted by the first model. Following these, grain protein content models are presented which forecast protein contents based on soil NO_3-N, potential yields, N fertilizer rates and other variables. Next, models to forecast grain protein contents and yields without the use of spring applied N fertilizer are discussed. Finally, residual NO_3-N prediction models are presented that estimated NO_3-N in the surface foot of soil after harvest.

Before the equations are applied, the following criteria must be met: 1) adequate phosphorus fertilizer should be drilled with the seed; 2) good stands of recommended winter wheat varieties should exist; 3) weed control must be accomplished; and 4) equations apply only to the fallow system of farming.

To consummate the "best fit" of the data, the data were split into two groups based on soil NO_3-N content in 4 ft of soil. Soils which had less than 120 lbs of N were placed in one group (designated as Group I) while those with NO_3-N greater than 120 lbs of N comprise the other (designated as Group II). However equations based on all the data are included in the appendix tables 6-19. Group I contains 38 locations while group II contains 9.

Variable description

Variable designation, description, units, mean and standard deviation are listed in Table 1. These are the variables used in developing potential yield and nitrogen (N) fertilizer requirements of winter wheat. The data used in computing these statistics are summarized in Appendix Table 1. The data utilized in the potential yield, N fertilizer requirements and grain protein predictions are indicated by underscoring with a dotted line.

Nitrate-nitrogen and soil water were measured from soil samples collected at each location during the period 1-15 May. Potential yield is not necessarily the maximum yield measured at each location. It is a more conservative measurement of optimum yield obtained with an N fertilizer rate that will not create a high potential for N water pollution.

Changes in variables X1-X3 for check plot prediction equation are contained in Table 2. In other words Table 2 summarizes yield and protein data for the 0-N treatments in Appendix Table 1.

Variables were entered into the regression analysis based on a prescribed F value. In subsequent regression equations, the F was set

Table 1. Variables used in developing predictive equations for potential grain yield, N fertilizer requirements and grain protein content of winter wheat.

Variable Designation	Variable Description	Units	Mean			Standard Deviation		
			All Loc.	Group I	Group II	All Loc.	Group I	Group II
X1	Grain protein content	%	12.46	12.33	13.00	1.39	1.36	1.44
X2	Maximum grain yield	Bu/A	37.04	36.71	38.39	8.83	8.24	11.46
X3	N fertilizer rate	# N/A	28.51	31.58	15.56	24.49	24.33	21.86
X4	Soil NO_3-N in 1' of soil	# N/A	30.07	24.60	53.19	23.41	18.96	27.32
X5	Soil NO_3-N in 2' of soil	# N/A	52.92	42.60	96.51	36.99	24.97	48.37
X6	Soil NO_3-N in 3' of soil	# N/A	66.98	52.92	126.31	44.43	29.62	48.91
X7	Soil NO_3-N in 4' of soil	# N/A	77.44	59.01	155.26	51.34	32.49	42.99
X8	Soil NO_3-N in 5' of soil	# N/A	82.11	58.75	180.74	65.50	42.14	53.99
X9	Soil NO_3-N in 6' of soil	# N/A	89.17	65.46	189.30	77.40	51.11	91.70
X10	Available soil water in 1' of soil	inches	1.64	1.60	1.84	0.86	0.67	1.45
X11	Available soil water in 2' of soil	inches	3.43	3.37	3.64	1.36	1.19	2.01
X12	Available soil water in 3' of soil	inches	4.81	4.73	5.13	1.67	1.61	1.98
X13	Available soil water in 4' of soil	inches	5.84	5.71	6.39	2.03	1.97	2.33
X14	Available soil water in 5' of soil	inches	5.97	5.71	7.11	3.22	3.39	2.20
X15	Available soil water in 6' of soil	inches	6.13	6.06	6.42	3.90	4.08	3.24
X16	Growing season rainfall (1-15May-1-15 Aug)	inches	4.47	4.46	4.51	1.60	1.65	1.31
X17	Ave. soil temp @ 50 cm (1-15May-15-30June)	C°	13.86	13.51	15.33	2.53	2.47	2.36
X18	Ave. soil temp @ 50 cm (15-30June-1-15Aug)	C°	18.71	18.51	19.56	2.14	2.24	1.45
X19	Evaporation rate (1-15May-15-30June)	Cm/day	0.57	0.56	0.62	0.16	0.14	0.22
X20	Evaporation rate (15-30June-1-15Aug)	Cm/day	0.65	0.65	0.65	0.14	0.16	0.09
X21	Soil organic matter	%	2.42	2.31	2.89	0.88	0.91	0.54

Table 2. Variables used in developing predictive equations for grain yield and grain protein content of winter wheat without spring applied N fertilizer.

