Development of Field-Specific Spring N Rate Recommendations for Winter Wheat

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ABSTRACT

Optimum spring N fertilizer rates for winter wheat in Virginia vary widely from field to field, but traditionally spring N is applied at a uniform rate to all fields. A recently-developed tissue test procedure provides a field-specific evaluation of crop N status and predicts optimum N rate for the second spring N application in a split spring application management system. However, this procedure is based on a small number of researcher-planted experiments utilizing a single cultivar; it fails to provide field-specific rate recommendations for the first spring N application; and it is not accessible to farmers who are unwilling to split their spring N applications. Our objectives were: to evaluate the reliability of the tissue test procedure in a large number of farmer fields; to develop a method for making field-specific N rate recommendations for the first spring application in a split-application management system; and to develop a method for making field-specific N rate recommendations in a single-application management system. Forty-five spring N rate experiments were established in farmer fields over a five-year period. A range of N fertilizer rates was applied in early spring (Zadoks growth stage 25) and again in mid-spring (Zadoks growth stage 30) in all possible combinations. Yield data were used to calculate economic optimum N rates at growth stage (GS) 25 and GS 30 with split-application management, and at GS 25 with single-application management. These optima were regressed against a variety of predictor

variables measured in the same fields. The reliability of the previously-developed tissue test procedure for making GS 30 N rate recommendations was confirmed. Tiller density was the best predictor of optimum GS 25 N rate with split-application management, while soil nitrate to 90 cm was the best predictor of optimum GS 25 N rate with single-application management. These three relationships fit together to form a flexible and powerful system for making spring N rate recommendations for winter wheat. This system increased estimated profit and apparent fertilizer efficiency in these experiments.

Acknowledgements

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Chapter I

Introduction

OVERVIEW

Soft red winter wheat production in Virginia varies from 110,000 to 160,000 hectares per year. Similar areas are devoted to wheat production in the neighboring states of Maryland and North Carolina. This crop is second only to corn in the amount of nitrogen (N) fertilizer used in the state of Virginia. Virginia's climate is humid, with about 100 cm of annual precipitation. Relatively little research has been done to develop field-specific nitrogen (N) fertilizer recommendations for wheat (and, until recently, for any crop) in the humid regions of the U.S.

Traditionally, winter wheat in Virginia has received 20 to 30 kg N ha^{-1} pre-plant incorporated in the fall and 90 to 100 kg N ha^{-1} top-dressed N solution in early to mid-February. However, we have observed optimum spring N rates to range from 0 to 190 kg N ha^{-1} for this crop. Clearly, the traditionally uniform rate of spring N application leads to many cases of gross over- and under-fertilization. Over-fertilization increases the potential for lodging, disease, and N transfer to ground and surface waters, as well as unnecessary expenditure on N fertilizer, while under-fertilization often results in large yield reductions. A method to predict the optimum spring N fertilization strategy for winter wheat on a field-by-field basis holds promise to increase yields and farmer profits while reducing agricultural non-point source pollution.

CONTEXT OF PRESENT RESEARCH

As our research is the first to establish the extremely wide range of optimum N rates for winter wheat in the mid-Atlantic region, very little data existed to explain why some fields produced excellent yields with no N fertilizer applied. On these fields, substantial lodging and yield losses often occur when N fertilizer is applied at customary rates. We hypothesized that this phenomenon was due mainly to carryover of residual fertilizer and mineralized N from the preceding cropping season. To test this hypothesis, soil mineral N in the root zone was measured approximately monthly from wheat planting (late fall) through spring at nine site-years (two cropping seasons). This research, presented in Chapter II, establishes that fall residual N levels vary widely in soils cropped to winter wheat in the Coastal Plain of Virginia, that a large but variable proportion of this fall residual N remains in the root zone until spring, and that residual N levels are strongly related to wheat response to N fertilization. Fields with high levels of spring residual N did not respond to N fertilization, implying that normal uniform-rate applications of spring N fertilizer resulted in excessive levels of soil mineral N in these fields. This situation is, for reasons explained in more detail below (and in succeeding chapters), highly undesirable both agronomically and environmentally. Field-specific tests are needed to identify such sites and prevent excessive fertilization.

Most soils cropped to winter wheat in Virginia's Coastal Plain are sandy, have high hydraulic conductivities and low water-holding capacities, and are subject to rapid percolation and leaching losses of fertilizer nitrogen. In many cases, the water table is quite close to the surface and N is transferred to groundwater quickly. A substantial proportion of unconfined groundwater in this region is transient, emerging in seeps and springs. Much of Virginia's Coastal Plain is drained by the Columbia and Yorktown aquifers, both of which are in extensive contact with the Chesapeake Bay and its lower tributaries (Reay and Simmons, 1992). Nitrate-N measured in the Columbia aquifer has generally ranged between 1 and 10 mg N L^{-1}, with the highest levels occurring under agricultural land (Reay and Simmons, 1992). These levels of nitrate are unlikely to have a major impact on human health, but could contribute significantly to the N budget of the region's surface waters.

Excess N is thought to be one of the most important factors causing the decline of the Chesapeake Bay. It is the nutrient most limiting to plant growth in the more saline portions of the Bay, and increasing levels have led to large increases in algal biomass. High algal biomass causes seasonal and regionally variable oxygen depletion (due to microbial oxidation of dead algal tissue) in the waters of the Bay, thus creating a high-stress environment for many of the Bay's fish and mollusk species. Algae also, by intercepting sunlight (chlorophyll-absorbed wavelengths in particular), may be partly responsible for the observed decline in submerged aquatic vegetation, an important source of habitat and oxygen for many Bay species. In recognition of these facts, Virginia, Maryland, and Pennsylvania have signed an agreement to (attempt to) reduce nitrogen inputs to the Chesapeake Bay.

At the time of traditional N applications in early to mid-February, soil moisture is usually high, having recharged over the winter. Combined with low evapotranspiration rates, this creates a situation in which precipitation water percolates rapidly through sandy Coastal Plain soils and nitrate leaching potential is high. As the spring progresses, evapotranspiration rates increase, soil moisture decreases, and net percolation decreases, thus the probability that applied fertilizer N will be leached out of the root zone also decreases. The degree to which N leaching remains possible throughout the wheat growing season is unknown.

Soils cropped to winter wheat in the Piedmont region of Virginia tend to be clayey and sloping with relatively low infiltration rates. Runoff is thus likely to be a more important mechanism for loss of fertilizer N than on Coastal Plain soils. Research on similar soils in Kentucky has shown that leaching from such soils can also be substantial (McMahon and Thomas, 1976), particularly during winter/early spring. At the time of traditional N applications, precipitation tends to be gentle, promoting infiltration, but there is relatively little soil cover in wheat fields, a factor that favors ponding and runoff. Runoff potential is probably much lower a month after traditional N applications due to a much higher degree of ground cover. Nitrogen in runoff water contributes to eutrophication problems in surface water bodies, as detailed above.

If fertilizer N is applied to the wheat crop at a rate greater than that needed for optimum yield, some luxury consumption by the crop will occur, but some fertilizer N will also remain in the soil. The relative balance of these two processes is unknown. Wheat grown in Virginia is followed predominantly by double-crop soybeans, a crop which is effective in extracting mineral N from the soil; thus part of any residual fertilizer N in the root zone at wheat harvest time is likely to be incorporated into soybean grain and residue. The rate at which nitrogen remaining in crop residues will be mineralized is variable and highly dependent on C:N ratio. Residue from wheat with excess N applied will have a relatively low C:N ratio, as will soybean residue, so mineralization will be relatively rapid and a considerable portion of this N may be subjected to winter leaching.

The preceding paragraphs establish that making fertilizer N applications to winter wheat later than is traditional would, in general, reduce transfer of N to ground and surface waters. This is additionally true because later applications are nearer to the time of maximum crop N uptake (Baethgen and Alley, 1989a); much of the N is thus in the soil for a relatively short time, and its window of exposure to transfer processes is reduced. Gravelle et al. (1988) showed that delaying part of the fertilizer application ("splitting" spring N) could be agronomically beneficial as well, increasing yields in one year out of two and decreasing lodging in both years. This conclusion is further validated by the report of Baethgen and Alley (1989a), who found that splitting spring N increased grain yields in one year out of two. Delaying the whole of the N fertilizer application for about a month gave yields equivalent to those from splitting spring N in both years.

In summary, splitting or delaying spring N applications to winter wheat would be environmentally beneficial. Limited previous research has shown such N application practices to be agronomically superior or equivalent to traditional practices. Basing the rate of these N applications on actual crop need evaluated in a particular field would reduce the frequency of occurrence of events that are both agronomically and environmentally undesirable. Baethgen and Alley (1989b) showed that wheat tissue N content at Zadoks growth stage 30 was strongly related to optimum N fertilizer rate at that time, and could be used to predict N needs on a field-specific basis. The strengthening and expansion of this recommendation system is the focus of Chapters III and IV.

We observed, during the course of the experiments described in Chapters III and IV, that at some experimental locations very little tillering (sometimes none) had occurred by the time that active growth and tillering resumed in the spring. Regardless of spring N application strategy, low tiller density appeared to be an important yield-limiting factor at all of these locations. Soil texture at these locations was in all cases extremely sandy. Lack of fall tillering appeared to be caused by severe N deficiency, apparently due to extremely facile fall leaching of mineral N from the sandy surface horizons of these soils. We established four experiments in the 1991-1992 growing season to examine the potential for various slow-release N materials or fall/winter topdressing to prevent fall/winter N deficiency on extremely sandy soils. There was very little precipitation in the Coastal Plain of Virginia during November and December of 1991, with the result that even plots receiving no fall N fertilizer were adequately tillered in these experiments. While the results we obtained thus did not address the purpose of these experiments, they did prove very suitable for demonstrating a statistical technique called nearest neighbor analysis that accounts for spatial yield variability in replicated field experiments. Spatial yield variability often is an important constraint limiting researcher ability to detect treatment differences; nearest neighbor analysis greatly increased statistical power to detect treatment differences in these experiments, as described in Chapter V.

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Chapter II

Residual soil nitrogen in humid region wheat production

ABSTRACT

The amount of soil mineral nitrogen (N) present when winter wheat (*Triticum aestivum* L.) is spring-fertilized is generally not taken into account when making N fertilizer rate recommendations in humid regions. This is partly because overwinter losses of soil N are thought to be extensive, resulting in little field-to-field variability in the amount of N fertilizer needed. Our objectives were to determine: whether agronomically significant levels of fall mineral N exist in fields planted to winter wheat in the Coastal Plain of Virginia; if so, the extent to which this mineral N remains within the rooting zone until spring; and whether this residual N affects crop response to spring N fertilization. We measured soil mineral N and conducted N-response experiments in nine farmer fields cropped to winter wheat--five in 1989-1990 and four in 1990-1991. Total soil mineral N was measured to 1.2 meters shortly after planting (Nov.) and approximately monthly thereafter through March, at which time rapid crop uptake begins. Soil mineral N in mid-November ranged from 69 to 237 kg N ha^{-1}, and in mid-March ranged from 19 to 167 kg N ha^{-1}. Wheat yield responded to spring N fertilizer applications in seven of the site-years; yield gains from N application ranged from 1.7 to 3.8 Mg ha^{-1}. At the two sites with the highest soil mineral N levels, check yields were 4.7 and 5.0 Mg ha^{-1}, and

no yield response to N fertilizer was observed; in fact, yields were depressed considerably by the application of N fertilizer. We conclude that high levels of soil mineral N can occur in the fall, that they can persist until spring, and that they can have considerable influence on optimum spring fertilization strategy. The wide range in residual mineral N that we observed and its strong correlation with yield response to fertilizer N demonstrates the need for field-specific N recommendations for winter wheat in humid regions.

INTRODUCTION

Variation in residual soil mineral N levels is commonly taken into account in making N fertilizer rate recommendations in semi-arid regions of the U.S. (Peterson and Voss, 1984; Westfall, 1984; Rauschkolb et al., 1984). The same cannot be said for humid regions of the U.S.; none of the states east of the Mississippi recommended any test for soil mineral N (Bandel and Fox, 1984; Gilliam and Boswell, 1984; Welch, 1984) until the development of soil nitrate tests for corn (Magdoff et al., 1984; Bundy et al., 1992). This appears, in part, to be due to the still widely-held perception that over-winter soil mineral N losses through leaching and denitrification are high in humid regions, leaving little field-to-field variability in residual N to take into consideration when making spring N fertilizer recommendations. Virginia, with tissue test-based N recommendations for wheat (Alley et al., 1989), and Maryland, with soil nitrate test-based recommendations for wheat (R.F. Mulford, 1993, personal communication) appear to be the only states east of the Mississippi currently making test-based field-specific N rate recommendations for a crop other than corn. Arkansas, west of the Mississippi but still considered a humid region, has implemented test-based field-specific N rate recommendations for both wheat (Miley et al., 1982) and cotton (Baker et al., 1992).

Wehrmann and Scharpf (1979) report finding high and variable residual soil mineral N (20 to 300 kg N ha^{-1}) in the spring in soils cropped to winter wheat in Germany. They found that fertilizer N need of the wheat crop was strongly related to the amount of residual soil mineral N and developed a system for making field-specific N recommendations based on mineral N levels.

The most extensive report on residual soil N and its effect on crop N response in the U.S. is that of Bundy and Malone (1988). They found that overwinter retention of fall profile nitrate varied from 45 to 66% at three Wisconsin locations in a year with above normal fall to spring precipitation. Only once (out of ten cases) did they observe a corn yield response to N fertilizer when spring soil nitrate to 90 cm was greater than 140 kg N ha^{-1}; and only once (out of five cases) did they fail to observe a corn yield response to N fertilizer when spring nitrate to 90 cm was less than 140 kg N ha^{-1}. Meisinger et al. (1987) reported that residual spring nitrate in a corn/wheat cropping system on the Eastern Shore of Maryland could contribute to the N needs of the wheat crop.

The rapid spread of the pre-sidedress soil nitrate test (PSNT) for corn (e.g. Blackmer et al., 1989; Fox et al., 1989) attests to the viability of soil mineral N for predicting crop N responsiveness in humid regions of the U.S. This test, of course, measures not only residual nitrate but also spring-mineralized nitrate. The pre-plant soil nitrate test reported by Bundy et al. (1992) utilizes earlier and deeper samples than the PSNT, thereby placing more emphasis on residual nitrate; this emphasis appears not to be misplaced, as the pre-plant soil nitrate test performed as well as the PSNT in predicting optimum N fertilizer rates at 41 locations in Wisconsin and Minnesota (Bundy et al., 1992).

MATERIALS AND METHODS

Nine experimental locations, each approximately .4 hectare in size, were selected in farmer fields in the Coastal Plain of Virginia in the 1988-1989 and 1989-1990 winter wheat growing seasons. Year, previous crop, and depth and texture of the A and argillic horizons are given for each location in Table 1.

Soil samples were collected from each location shortly after planting (early to mid-November) and approximately monthly thereafter until mid-March, at which point rapid N uptake by the crop begins in this region. Each sampling consisted of fourteen well-spaced cores taken to a depth of 1.2 meters, divided into 30-cm depth increments, composited, mixed thoroughly, subsampled, and frozen immediately using dry ice. Samples were thawed and extracted in duplicate with 2M KCl (Keeney and Nelson, 1982); extracts were centrifuged rather than filtered to avoid extract contamination from filters (Scharf and Alley, 1988).

Nitrate in the soil extracts was determined colorimetrically with a QuikChem Automated Ion Analyzer according to QuikChem Method No. 12-107-04-1-B (Lachat Instruments, Milwaukee, WI), a Griess-Ilosvay method (Keeney and Nelson, 1982). Ammonium in the soil extracts was also measured colorimetrically using the same instrument and QuikChem Method No. 12-107-06-2-A, a modified indophenol blue method (Keeney and Nelson, 1982) in which salicylate is substituted for phenol. Soil nitrate and ammonium contents were calculated (dry weight basis); when the difference between duplicates

Table 1. Previous crops and soil characteristics for experimental locations used to study soil mineral N levels and movement.

location	year	previous crop	A horizon: depth	A horizon: texture	argillic horizon: depth	argillic horizon: texture
			cm		cm	
1	1988-1989	corn	0-25	l	25-127	cl
2	1988-1989	corn	0-15	sl	30-76	scl
3	1988-1989	corn	0-20	l	33-107	scl
4	1988-1989	soybeans	0-23	sl	23-69	cl
5	1988-1989	soybeans	0-23	sl	23-140	scl
6	1989-1990	corn	0-23	sil	23-137	cl
7	1989-1990	corn	0-30	ls	66-127	scl
8	1989-1990	soybeans	0-18	ls	18-66	scl
9	1989-1990	soybeans	0-23	sl	23-107	scl

was greater than 1 g N kg^{-1} soil, that sample was re-extracted.

Urea-ammonium nitrate solution was applied in the spring at rates ranging from 0 to 238 kg N ha^{-1}. A carbon dioxide-pressurized backpack sprayer equipped with four Teejet "rain-drop" tips was used to apply the N solution. Experiment design was a randomized complete block with four replications. Wheat grain was harvested from a 1.5 m wide swath of each plot with a Hege 140 plot combine. Grain yields were adjusted to 135 g kg^{-1} moisture content.

RESULTS AND DISCUSSION

Soil mineral N (nitrate + ammonium) measurements from November to March are shown in Figure 1. Considerable site-to-site variation was observed in the amount of mineral N present in the soil profile in November. The four locations at which mineral N levels were highest in the fall (locations 1, 2, 3, and 6) all had been cropped to corn prior to planting with wheat. Location 7, also previously cropped to corn, had the lowest fall mineral N levels of the nine locations. Much more variability in soil mineral N levels was seen following corn (from 69 to 237 kg N ha^{-1}) than following soybeans (from 92 to 111 kg N ha^{-1}). This is probably because corn crops receive substantial amounts of N fertilizer, but corn yields (and therefore, N uptake) are highly variable and unpredictable due to the low available water holding capacity of most Coastal Plain soils and variability in summer rainfall. The levels of fall soil mineral N observed in these experiments are high enough that they might contribute substantially to the N needs of the winter wheat crop.

Soil mineral N measured in March ranged from 27 to 96 percent of November levels (Table 2). Total November-to-March precipitation was near the long-term average in both years of the study (Table 3). These results are in general agreement with those of Bundy and Malone (1988), who observed overwinter retention of 45 to 66 percent of fall soil nitrate at three locations in Wisconsin. The wide variation in overwinter retention that we observed makes it clear that fall mineral N measurements are unlikely to be helpful in making spring N fertilizer recommendations.

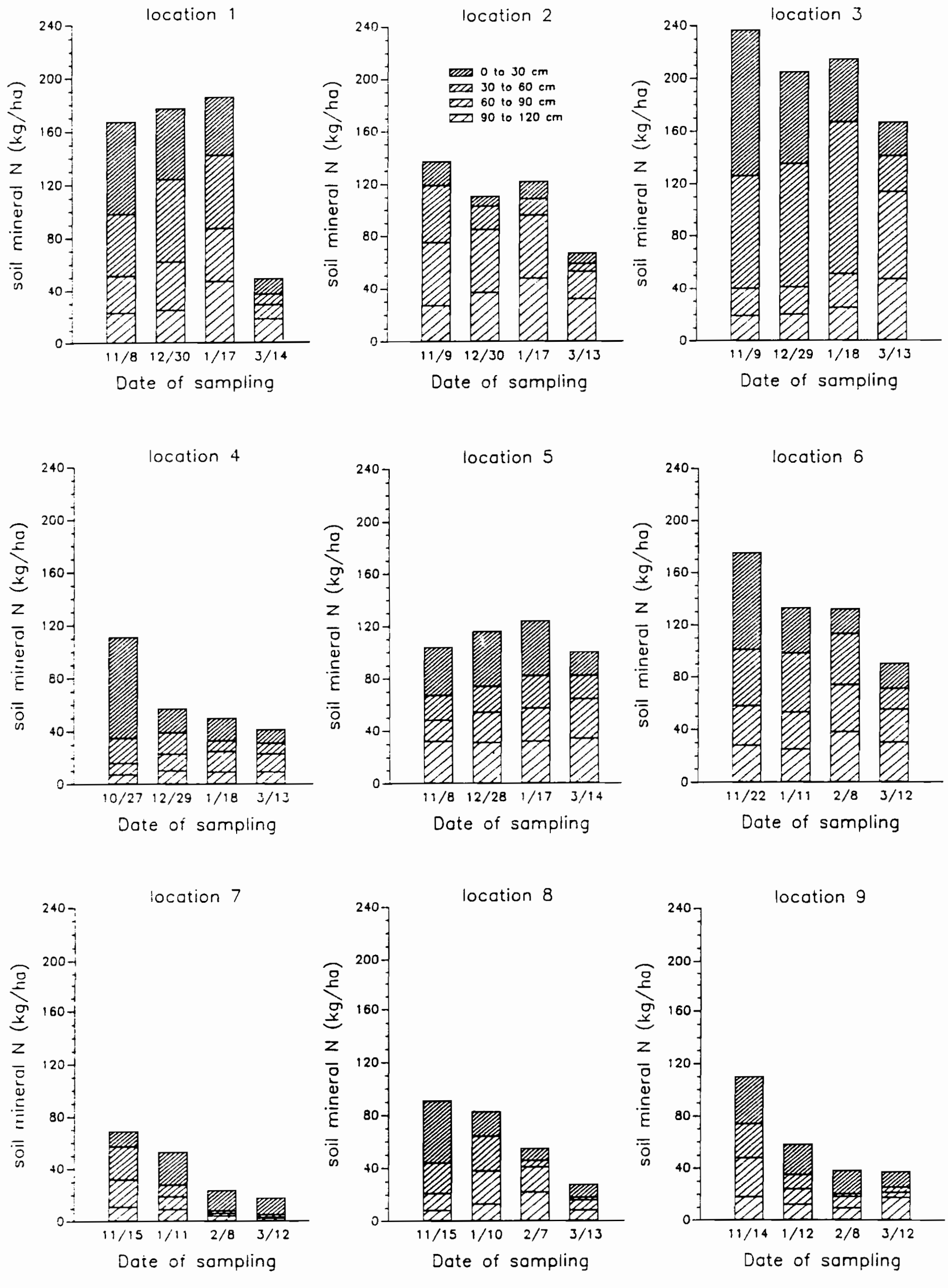

Figure 1. Soil mineral N (nitrate + ammonium) measured periodically through the winter in soils cropped to winter wheat in the coastal plain of Virginia.

Table 2. Overwinter retention of soil mineral N at nine locations cropped to winter wheat in the Coastal Plain of Virginia.

location	Mineral N to 1.2 meters in: November	Mineral N to 1.2 meters in: March	overwinter retention
	kg N ha^{-1}	kg N ha^{-1}	%
1	168	49	29
2	137	67	49
3	237	167	70
4	111	42	37
5	104	100	96
6	175	90	51
7	69	19	27
8	92	28	30
9	110	38	35
mean	133	66	47

Table 3. Precipitation in the Virginia Coastal Plain during the winters of 1988-1989 and 1989-1990.

	precipitation measured in:		
month	1988-1989	1989-1990	20-year average
	cm	cm	cm
Nov	10.7	9.7	7.6
Dec	1.8	6.6	8.4
Jan	5.6	9.1	8.9
Feb	12.4	7.6	8.1
Mar	18.5	9.4	9.9

We have commonly observed winter wheat roots to a depth of 1.2 meters, and consider this the depth to which soil mineral N may be extracted by the wheat crop. Soil mineral N measured to this depth in March was greater than 70 kg N ha^{-1} at locations 2, 3, 5, and 6; this residual soil N would be expected to supply a substantial portion of the N needed by the crop. Considerable variability in the amount of soil mineral N available to the wheat crop in the spring occurred following both corn and soybeans. This variability implies that some method for evaluating spring N availability and N fertilizer need on a field-by-field basis would be desirable regardless of which of these two crops the wheat follows.

Movement of mineral N from the 30- to 60-cm layer to deeper layers is evident from January to March at location 3 (Figure 1). This pattern of increasing mineral N in the deeper layers over time is observed at most of the experimental locations. Such downward movement of substantial amounts of mineral N indicates that leaching is probably a primary mechanism of N loss from the rooting zone in this region.

Soil mineral N measured at location 1 dropped sharply between January and March (Figure 1); while this was probably in part due to leaching and denitrification losses (heavy rainfall occurred in March), it was also probably due to crop uptake. We have measured over 100 kg N ha^{-1} in the above-ground portion of the wheat crop at this growth stage in our climate. March is probably, in our climate, too late to make soil mineral N measurements to use directly in making field-specific N fertilizer recommendations due to uncertainty about how much has already been depleted by crop uptake.

Grain yield was regressed quadratically against N fertilizer rate and yield gain calculated as the yield difference between yield with zero N fertilizer and the highest yield on the regression curve. Top yields in the nine experiments ranged from 4.4 to 6.8 Mg ha^{-1}, and yield gain due to N fertilizer ranged from 0 to 3.8 Mg ha^{-1}. Yield gain due to N fertilizer was inversely correlated with residual soil mineral N measured in January (Figure 2). In particular, zero yield gain due to N fertilizer was observed at locations 1 and 3 despite adequate growing conditions (check yields of 5.0 and 4.7 Mg ha^{-1}, respectively); nitrogen sufficient to produce these yields was supplied by the soil, mainly from residual mineral N judging by the high levels we observed at these locations.