Variable Designation	Variable Description	Units	Mean			Standard Deviation		
			All Loc.	Group I	Group II	All Loc.	Group I	Group II
X1	Grain protein content	%	11.40	11.13	12.56	1.97	2.03	1.16
X2	Grain yield	Bu/A	32.11	31.36	35.30	8.01	7.44	9.99
X3 thru X21 are identical to Table 1								

at .05 consequently variables were chosen and regression analysis performed when in fact the variable may have contributed significantly or very little to regression mean square. The data were entered into a second multiple regression program (18) as a cross-check on the primary program used.

Potential grain yield models

Multiple regression equations for potential yield are summarized in Tables 3 and 4. Variables X10-X21 were designated as independent.

In Table 3, growing season rainfall (X16) appears to be the most important and significant variable of the entire list. Available soil water variables (X11 and X13) were not included until the final steps and they were both nonsignificant. This phenomenon appears confusing at first; however, remember the equations were developed with data from fallow management systems and adequate water should have been stored prior to seeding. This is reflected in the low standard deviations for the soil water variables given in Table 1. Evaporation rate (X19) during the early part of the growing season was included at the second step and raised R^2 about 12%. Soil organic matter and early season soil temperature (X21 and X17) variables were included in equations 3 and 4; however, only X21 was significant when it was included in equation 4. Equation three (3) appears to be the most useful for predicting potential yield, it will predict potential yield within about 7 bu/A 66% of the time assuming at least

Table 3. Multiple linear regression equation expressing potential grain yield of winter wheat as a function of soil and climatic data (group I data).

	Equation	F 1/	SE 2/	R
1.	Y = 25.38 + 2.54x16**	12.63**	7.19	.510
2.	Y = 36.19 + 2.55x16** - 19.28x19*	10.14**	6.75	.606
3.	Y = 32.87 + 2.38x16** - 19.72x19* + 1.86x21	7.83**	6.61	.639
4.	Y = 26.30 + 2.27x16** + 0.54x17 - 21.12x19* + 2.12x21#	6.30**	6.57	.658
5.	Y = 27.46 - 0.25x13 + 2.35x16** + 0.52x17 - 21.39x19* + 2.25x21#	4.95**	6.65	.660
6.	Y = 27.52 - 0.39x11 + 2.34x16** + 0.53x17 - 21.43x19* + 2.16x21#	4.95**	6.66	.660

1/ F ratio due to regression; total df = 37
2/ SE = Standard error of the estimate
sign. p = .10; * sign. p = .05; ** sign. p = .005

3-5 inches of available water is present in 4-6 feet of soil and plant nutrients are not limiting. However variables X16 and X19 are intangible and cannot be precisely known at the outset of spring growth. It is proposed that long term averages from official weather station records be used for these variables. By using rainfall probability publications (17) and Caprio's information on evaporation (5) one could calculate the odds for harvesting a certain yield providing the required plant nutrients are supplied. Then the N fertilizer recommendation equation can be employed to predict the actual N fertilizer necessary to achieve the estimated yield potential.

Equation 3 is limited because it accounts for about 41% of the total variation. Obviously the other climatic factors measured did not increase the regression mean square, and only equation 4 produced a lower standard error of estimate. Perhaps measurements in total radiation, net radiation or more frequent measurements of the variables already discussed would increase the R^2 of the potential yield equation.

The equations for Group II locations appear a little erratic, probably due to the low df. Rainfall (X16) was not included until equation 4 and was non-significant when it was entered. However it did become significant when X18 and X10 were also entered in equation 5 and 6. Caution should be exercised in attaching significance to equation 5 and 6 because the number of variables included are only slightly less than the total df. Since soil NO_3-N was uniformily high in these 9 locations and variation in rainfall was not great, these variables would not be expected to contribute significantly to prediction of potential yields. Thus, factors such as soil temperature, pan evaporation and organic matter content should be responsible for some of the variation in yield observed at these locations. Equations 3-6 in Table 4 substantiate this argument. Considering total df involved, standard error of estimate and R, equation 3 is proposed as the most reliable predictive model for potential yield of Group II locations.

Nitrogen fertilizer requirement model

Tables 5-12 contain the equation which predict N fertilizer requirements of winter wheat for both groups of data; Tables 5-8 represent Group I and Tables 9-12 Group II. Equations were generated in this analysis by regressing N fertilizer rate (X3) at optimum yield against potential yield (X2), soil NO_3-N and water at a given depth, plus all the other variables listed in Table 1.

In the equations representing Group I data, 64% of the variation was accounted for by the inclusion of all the variables at a given soil depth. This is a considerably high amount of the varation in view of the fact that factors such as variety, seeding rate, drill type and phosphorus fertilizer material are not included as variables.

Table 4. Multiple linear regression equations expressing potential grain yield of winter wheat as a function of soil and climatic variables (group II data).

Equation	F [1/]	SE [2/]	R
1. Y = - 3.32 + 14.44x21*	6.11*	8.95	.683
2. Y = - 44.54 + 2.03x17 + 17.91x21*	4.77#	8.22	.784
3. Y = - 133.54 + 6.36x17* + 56.53x19* + 13.69x21*	7.70*	6.11	.907
4. Y = - 134.14 + 2.44x16 + 6.07x17* + 63.42x19* + 10.15x21	6.48*	5.92	.931
5. Y = 35.84 + 6.62x16* + 5.14x17* - 6.30x18* + 75.14x19** - 10.17x21	11.71*	4.13	.975
6. Y = 52.17 - 1.23x10 + 6.72x16* + 5.52x17* - 7.13x18 + 80.94x19** - 12.85x21	11.18#	3.90	.985

1/ F ratio due to regression; total df = 8.
2/ SE = Standard error of the estimate
sign. p = .10; * sign, p = .05; ** sign. p = .005

Table 5. Multiple linear regression equations expressing N fertilizer requirements of winter wheat as a function of potential yield, soil and climatic variables (1' soil samples; group I data).

	Equation	1/ F	2/ SE	R
1.	$Y = -16.33 + 1.30x2^{*}$	8.75^{*}	22.12	.442
2.	$Y = -8.57 + 1.44x2^{**} - 0.52x4^{*}$	9.74^{**}	20.05	.598
3.	$Y = -2.57 + 1.60x2^{**} - 0.45x4^{*} - 5.81x21$	7.52^{**}	19.68	.632
4.	$Y = -27.16 + 1.80x2^{**} - 0.43x4^{*} + 32.97x19 - 6.61x21^{\#}$	6.23^{**}	19.45	.656
5.	$Y = 9.74 + 1.90x2^{**} - 0.39x4^{*} - 2.39x18 + 42.81x19 - 8.05x21^{*}$	5.76^{**}	18.98	.688
6.	$Y = 12.32 + 2.00x2^{**} - 0.46x4^{*} - 3.69x18^{*} + 45.26x19^{\#} + 33.21x20 - 9.26x21^{*}$	5.14^{**}	18.82	.706
7.	$Y = 9.50 + 1.96x20^{**} - 0.54x4^{*} + 5.36x10 - 3.85x18^{*} + 43.75x19^{\#} + 36.73x20 - 9.68x21^{*}$	4.57^{**}	18.80	.718
8.	$Y = 12.24 + 1.93x2 - 0.57x4 + 5.79x10 + 0.81x17 - 4.57x18 + 42.68x19 + 38.28x20 - 9.51x21$	3.90^{**}	19.08	.720

1/ F ratio due to regression; total df = 37
2/ SE = Standard error of the estimate
sign. p = .10; * sign, p = .05; ** sign. p = .005

Table 6. Multiple linear regression equations expressing N fertilizer requirements of winter wheat as a function of potential yield, soil and climatic variables (2' soil samples; group I data).

Equation	F 1/	SE 2/	R
1. Y = - 16.33 + 1.30x2*	8.75*	22.12	.442
2. Y = - 5.02 + 1.61x2** - 0.53x5**	16.17**	18.03	.693
3. Y = - 15.53 + 1.59x2** - 0.63x5** + 4.67x11#	12.31**	17.56	.722
4. Y = - 45.46 + 1.80x2** - 0.65x5** + 5.09x11# + 38.10x19#	10.63**	17.03	.750
5. Y = - 43.96 + 1.88x2** - 0.61x5** + 4.86x11# + 40.31x19# - 2.95x21	8.57**	17.11	.757
6. Y = - 25.93 + 1.93x2** - 0.56x5** + 4.73x11# - 1.14x18 + 44.72x19# - 3.96x21	7.17**	17.20	.762
7. Y = - 25.62 + 2.02x2** - 0.61x5** + 4.86x11# - 2.32x18 + 47.69x19* + 31.60x20 - 4.99x21	6.57**	16.98	.778
8. Y = - 23.16 + 1.92x2** - 0.70x5** + 6.23x11* + 2.58x17 - 4.40x18# + 45.52x19* + 35.20x20 - 3.77x21	6.04**	16.84	.790
9. Y = - 21.09 + 1.77x2 - 0.71x5 + 5.89x11 + 1.40x16 + 2.60x17 - 4.54x18 + 42.40x19 + 39.57x20 - 3.76x21	5.30**	17.01	.794

1/ F ratio due to regression; total df = 37
2/ SE = Standard error of the estimate
sign. p = .10; * sign, p = .05; ** sign. p = .005