Not only was there no yield gain due to N fertilization at locations 1 and 3, but considerable yield depression was caused by N fertilizer application at these locations. This yield depression was associated with high levels of lodging. We have also observed that considerable yield depression in wheat can occur due to N over-application even without lodging. Wheat is more prone to economic losses from over-application of N than many other crops--both yield losses and losses due to slowed combining of lodged wheat. We calculated estimated profit at locations 1 and 3 and concluded that applying the traditional 90 kg N ha^{-1} reduced profits by \$262 ha^{-1} at location 1 (\$43 ha^{-1} N cost, \$209 ha^{-1} due to yield depression, and \$10 ha^{-1} due to slowed combining) and \$91 ha^{-1} at location 3 (\$43 ha^{-1} N cost, \$24 ha^{-1} due to yield depression, and \$24 ha^{-1} due to slowed combining) relative to the optimum N application of zero. It is economically and environmentally beneficial to identify such sites with a field-specific test.

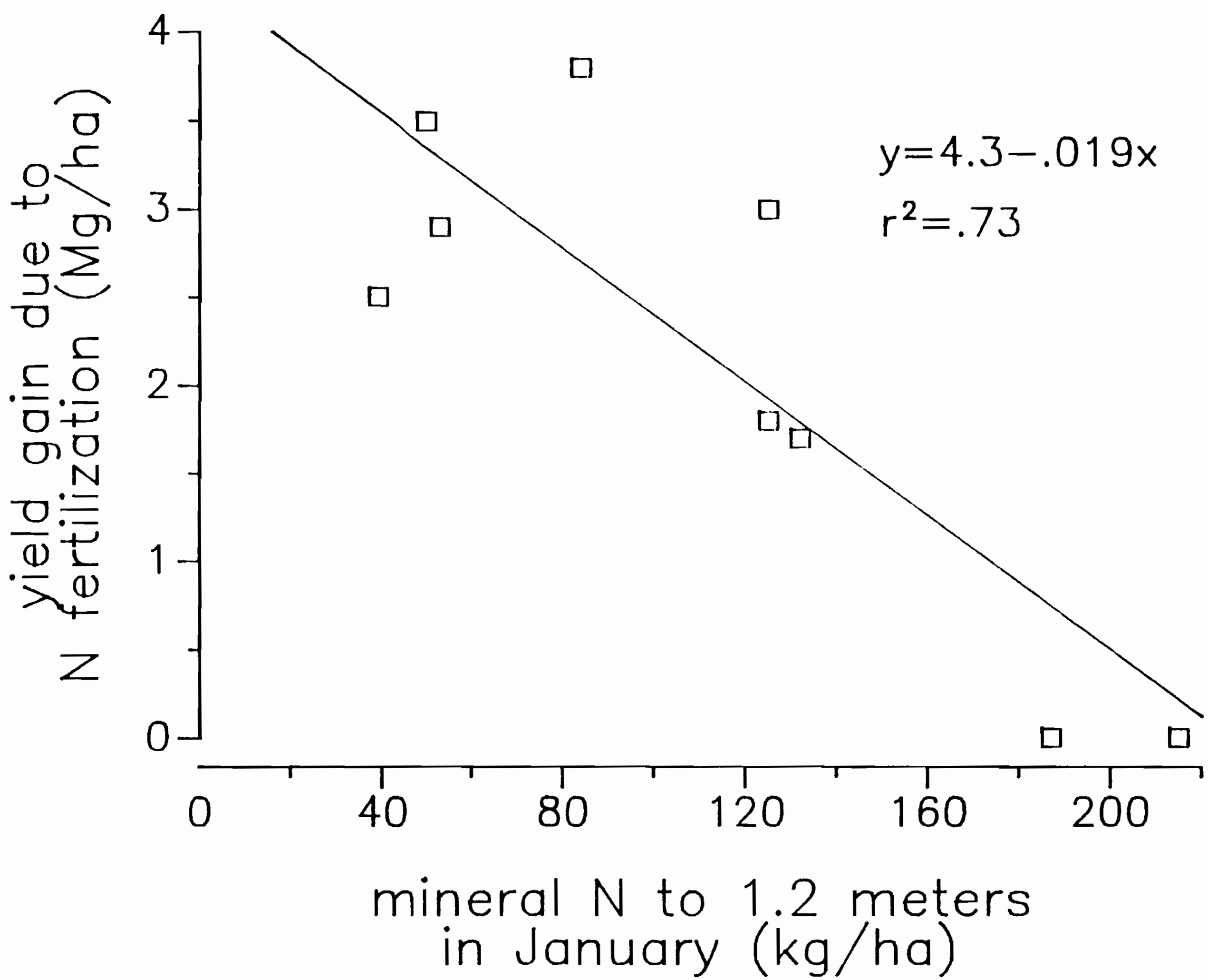

Figure 2. Wheat yield gain due to spring N fertilizer application as a function of January soil mineral N measured to a 1.2 meter depth.

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Chapter III

Field-specific spring N rate recommendations for winter wheat. I. Farmer-field validation of tissue test-based recommendations

ABSTRACT

A system for predicting optimum spring nitrogen (N) fertilizer rates for winter wheat in the mid-Atlantic region of the U.S. was previously developed from a small set of experiments using a single wheat variety and in which all cultural operations were conducted by researchers. The objective of the research reported here was to evaluate whether this system could be successfully applied to the more varied environment of farmer fields. Thirty-nine N response experiments were carried out in farmer fields over five growing seasons encompassing a wide and representative range of soil types and wheat varieties. The relationship between wheat tissue N content at Zadoks growth stage (GS) 30 and optimum N rate at GS 30 was weaker in farmer fields ($r^2 = .51$) than in the researcher-planted experiments ($r^2 = .59$) but was still strong enough to be useful. Economic analyses indicate that tissue test-based N rate recommendations increased profit by an average of \$36 ha^{-1} relative to traditional N application practices. Apparent fertilizer efficiency was measured in ten of the experiments and was significantly higher for N applications based on the tissue test system than for traditional N applications.

INTRODUCTION

Field-specific N rate recommendations are generally not used at present for winter wheat grown in humid regions of the U.S., but would be highly desirable due to the high potential for nitrate leaching to ground and surface waters when N fertilizer is applied in excess of the amount that can be efficiently used by the crop in these regions. This is especially true because percolation rates are higher at the time when N fertilizer is applied to winter wheat than at times when N fertilizer is applied to most other crops.

A system for making field-specific N rate recommendations for winter wheat at Zadoks growth stage (GS) 30 (Zadoks et al., 1974) was reported by Baethgen and Alley (1989). This system used either tissue N content or crop N uptake at GS 30 as the basis for the N rate recommendation. Values of these variables were strongly related to optimum N fertilizer rates measured in the same fields--as tissue N content or crop N uptake increased, optimum N fertilizer rate decreased. Tissue N content was chosen as the test to use in the recommendation system propagated to farmers in Virginia because it is easier to measure than N uptake (Alley et al., 1989).

Baethgen and Alley (1989) determined that the critical N concentration (concentration at which 90% relative yield is attained without further N fertilization) for winter wheat at Zadoks GS 30 was 39.5 g N kg^{-1} tissue. This closely agrees with the critical level of 35 g N kg^{-1} tissue reported by Roth et al. (1989) (Feekes GS 5 is the same as Zadoks GS 30) and with the critical level of 38 g N kg^{-1} tissue reported by Vaughan et al. (1990) ("leaves" at

Feekes 5 as defined by Vaughan et al. is the same as the samples reported in the Baethgen and Roth papers). The close agreement between these sources is a little surprising given the large climatic differences--Baethgen and Alley (1989) and Roth et al. (1989) are both from the humid east (Virginia and Pennsylvania, respectively), while Vaughan et al. (1990) did their research in the semi-arid climate of eastern Colorado. There appears to be potential for wide adaptability of N recommendation systems for winter wheat based on tissue N content.

While critical concentrations can be used to identify sites that are not likely to respond to fertilizer N applications, it is desirable to have a system that can predict the economic optimum fertilizer rate for fields that test below the critical level. Measuring the optimum N rate in field experiments and regressing it against possible predictor variables (e.g. tissue N content) measured in the same experiments is a powerful approach that has been used by only a few investigators. Wehrmann and Scharpf (1979) measured optimum N fertilizer rates for winter wheat in Germany and found that they were strongly related to soil mineral N measured to a 1 meter depth; from this relationship they developed a predictive system (the N_{min}-method) that not only identifies fields not needing fertilization, but predicts the optimum N fertilizer rate for fields needing fertilization. Such a system provides a means of reducing N fertilizer rates with confidence on selected fields, thus reducing the potential for both leaching of nitrate and (in small grains) lodging. Other researchers who have used this approach include Baethgen and Alley (1989), Beauchamp and Kachanowski (1991), and Bundy et al. (1992).

While Baethgen and Alley (1989) found a strong correlation between wheat tissue N content at GS 30 and optimum N rate at GS 30, their research consisted of only eight experiments, all of which utilized a single variety and were conducted under highly-controlled research conditions. Our objective in undertaking the present research was to further evaluate the reliability of GS 30 N fertilizer recommendations for winter wheat based on tissue N content over a wide range of varieties and soil types and in conditions representative of farmer fields.

MATERIALS AND METHODS

Experimental sites were established with cooperating farmers in the Coastal Plain (35 sites), Piedmont (1 site), and Ridge and Valley (3 sites) physiographic regions of Virginia. Sites were selected approximately a month after planting based on the following criteria: stand uniformity, soil uniformity (as determined by soil probe to 1 m depth), and whether soil type was representative of soils cropped to wheat in Virginia. Relevant site information is summarized in Table 4.

Experimental treatments were N rates applied at Zadoks growth stages (GS) 25 and 30 (Zadoks et al., 1974) in a complete factorial design. Total spring N applications in the first two years of the study ranged up to 336 kg N ha^{-1} to ensure that the optimum N rate would be within the range of rates that we applied. With the experience from these two years, we felt confident that we could capture the optimum N rate while using a smaller range. Nitrogen rates were reduced for the third through the fifth years of the study, ranging from 0 to 238 kg ha^{-1} total spring N fertilizer. Rates used for the two phases of the study are given in Table 5. Treatments were arranged in randomized complete blocks with four replications at each experimental location. Individual plots measured 5 m by 5.5 m.

Urea ammonium nitrate solution was used as the N source for treatment application in all experiments. The N solution was applied with a carbon dioxide pressurized backpack sprayer whose boom was fitted with Teejet "raindrop" tips. Flow rates for each tip size were measured at each

Table 4. Brief site descriptions of locations used in studying optimum spring N fertilizer rates for winter wheat.

			Soil	
Location Number	Year	Variety	Series and Surface texture	Subgroup
1	1991-1992	Coker 983	Pamunkey l	Ultic Hapludalf
2	1991-1992	Coker 9803	Bojac ls	Typic Hapludult
3	1991-1992	Madison	Suffolk sl	Typic Hapludult
4	1991-1992	Madison	Emporia sl	Typic Hapludult
5	1991-1992	Madison	Cecil cl	Typic Kanhapludult
6	1991-1992	Wakefield	State sl	Typic Hapludult
7	1991-1992	Pioneer 2548	Kempsville sl	Typic Hapludult
8	1991-1992	Pioneer 2548	Suffolk ls	Typic Hapludult
9	1991-1992	Massey	Catpoint ls	Typic Quartzipsamment
10	1990-1991	Madison	Savannah sl	Typic Fragiudult
11	1990-1991	Wakefield	State sl	Typic Hapludult
12	1990-1991	Wakefield	Munden sl	Aquic Hapludult
13	1990-1991	Florida 302	Pamunkey l	Ultic Hapludalf
14	1990-1991	Coker 983	Conetoe s	Arenic Hapludult
15	1989-1990	Coker 916	Pamunkey l	Ultic Hapludalf
16	1989-1990	Coker 983	Altavista fsl	Aquic Hapludult
17	1989-1990	Pioneer 2555	Kempsville sl	Typic Hapludult
18	1989-1990	Coker 916	Suffolk fsl	Typic Hapludult
19	1989-1990	Madison	State sl	Typic Hapludult
20	1989-1990	Pioneer 2555	Emporia sl	Typic Hapludult
21	1988-1989	Coker 916	Bojac sl	Typic Hapludult
22	1988-1989	Coker 983	Bojac sl	Typic Hapludult
23	1988-1989	Coker 916	Emporia fsl	Typic Hapludult
24	1988-1989	Pioneer 2555	Pamunkey l	Ultic Hapludalf
25	1988-1989	Coker 9227	State sl	Typic Hapludult
26	1988-1989	Coker 916	Emporia l	Typic Hapludult
27	1988-1989	Massey	Altavista sl	Aquic Hapludult
28	1987-1988	Saluda	Bojac sl	Typic Hapludult
29	1987-1988	Coker 983	Bojac sl	Typic Hapludult
30	1987-1988	Pioneer 2550	Pamunkey l	Ultic Hapludalf
31	1987-1988	Coker 916	Emporia fsl	Typic Hapludult
32	1987-1988	Coker 916	Kempsville sl	Typic Hapludult
33	1987-1988	Coker 9733	Kempsville sl	Typic Hapludult
34	1987-1988	Saluda	Suffolk fsl	Typic Hapludult
35	1987-1988	Massey	State sl	Typic Hapludult
36	1987-1988	Coker 916	Pamunkey l	Ultic Hapludalf
37	1987-1988	Coker 916	Hayter l	Ultic Hapludalf
38	1987-1988	Coker 916	Hayter l	Ultic Hapludalf
39	1987-1988	Coker 916	Ross sl	Cumulic Hapludoll

Table 5. Fertilizer N rate treatments used in experiments to study the relationship between tissue N content and optimum N fertilizer rate at growth stage 30.

Treatment number	Rates used in 1988 and 1989 harvest years		Rates used in 1990 to 1992 harvest years	
	N rate at GS 25†	N rate at GS 30	N rate at GS 25	N rate at GS 30
	kg N ha^{-1}	kg N ha^{-1}	kg N ha^{-1}	kg N ha^{-1}
1	0	0	0	0
2	0	56	0	34
3	0	112	0	68
4	0	168	0	102
5	28	0	0	136
6	28	56	34	0
7	28	112	34	34
8	28	168	34	68
9	56	0	34	102
10	56	56	34	136
11	56	112	68	0
12	56	168	68	34
13	112	0	68	68
14	112	56	68	102
15	112	112	68	136
16	112	168	102	0
17	168	0	102	34
18	168	56	102	68
19	168	112	102	102
20	168	168	102	136

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

experimental location prior to N application, proper walking speed to obtain the desired application rate was calculated, and a stop watch and metronome were used to calibrate and maintain proper walking speed during N application.

Plant tissue samples were collected at GS 30 by clipping the entire above-ground portion of the plant from two 1-m sections of row per plot. For each N rate applied at GS 25, one plot was sampled from each replication. Samples were dried, ground to pass a 40-mesh screen, and analyzed for total Kjeldahl N content using QuikChem Method No. 13-107-06-2-B (Lachat Instruments, Milwaukee, WI) modified to obtain a higher digestion temperature and a larger N concentration range. Data quality control was maintained with frequent analysis of a National Institute of Standards and Technology plant tissue sample (SRM 1547) of known N content. All samples were digested and analyzed in duplicate. When the difference between the two values for duplicates was greater than 1 g N kg^{-1} tissue, that sample was re-digested and analyzed.

At physiological maturity, plots were rated for lodging using the Belgium scale (Szöke et al., 1979) and harvested with a Hege 140 plot combine; yields were corrected to 135 g kg^{-1} moisture. Post-harvest tissue samples were taken from four treatments at locations 10-16 and 18-20: zero spring N, 102 kg N ha^{-1} at GS 25 (representing traditional practice), 68 kg N ha^{-1} at GS 25 and the N rate closest to the tissue test recommendation at GS 30, and the highest N rate (102 kg N ha^{-1} at GS 25 and 134 kg N^{-1} at GS 30). Sampling and analysis procedures were the same as for the GS 30 tissue samples. Apparent fertilizer efficiencies [(N uptake - check N uptake)/fertilizer applied] were calculated assuming that N uptake measured in above-ground tissue at harvest represented 85% of actual total N uptake, with the other 15% either present in the root system and dropped leaves or volatilized from leaves (Daigger et al., 1976; Harper et al., 1987). Analysis of variance was used to determine whether there was a treatment effect on apparent fertilizer efficiency.

For each GS 25 N rate, GS 30 N rate was quadratically regressed against yield at each site; the economic optimum N rate at GS 30 was calculated from this regression equation and current prices for wheat grain and N fertilizer. Thus, at each experimental location, four (five in 1988-1989 and 1989-1990) optimum GS 30 N rates were calculated, each corresponding to one GS 25 N rate and with an associated tissue N measurement at GS 30. Optimum GS 30 N rate was regressed against GS 30 tissue N content for all locations. All calculations for regression analysis and analysis of variance were done using SAS (SAS Institute, Cary, NC).

Profit was estimated for each plot as wheat value (yield x wheat price) - N fertilizer cost (N rate x N price) - combining cost increase due to lodging (up to \$50 ha^{-1} for completely lodged wheat) - other production costs (estimated as \$400 ha^{-1} for all experiments). The least-squares quadratic response surface was calculated for estimated profit as a function of N rate at GS 25 and N rate at GS 30 at each location. These response surfaces were used in comparing the economics of traditional N application practices to the economics of the tissue test recommendation system.

RESULTS AND DISCUSSION

Average top yield for the thirty-nine experiments was 5.7 Mg/ha, indicating generally good cultural practices and fertility levels for other plant nutrients. The wheat crop was highly responsive to N fertilizer applications (the difference between the check yield and the highest treatment yield was greater than 2 Mg ha^{-1}) at twenty-six locations, moderately responsive (yield response between 1 and 2 Mg ha^{-1}) at five locations, non-responsive (no treatment yield more than 1 Mg ha^{-1} above or below check yield) at five locations, and negatively responsive (some treatments with yields more than 1 Mg ha^{-1} below check yield) at two locations. Examples of these four categories are presented graphically in Figure 3. At one location, moderate N rates gave a yield increase greater than 1 Mg ha^{-1}, but high N rates resulted in yields more than 1 Mg ha^{-1} below check yields.

The relationship that we found between wheat tissue N concentration at GS 30 and optimum N fertilizer rate at GS 30 (Figure 4) is very similar to that reported by Baethgen and Alley (1989), though the slope of the least-squares regression line is somewhat less steep and its r^2 value somewhat lower than what they reported. The lower r^2 value is not unexpected given that our conditions (varieties, soil types, cultural practices) were much more variable than theirs.

Results from all 1988-1989 experiments were excluded from Figure 4b. Rainfall in March 1989 was nearly double the average March rainfall, resulting in extended waterlogged conditions at many experiments for the month prior to GS 30. Wheat dry matter accumulation measured at GS 30 averaged less

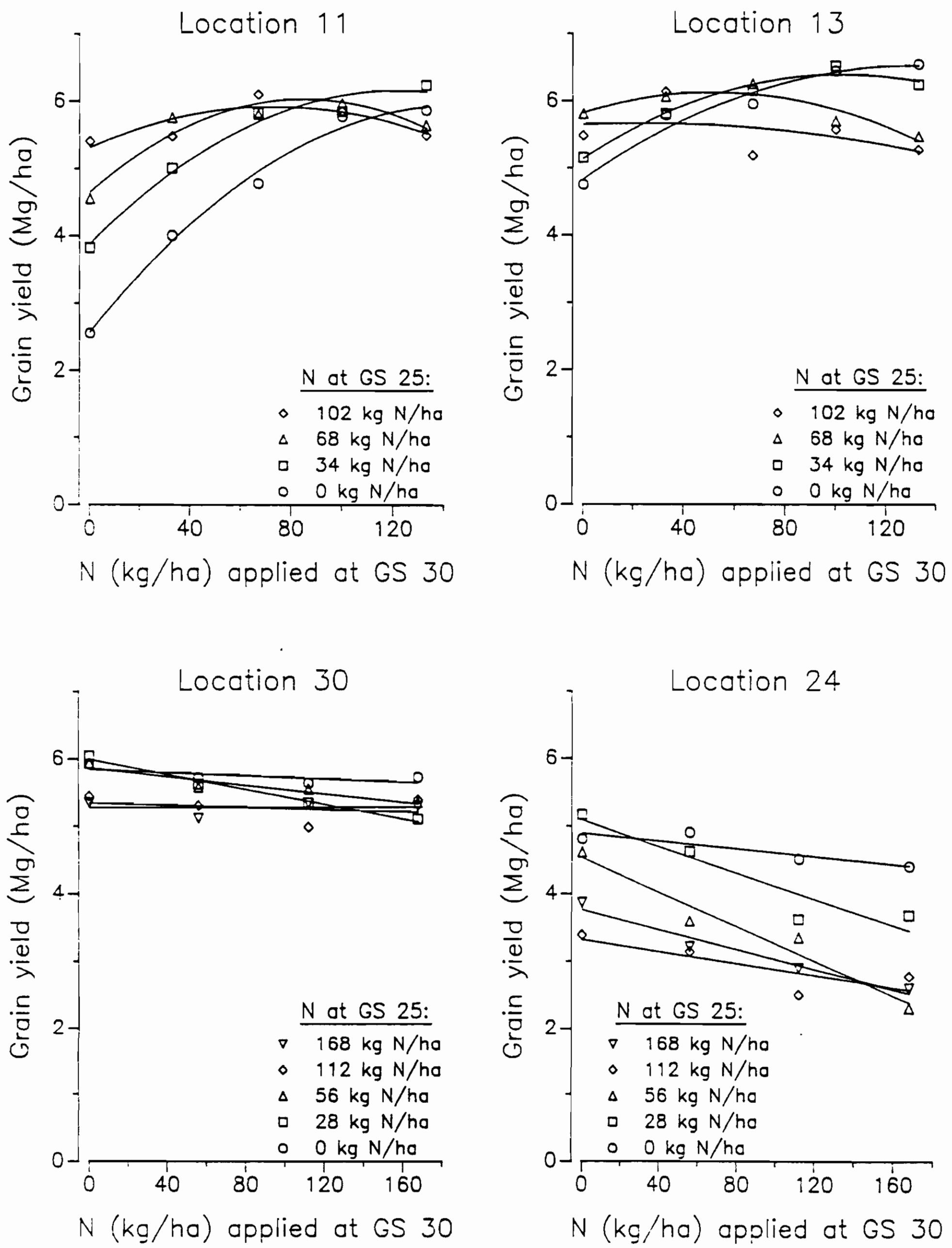

Figure 3. Wheat yield responses to N fertilizer applications at several locations. Location 11 would be generally characterized as highly responsive (as defined in text), location 13 as moderately responsive, location 30 as non-responsive, and location 24 as negatively responsive.

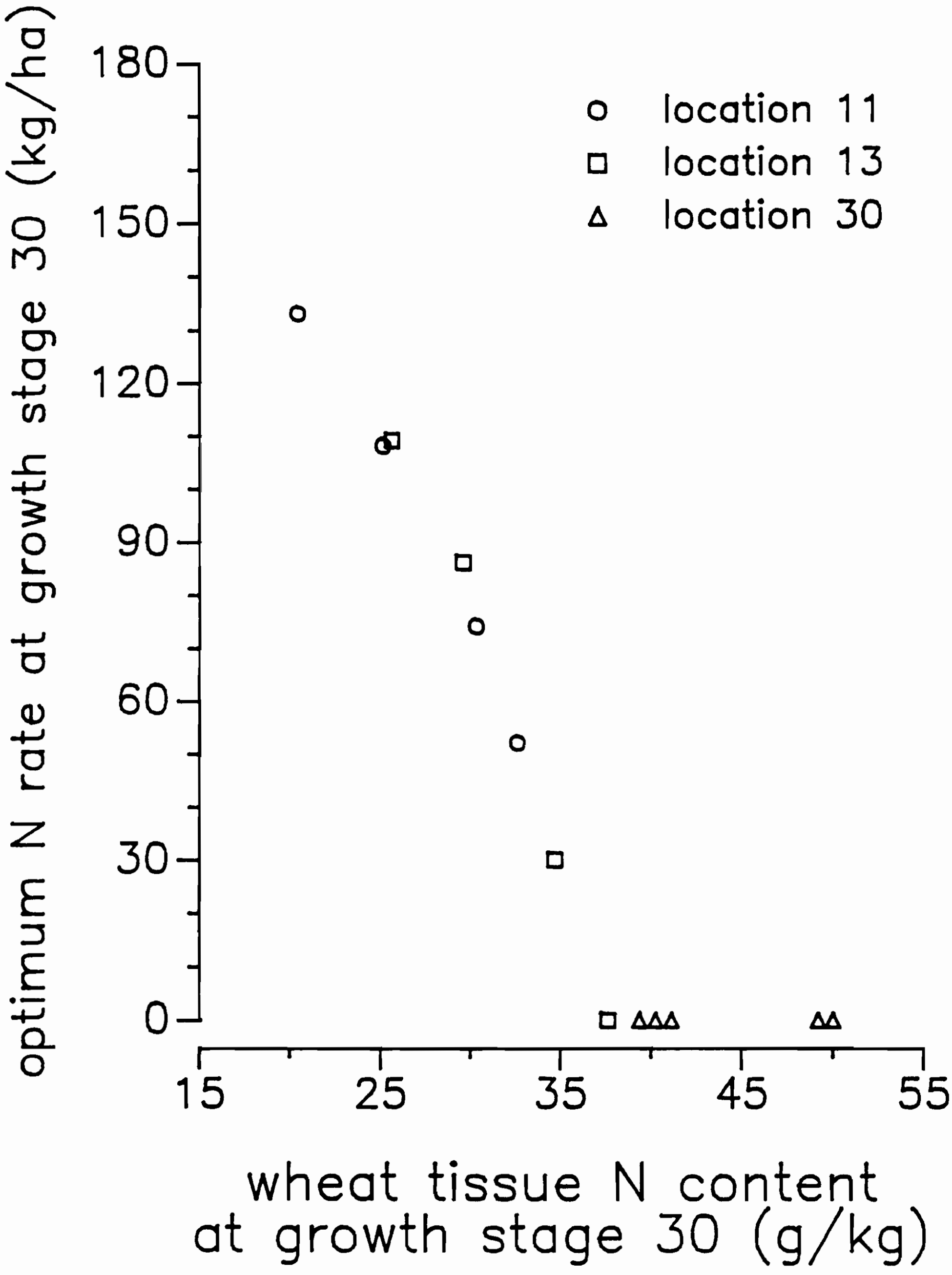

Figure 4a. Optimum N rate for winter wheat at growth stage 30 regressed against wheat tissue N content at growth stage 30 for locations 11, 13, and 30. Values for optimum GS 30 N rates were derived from the yield response curves in Figure 3.

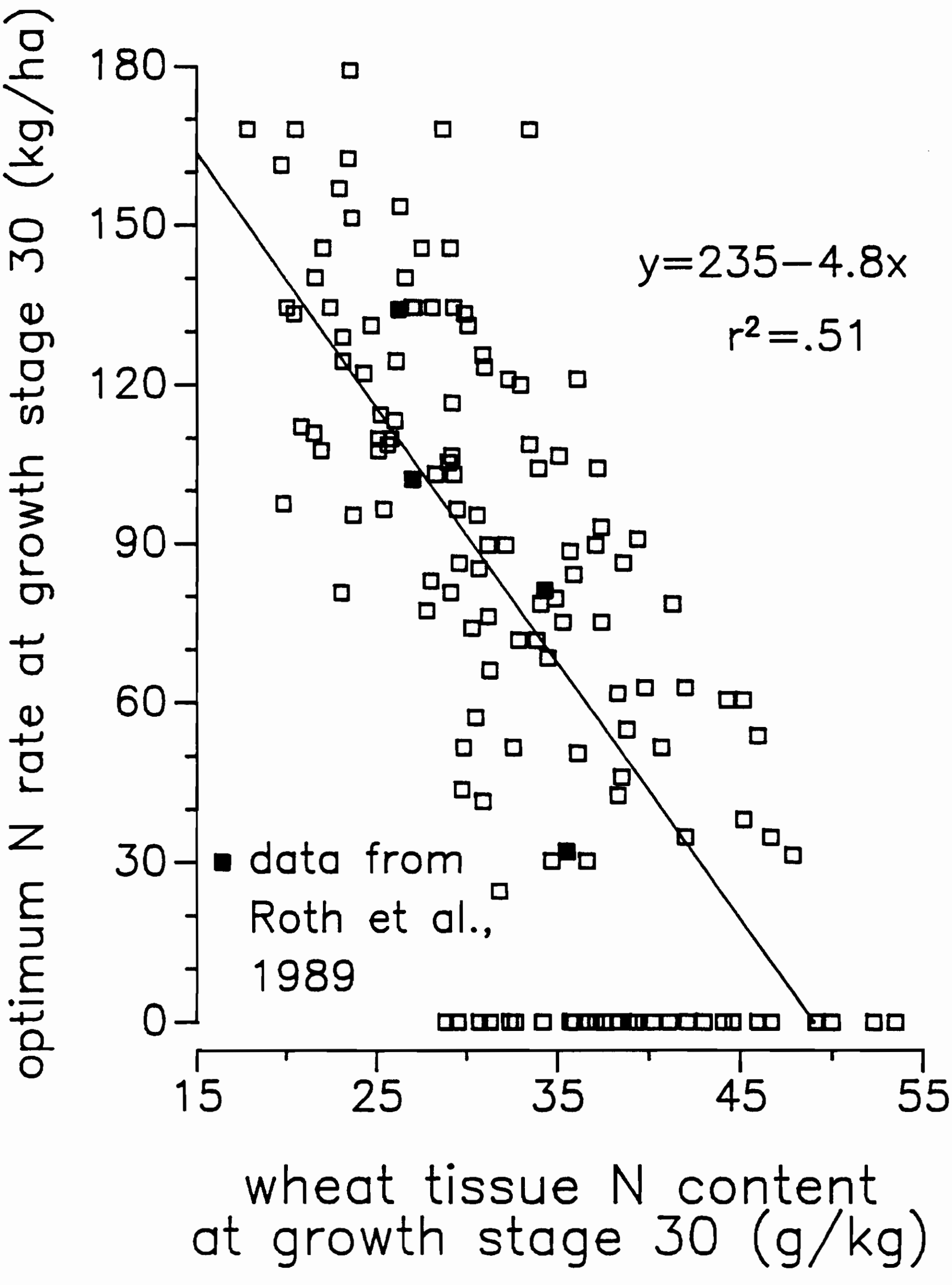

Figure 4b. Optimum N rate for winter wheat at growth stage 30 regressed against wheat tissue N content at growth stage 30. Data are from four years and thirty-one locations. Omitted locations are explained in the text.

than half of that measured in previous years, causing tissue N to be very concentrated. Fourteen 1988-1989 location/GS 25 N rate combinations had average tissue N contents above 50 g N kg^{-1} tissue, relative to only two treatments from all other years combined. While including data from this year only decreases the regression r^2 to 0.48, it changes the regression line considerably. Since we want to use this relationship as a basis for making field-specific N rate recommendations, we felt that it was better to exclude the results from this unusual season. All experimental locations from this season, however, are included in the economic analysis of the recommendation system that follows. Location 17 was excluded from both Figure 4b and the economic analyses due to a severe weed infestation.

Roth et al. (1989) calculated economic optimum N rates for four experiments with winter wheat in Pennsylvania, and measured tissue N content at GS 30 in the same experiments. Data from these four experiments (from their Table 3) agree well with our results and fall close to the least-squares regression line when plotted on Figure 4b. This indicates that our results are likely valid on at least a regional scale.

While the relationship shown in Figure 4b is highly significant, it also contains a large amount of scatter. It is legitimate to ask whether this relationship is good enough to form the basis for a recommendation system. To answer this question, we compared estimated profit for traditional N application practices (90 kg N ha^{-1} at GS 25) to estimated profit with 60 kg N ha^{-1} applied at GS 25 (Baethgen et al., 1989) and GS 30 N rate based on tissue test results interpreted using the regression line in Figure 4b. Estimated profit was higher for tissue-test based N applications than for traditional N applications at twenty-eight out of thirty-eight experimental locations (Table 6), and averaged \$36 ha^{-1} higher. A paired-t test provides very strong evidence ($p = .0001$) that this difference is real. We feel that this comparison clearly justifies the use of the relationship in Figure 4b as the basis for a N rate recommendation system.

Figure 4b includes quite a few points with tissue N content below 40 g N kg^{-1} tissue but with optimum GS 30 N rate equal to zero. In a few cases, this appeared to be due to some other serious yield-limiting constraint, as final yields were low. These cases were, however, the exception rather than the rule: average yield was 5.4 Mg ha^{-1} for location/GS 25 N rate combinations for which optimum GS 30 N rate was zero. Many of these points are from locations in the non-responsive category (as defined above). At one such location, mineral N levels were very low in the top 60 cm of soil, but were high below 60 cm. Nitrogen availability was apparently low up to the time of tissue sampling, but high thereafter. Several other locations in this category had high organic matter levels in their surface horizons, raising the possibility that the tissue test may sometimes underestimate availability of mineralizing N. None of these experiments was conducted on sites with recently-incorporated organic N sources and the usefulness of tissue test N rate recommendations in such cases must be regarded with caution. However, while either soil organic matter content or mineralizable N (measured as described in Chapter IV) in the top 30 cm of soil is significant when added as a predictor to the regression in Figure 4b, neither increases the regression R^2 much nor significantly increases estimated profit when incorporated into the recommendation system.

Table 6. Estimated profit as a function of spring N application strategy for winter wheat at thirty-eight experimental locations in Virginia.

Location Number	Estimated profit when spring N application strategy is: 90 kg N ha^{-1} GS 25[†], 0 kg N ha^{-1} GS 30	60 kg N ha^{-1} GS 25, Tissue test rec. GS 30
	\$ ha^{-1}	\$ ha^{-1}
1	269	282
2	89	185
3	173	170
4	180	254
5	207	254
6	190	259
7	161	190
8	62	180
9	-64	-12
10	-20	-10
11	64	128
12	74	141
13	119	136
14	-203	-188
15	373	358
16	119	217
18	-5	12
19	217	242
20	44	116
21	203	200
22	-22	-42
23	27	10
24	40	82
25	54	86
26	161	163
27	124	153
28	96	185
29	69	131
30	301	291
31	116	175
32	294	279
33	267	314
34	64	114
35	42	146
36	321	314
37	403	393
38	343	329
39	227	306
average:	136	172

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Wheat variety and soil series both explain a significant amount ($\alpha = .05$) of variability when added as class variables to the regression in Figure 4b. Most varieties or soil series that are substantially different than the average are represented by only one or two locations; we do not feel that adjustment of tissue test recommendations based on variety or soil series would be reliable with available data. The variety "Madison" is a possible exception to this statement--it seems to need about 10 kg N ha^{-1} more than other varieties when it has the same tissue N content. Soil productivity class groupings from VALUES (Virginia Agricultural Land Use Evaluation System) do not explain a significant amount of variability when added as class variables to the regression in Figure 4b.

Apparent fertilizer efficiency values measured in ten experiments in the 1989-1990 and 1990-1991 seasons are presented in Table 7. The treatment with 102 kg N ha^{-1} at GS 25 and zero N at GS 30 represents traditional practice. At locations 15 and 16, apparent fertilizer efficiency was significantly higher in plots receiving 68 kg N ha^{-1} at GS 25 and the closest rate to tissue test recommendation at GS 30 than in plots receiving "traditional" N applications. The same is true for data from all ten locations when they are analyzed together--many locations show similar trends but are sub-significant when analyzed individually. These results are probably due both to efficient uptake when application rates are tailored to crop need and to the higher potential for leaching loss of N fertilizer applied at GS 25. They suggest that, overall, farmer adoption of N application practices based on tissue test recommendations would increase the efficiency of N fertilizer applications to wheat and reduce the potential for nitrate contamination of ground and surface waters.

Table 7. Apparent fertilizer efficiency measured at ten experimental locations for three different spring N fertilizer application strategies.

spring N rate treatment	apparent N fertilizer efficiency at location:										
	10	11	12	13	14	15	16	18	19	20	combined
N25[†]=102 N30=0	0.28	0.59	0.43	0.74	0.32ab	0.40b	0.10c	0.47	0.50	0.40	0.43b
N25=102 N30=136	0.31	0.50	0.44	0.60	0.22b	0.40b	0.27b	0.44	0.41	0.40	0.39b
N25=68 N30=tissue test rec.	0.38	0.59	0.60	0.56	0.40a	0.86a	0.39a	0.40	0.39	0.47	0.50a
p for treatment differences	0.69	0.45	0.43	0.32	0.03	0.01	0.0004	0.76	0.29	0.76	0.0006

[†]N25=N fertilizer rate applied at growth stage 25 (spring greenup), in kg ha^{-1}

N30=N fertilizer rate applied at growth stage 30 (pre-jointing), in kg ha^{-1}

Values within a column followed by different letters are significantly different at alpha=0.05

Comparison of apparent fertilizer efficiency with 102 kg N ha^{-1} applied at GS 25 and either 0 or 136 kg N ha^{-1} applied at GS 30 (Table 7) reveals that there is no significant overall difference between the two treatments, and there is only one location (16) with an individually significant difference. This suggests that uptake of even excessive N applications at GS 30 was quite efficient. The treatment with 102 kg N ha^{-1} applied at GS 25 and 136 kg N ha^{-1} applied at GS 30 was the treatment with the highest N rates applied in these experiments, and in many cases resulted in lodging and yield depression.

Relative to traditional uniform-rate N application practices for winter wheat in Virginia, field-specific N application practices based on tissue testing appear to hold great promise for increasing profitability and minimizing nitrate leaching potential. Fields needing little or no additional N fertilizer at GS 30 can be identified, thus reducing the incidence of over-fertilization, while fields that need and can efficiently use substantial N applications can also be identified, thus avoiding under-fertilization and ensuring the efficient use of other inputs to the cropping system.

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Chapter IV

Field-specific spring N rate recommendations for winter wheat. II. A flexible multi-component recommendation system.

ABSTRACT

A system for predicting the optimum nitrogen (N) fertilizer rate for winter wheat at Zadoks growth stage (GS) 30 was previously developed. This system is based on the relationship between measured economic optimum N rate at GS 30 and wheat tissue N content measured at GS 30. However, winter wheat often needs an application of spring N prior to GS 30 to achieve optimum yield--apparently this application is needed to stimulate the development of additional tillers. Our objective in the present research was to develop a test to determine which fields need this earlier (growth stage 25) spring application, and to predict the optimum N application rate at this time either with split application management (the second spring application would then be based on the previously developed tissue test) or as a single spring N application. Nitrogen rate experiments were conducted over a period of five years in which the optimum N rate at GS 25 was measured both with and without subsequent GS 30 N applications. These measured optimum N rates were regressed against a variety of possible predictor variables measured in the same fields. Tiller density measured at GS 25 was a good predictor of optimum N rate at GS 25 in a split spring application program. Using this relationship in conjunction with the GS 30 tissue test to make N recommendations for winter wheat

increased estimated profit relative to using the tissue test alone. Soil nitrate measured to 0.9 m depth was the best predictor of optimum N rate at GS 25 when that is to be the only spring N application, and improved estimated profit relative to applying 90 kg N ha^{-1} at all sites; however, the economic performance of split spring N applications was substantially better than for any method of making single spring N applications. The recommendation system developed by integrating these component relationships is powerful and flexible, and provides field-specific N rate recommendations for all spring N applications to winter wheat regardless of management decisions about splitting spring N applications.

INTRODUCTION

Traditionally, winter wheat in Virginia receives 20 to 30 kg N ha^{-1} pre-plant in the fall and another 90 to 100 kg N ha^{-1} in early to mid-February, at or slightly before spring green-up, also referred to as growth stage (GS) 25 (Zadoks et al., 1974). We have, however, measured optimum spring N rates for wheat ranging from 0 to 190 kg N ha^{-1} (Scharf, P.C. and M.M. Alley, unpublished data), indicating that use of the traditional uniform rate often leads to gross over- or under-fertilization. Over-fertilization can cause increased nitrate leaching, in addition to unnecessary expenditure on N, while under-fertilization can cause considerable yield loss. Clearly, there is a need for field-specific N rate recommendations in this cropping system so that N applications more closely match crop N need.

A number of semi-arid states have for some years made field-specific N rate recommendations for wheat based on either soil nitrate measurements (sometimes in conjunction with soil water measurements) (Peterson and Voss, 1984; Westfall, 1984; Alley et al., 1988) or tissue N measurements (Vaughan et al., 1990). Development of field-specific recommendations in humid regions of the U.S. has been slower, due to the more transitory nature of soil N in these regions; however, the need is even greater than in semi-arid regions due to the greater potential for leaching and fertilizer N transport to ground and surface waters. Only Virginia (Alley et al., 1989), Arkansas (Adams et al., 1985), and Maryland (R.F. Mulford, 1993, personal communication; Meisinger et al., 1987) have developed test-based field-specific N rate recommendations for wheat in the humid regions of the U.S.

The recommendation system that we have developed in Virginia (Baethgen and Alley, 1989b; Alley et al., 1989; Chapter III of this dissertation) is based on the relationship between measured optimum N rate at Zadoks growth stage (GS) 30 and wheat tissue N content at GS 30. Growth stage 30 is the pre-jointing stage and usually occurs about a month after GS 25, the traditional time for N applications. Growth stage 30 is a better time to apply fertilizer N because it occurs immediately before the period of maximum N uptake (Baethgen and Alley, 1989a), minimizing the time that the fertilizer N is exposed to leaching processes. Leaching potential is also usually lower at GS 30 than at GS 25 due to higher evapotranspiration rates and lower soil moisture levels. A substantial proportion of fertilizer N applied at GS 25 may, in our climate, be lost before rapid N uptake by the crop begins. In many cases, optimum yield can be achieved with a single N fertilizer application at GS 30, but in other cases N fertilizer applications at both GS 25 and GS 30 are needed to achieve optimum yields (Scharf, P.C. and M.M. Alley, unpublished data). Our working hypothesis is that an N application at GS 25 is needed to stimulate formation of additional tillers when tiller density is sub-optimal (tiller formation has ended by GS 30). Miller et al. (1991) have shown that attaining an adequate tiller density is critical in achieving optimum rice yields.

Currently, farmers who use the tissue test recommendation system apply 50 to 60 kg N ha^{-1} at GS 25 (Baethgen et al., 1989) and then apply N at GS 30 based on tissue test results. Thus, only farmers who are willing to split spring N applications can use the system. A way to identify those fields where no GS 25 N application is needed would make a single tissue test-based N application at GS 30 possible for farmers who are not willing to split. Predicting optimum

N rate at GS 25 would also be desirable, so that only as much N is applied at this stage as is needed; the main nutritional needs of the crop can then be met with a more efficient GS 30 application. Finally, if an N application is indicated at GS 25 and the farmer is not willing to split, it would be desirable to have a system to predict the optimum rate for a single GS 25 N application. Our objective in this research was to develop a system for making field-specific N rate recommendations at GS 25, both for split- and single-application spring N management. These elements, in conjunction with the previously developed tissue test system, would form a flexible recommendation system that would provide field-specific rate recommendations for all N applications, regardless of management decisions about splitting spring N applications.

MATERIALS AND METHODS

Experimental sites were established with cooperating farmers and are described in Table 4 (Chapter III). In addition, six experimental sites were established in 1990-1991 solely to investigate optimum N rate at GS 25 in a split application management system. Table 8 summarizes relevant information for these sites; they are numbered as a continuation of the sites listed in Table 4. Sites were selected approximately a month after planting based on the following criteria: stand uniformity, soil uniformity (as determined by soil probe to 1 m depth), and whether soil type was representative of soils cropped to wheat in Virginia.

Experimental treatments were N rates applied at Zadoks growth stages 25 and 30 in a complete factorial design. Total spring N applications in the first two years of the study ranged up to 336 kg N ha^{-1} to ensure that the optimum N rate would be within the range of rates that we applied. With the experience from these two years, we felt confident that we could capture the optimum N rate while using a smaller range. Nitrogen rates were reduced for the third through the fifth years of the study, ranging from 0 to 238 kg ha^{-1} total spring-applied N fertilizer. Rates used for the two phases of the study are given in Table 5 (Chapter III). Treatments were arranged in randomized complete blocks with four replications at each experimental location. Individual plots measured 5 m by 5.5 m.

Urea ammonium nitrate solution was used as the N source for treatment application in all experiments. The N solution was applied with a carbon dioxide pressurized backpack sprayer whose boom was fitted with Teejet

Table 8. Brief site descriptions of supplemental locations used in studying optimum N fertilizer rates at growth stage 25 when a second spring N application is to be made at growth stage 30. Other experimental sites are described in Table 4.

			Soil	
Location Number	Year	Variety	Series and Surface texture	Subgroup
40	1990-1991	Coker 983	Conetoe s	Arenic Hapludult
41	1990-1991	Coker 983	State sl	Typic Hapludult
42	1990-1991	Coker 983	Suffolk ls	Typic Hapludult
43	1990-1991	Massey	Emporia sl	Typic Hapludult
44	1990-1991	Coker 9776	Hayter l	Ultic Hapludalf
45	1990-1991	Massey	Groseclose l	Typic Hapludult

"raindrop" tips. Flow rates for each tip size were measured at each experimental location prior to N application, proper walking speed to obtain the desired application rate was calculated, and a stop watch and metronome were used to calibrate and maintain proper walking speed during N application.

Soil samples were collected from locations 1 to 39 in late January or early February to a depth of 120 cm (except in the 1987-1988 growing season, when samples were collected only to 90 cm). At some locations, stones limited sampling depth. Each sampling consisted of fourteen well-spaced cores divided into 30-cm depth increments, composited, mixed thoroughly, subsampled, and frozen immediately using dry ice. Samples were thawed and extracted in duplicate using 2M KCl (Keeney and Nelson, 1982); extracts were centrifuged rather than filtered to avoid extract contamination from filters (Scharf and Alley, 1988).

Nitrate in the soil extracts was determined colorimetrically with a QuikChem Automated Analyzer using QuikChem Method No. 12-107-04-1-B (Lachat Instruments, Milwaukee, WI), a cadmium reduction/Griess-Ilosvay method (Keeney and Nelson, 1982). Ammonium in the soil extracts was also measured colorimetrically with the same instrument using QuikChem Method No. 12-107-06-2-A, a modified indophenol blue method (Keeney and Nelson, 1982) in which salicylate is substituted for phenol. Results were converted to kg N ha^{-1} assuming a bulk density of 1.6 g cm^{-3}, the average value for twenty measurements (at a variety of depths) that we made on Coastal Plain soils cropped to winter wheat. When two duplicates gave estimates differing by 5 kg N ha^{-1} or more, that sample was re-extracted and analyzed. Potentially mineralizable N was measured for the 0 to 30 cm samples from the 1989-1990, 1990-1991, and 1991-1992 growing seasons using the method described by Waring and Bremner (1964), except that ammonium determinations were made by automated colorimetric analysis as described above for soil extracts. Soil organic matter was measured in upper 30 cm of soil at all locations using the method of Walkley and Black (1934).

All tillers with three or more leaves were counted from six representative 1 m sections of row per experiment at growth stage 25 in all experiments conducted in 1989-1990, 1990-1991, and 1991-1992. Width of thirty contiguous rows was measured to get a reliable estimate of row width, which was used to calculate average tiller density from the tiller counts. Tiller density was measured in the same way at growth stage 30 at locations 4 and 8 in plots receiving each of the four N rates applied at growth stage 25.

All above-ground tissue was clipped from the sections of row where tiller counts were made, composited, dried, and ground to pass a 40-mesh screen. Total Kjeldahl nitrogen content was measured as described in Chapter III.

At physiological maturity, plots were rated for lodging using the Belgium scale (Szöke et al., 1979) and then harvested with a Hege 140 plot combine; yields were corrected to 135 g kg^{-1} moisture. Profit was estimated for each plot as wheat value (yield x wheat price) - N fertilizer cost (N rate x N price) - combining cost increase due to lodging (up to \$50 ha^{-1} for completely lodged wheat) - other production costs (estimated as \$400 ha^{-1} for all experiments). The least-squares quadratic response surface was calculated for estimated profit as a function of N rate at GS 25 and N rate at GS 30 at each location. The GS 25 N rate corresponding to the highest point on this response surface was the economic optimum GS 25 N rate in a split spring application. These response surfaces were also used to make economic comparisons between different proposed N recommendation systems.

Using yield data only from plots that did not receive any N at GS 30, economic optimum N rate for a single N application at GS 25 was calculated at each location. Calculated optima that were more than ten percent higher than the highest N rate actually applied were not used. At such locations, when total spring N explained yield variation as well as the full quadratic response surface model (R^2 difference of no more than 0.02), we concluded that there was no effect of N timing and used the optimum total spring N rate as an estimate of optimum N rate for a single GS 25 application.

Optimum N rate at GS 25 in a split and optimum N rate at GS 25 as a single application were each regressed against a variety of predictor variables, including soil mineral N measurements, tissue N content, and tiller density. All calculations for least-squares linear and response-surface regression analysis were done using SAS (SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

Response surfaces describing estimated profit as a function of N fertilizer rates at growth stage 25 and GS 30 are shown for two experimental locations in Figures 5 and 6. The highest point on a response surface corresponds to the optimum N rate at GS 25 for that location, given that a second spring N fertilizer application is planned for GS 30. Figure 6 is an example of a location needing N fertilizer at GS 25, with an optimum GS 25 N rate of 60 kg ha^{-1}, while Figure 5 is an example of a location not needing N fertilizer at GS 25 (optimum GS 25 N rate is zero).

Optimum GS 25 N rates obtained in this way were regressed against a variety of possible predictor variables measured in the same fields. Our working hypothesis is that N fertilizer applications are beneficial at GS 25 only if needed to stimulate the formation of additional tillers; this will occur when tiller density is sub-optimal and mineral N in the effective rooting zone is not sufficient to stimulate formation of additional tillers. Predictor variables were chosen for their potential to identify this situation. Tiller density measurements made at GS 30 in the two 1991-1992 experiments with the lowest tiller densities at GS 25 demonstrate that GS 25 N applications do stimulate formation of additional tillers (Figure 7). Both of these locations required GS 25 N applications, in addition to the main N application at GS 30, to achieve optimum yield.

Growth stage 25 tiller density was, as expected, the best single variable for

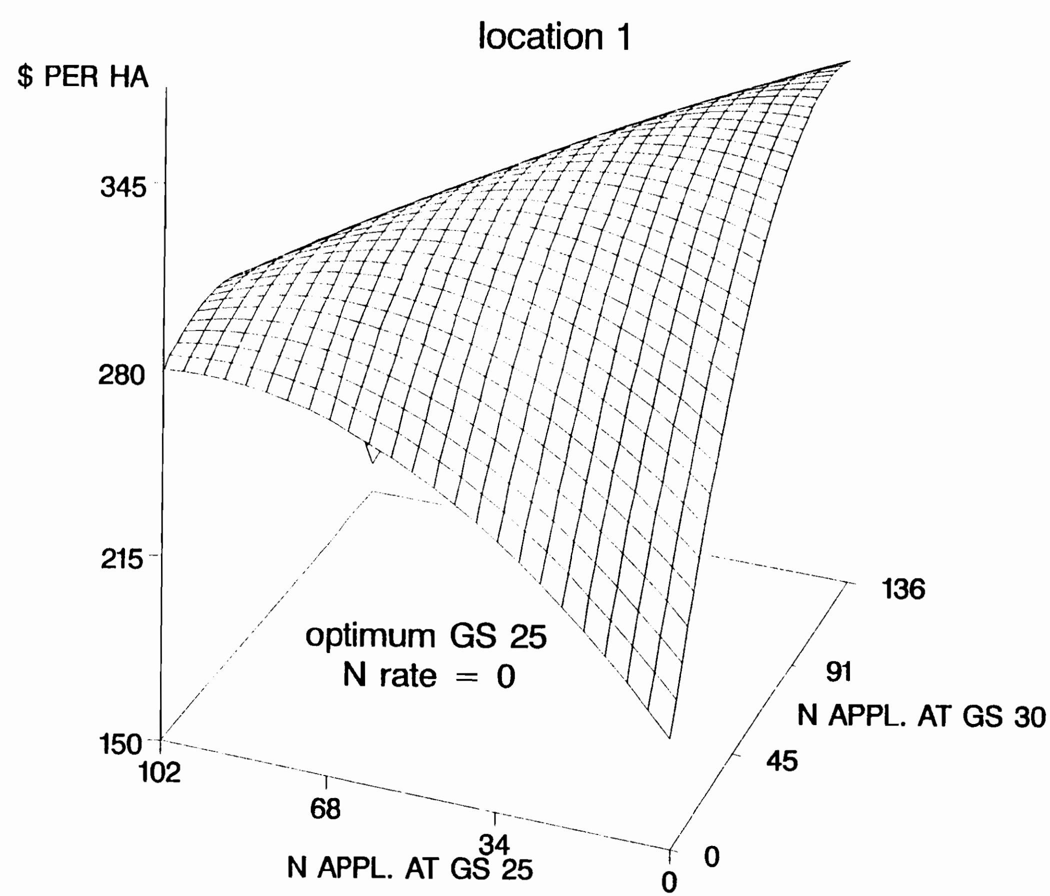

Figure 5. Least-squares response surface describing estimated profit as a function of N rate at growth stage 25 and N rate at growth stage 30 for location 1. Similar response surfaces were calculated for all experimental locations and were used to determine optimum GS 25 N rate with split spring N applications, as well as to make economic comparisons between recommendation systems.

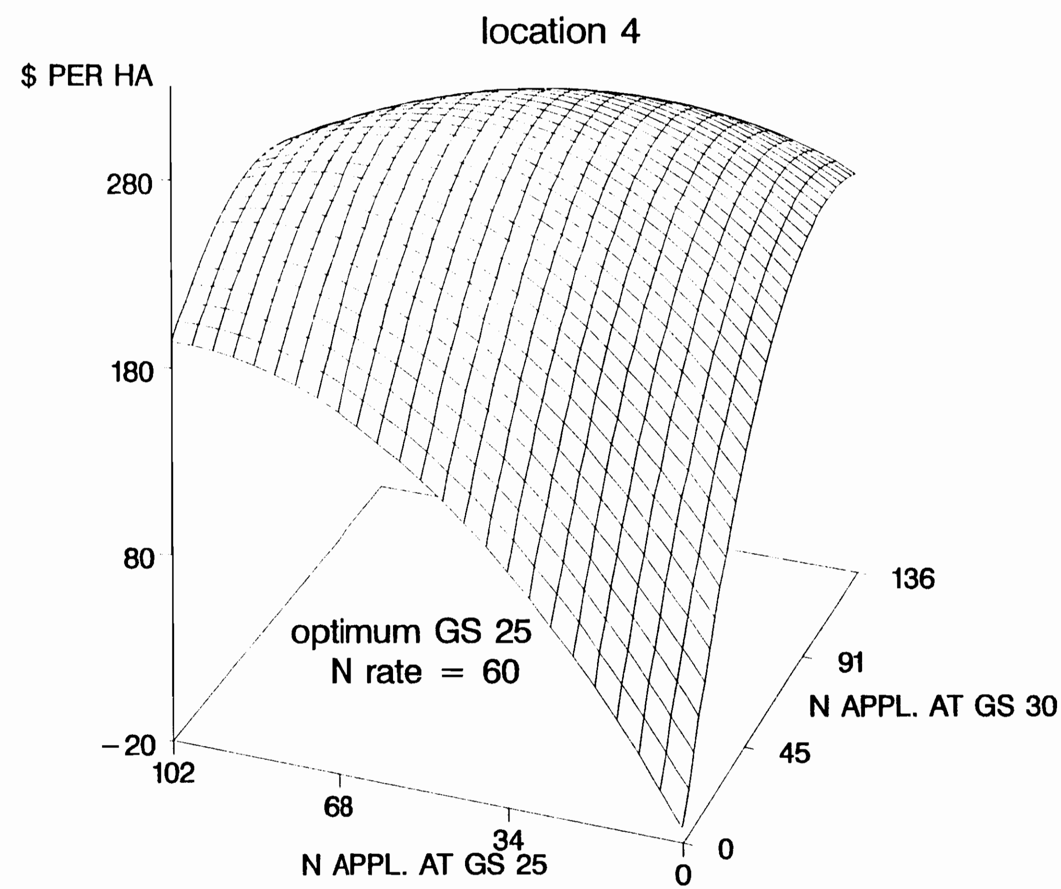

Figure 6. Least-squares response surface describing estimated profit as a function of N rate at growth stage 25 and N rate at growth stage 30 for location 4. Similar response surfaces were calculated for all experimental locations and were used to determine optimum GS 25 N rate with split spring N applications, as well as to make economic comparisons between recommendation systems.

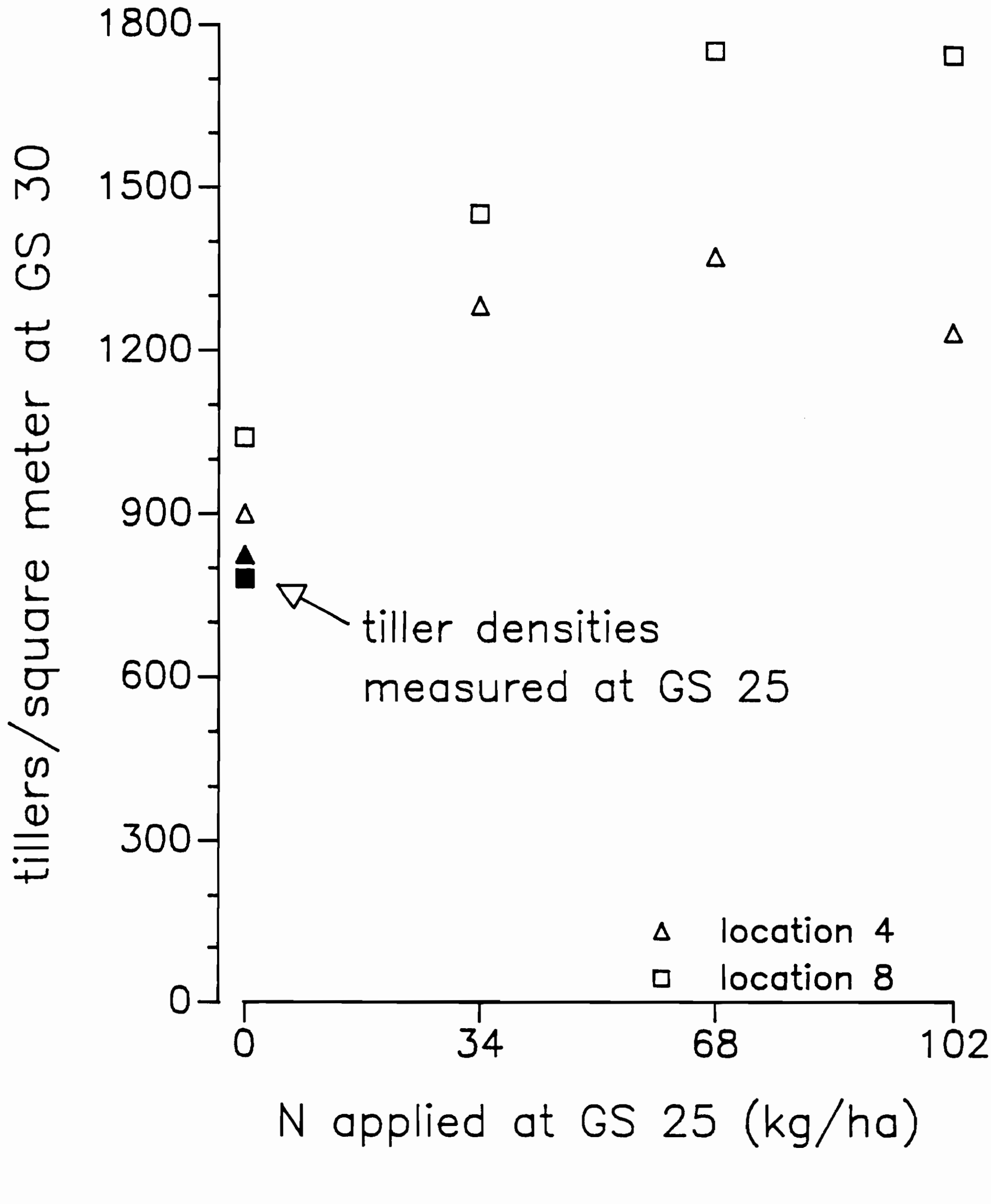

Figure 7. Growth stage 25 N applications increase tiller density at growth stage 30.

predicting optimum N rate at GS 25 in a split spring application (Table 9). Tissue N content at GS 25 was the only variable that significantly improved this regression (Table 9), but economic comparisons indicated no benefit to using both variables to make GS 25 N rate recommendations (data not shown). The least-squares regression line relating tiller density to optimum GS 25 N rate in a split (Figure 8) can be used to predict optimum N rates in farmer fields, and, in conjunction with the tissue test method presented in Chapter III, provides field-specific rate recommendations for both halves of a split spring N application. When tiller density is high (above 1000 tillers m^{-2}), no benefit is expected from a GS 25 N application and all N fertilizer can be applied at GS 30 at a rate based on tissue test results.

Low tiller density at GS 25 can be caused by N-limited conditions, but may also occur in late-planted fields with sufficient soil mineral N. In this case, it is possible that no N fertilizer would be needed at GS 25 even though low tiller density would seem to indicate a need. None of the experiments reported here were late-planted, so these results do not address this possibility.

Variables chosen to regress against optimum single-application GS 25 N rate reflect the fact that a single application at this time must not only stimulate tiller formation when needed, but must supply the main nutritional needs of the wheat crop. Soil mineral N at deeper levels was therefore considered, due to its potential to supply N to the crop at a point later in the growing season. Soil nitrate to a 90 cm depth was the best predictor of optimum single-application N rate at GS 25 (Table 10). No significant improvement to this regression could be made by adding a second predictor variable. The least-squares

Table 9. Regression relationships between optimum N rate at growth stage 25 with split application management and some potential predictor variables.

Variable	Regression R^2
tiller density	.66
nitrate to 30 cm	.24
nitrate to 60 cm	.29
mineral N[†] to 30 cm	.30
mineral N to 60 cm	.28
potentially mineralizable N	.12
tissue N content	.21
tiller density + tissue N content	.75

[†]mineral N = nitrate + ammonium

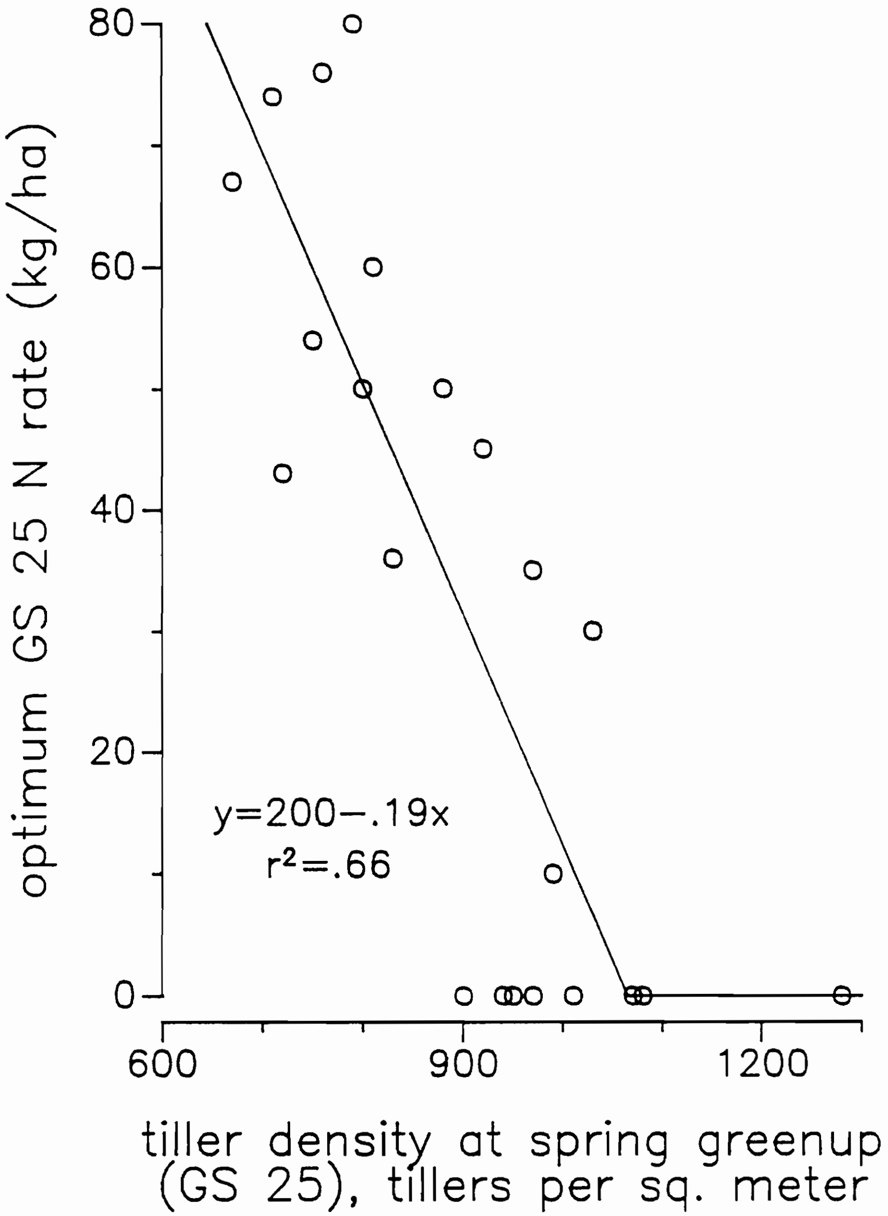

Figure 8. Optimum N rate at growth stage 25 in a split-application management system as a function of tiller density at growth stage 25. The regression line can be used as a basis for making field-specific N rate recommendations for the first (GS 25) spring N application with split-application management.

Table 10. Regression relationships between optimum N rate at growth stage 25 with single application management and some potential predictor variables.

Variable	Regression R^2
nitrate to 30 cm	.39
nitrate to 60 cm	.46
nitrate to 90 cm	.52
nitrate to 120 cm	.37
mineral N[†] to 30 cm	.28
mineral N to 60 cm	.44
mineral N to 90 cm	.48
mineral N to 120 cm	.38
potentially mineralizable N	.40
org. matter in A horizon	.16
tissue N content at GS 25	.22
tiller density	.01

[†]mineral N = nitrate + ammonium

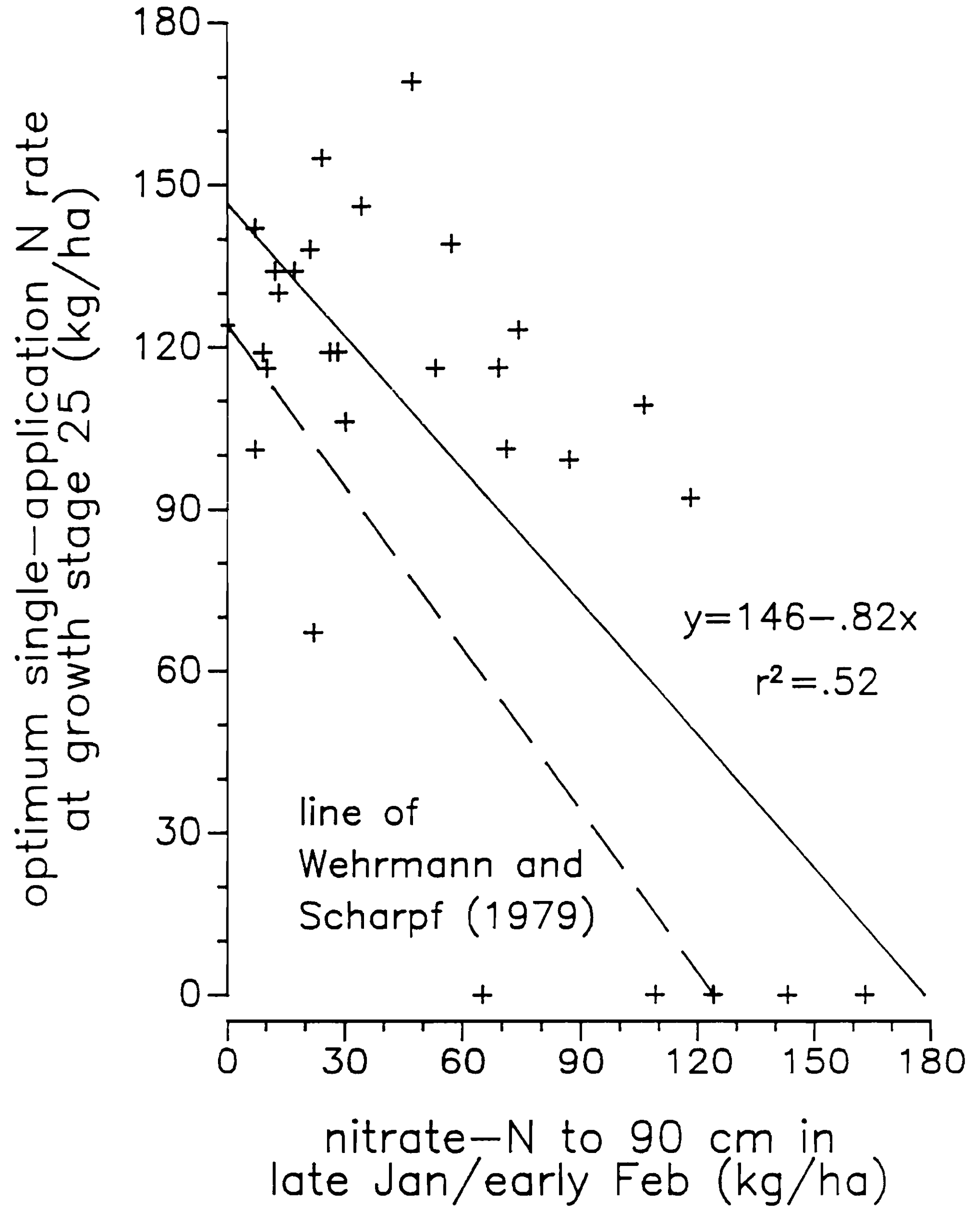

Figure 9. Optimum N rate at growth stage 25 in a single-application management system as a function of soil nitrate to 90 cm in late January or early February. The regression line can be used as a basis for making field-specific N rate recommendations when all spring N is to be applied in a single early application.

regression line relating these two variables (Figure 9) can be used as the basis for field-specific rate recommendations when a single application is to be made at GS 25. This can be the case when low tiller density indicates the need for an N application at GS 25, but the farmer is not willing to split spring N applications on that field.

The data points in Figure 9 tend to be concentrated at both ends of the line, with relatively few intermediate points; this might be cause for some concern about the reliability of this relationship. However, the extremely similar relationship found by Wehrmann and Scharpf (1979), who also worked in a humid climate, provides strong evidence for the validity of the data in Figure 9 and the conclusions that we've drawn from them. Bundy et al. (1992) report a very similar relationship (but reflecting higher N needs) between soil nitrate level and optimum N rate in a corn cropping system.

Chapters III and IV of this dissertation present three separate field-specific recommendation systems, each of which provides, in a particular situation, field-specific spring N rate recommendations for winter wheat. These three systems complement each other to provide test-based field-specific N rate recommendations for all spring N applications to winter wheat while leaving the farmer with management flexibility on the question of whether to split spring N applications (Figure 10).

Locations 1 to 20 were the only ones for which we had all the data to determine N rate recommendations for all possible N recommendation systems derived from this research. Estimated profit for different possible recommendation systems was compared for these locations (Table 11). The

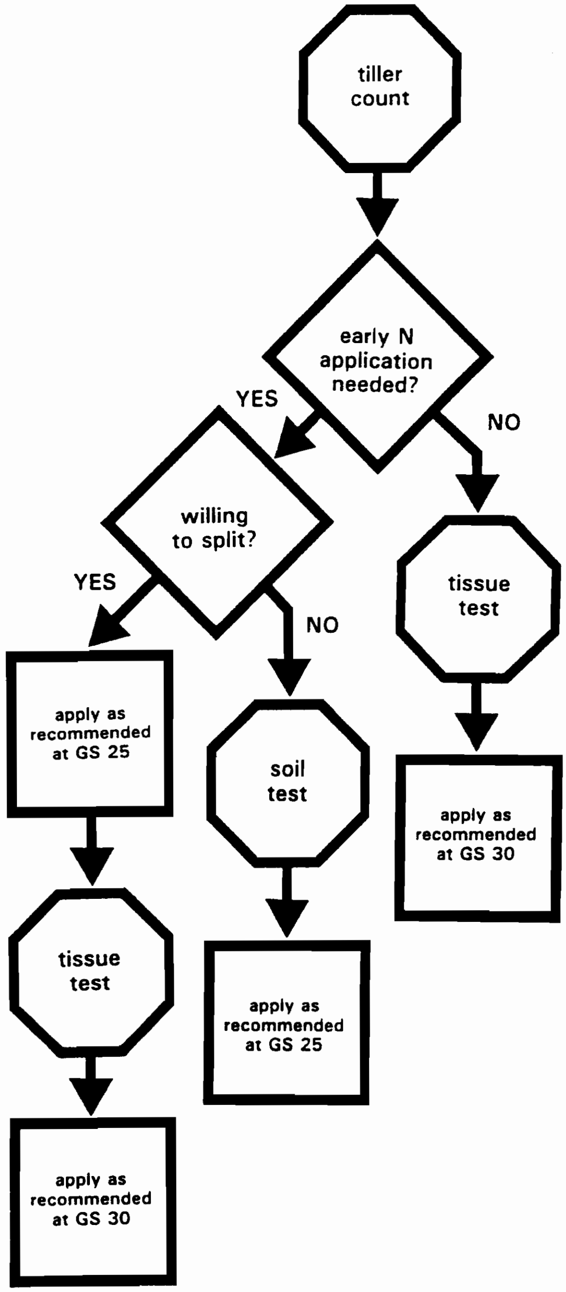

Figure 10. Flow chart showing how the three separate component recommendation systems fit together to form a flexible, integrated spring N recommendation system for winter wheat. Octagons represent field-specific tests, diamonds represent decisions, and squares represent N applications. With this system, all spring N application rates can be based on field-specific tests regardless of management decisions about whether to split spring N.

Table 11. Estimated profit as a function of spring N application strategy for winter wheat at nineteen experimental locations in Virginia. Only economic differences due to N application practices were considered.

Location Number	Estimated profit when spring N application strategy is: 90 kg N ha^{-1} at GS 25†, 0 kg N ha^{-1} at GS 30	60 kg N ha^{-1} at GS 25, GS 30 based on tissue test	GS 25 based on tiller density, GS 30 based on tissue test	single-application management‡	optimum from response surface
	$ ha^{-1}				
1	269	282	296	296	333
2	89	185	175	170	193
3	173	170	193	200	232
4	180	254	254	183	254
5	207	254	289	277	309
6	190	259	254	257	277
7	161	190	203	203	205
8	62	180	175	124	203
9	-64	-12	-10	-111	-7
10	-20	-10	-10	2	2
11	64	128	133	84	136
12	74	141	138	79	143
13	119	136	175	193	193
14	-203	-188	-188	-242	-165
15	373	358	356	338	435
16	119	217	257	264	267
18	-5	12	12	5	27
19	217	242	242	235	282
20	44	116	119	40	121
average:	108	153	162	137	181

†GS 25 = Zadoks growth stage 25 (spring greenup), GS 30 = Zadoks growth stage 30 (pre-jointing)

‡single-application management is defined, for this table, as a single N application at GS 30 whose rate is based on a tissue test when GS 25 tiller density exceeds 800 m^{-2}, or a single N application at GS 25 whose rate is based on soil nitrate levels when GS 25 tiller density is less than 800 m^{-2}.

traditional practice of applying 90 kg N ha^{-1} at GS 25 gave an average estimated return of \$108 ha^{-1}. Split spring N applications with a fixed-rate early application of 60 kg N ha^{-1} and a second application whose rate is based on tissue test results gave a large increase in estimated profit to \$153 ha^{-1}. Using tiller density measurements to obtain a field-specific rate for the firstapplication in a split as well gave a small but significant additional increase in profit to \$162 ha^{-1}, indicating that there is financial incentive to fine-tune the rate of the first application in the split. Tiller density measurements can also be beneficial by helping farmers to prioritize their GS 25 N application activities--fields with low tiller densities are most in need of an N application at this time and should be fertilized first if possible. Total spring N recommended was about the same for these two recommendation systems, but about 30 kg N ha^{-1} was shifted from GS 25 to GS 30 by using tiller density-based recommendations at GS 25. This is environmentally desirable, since leaching potential is higher at GS 25 than at GS 30.

Figure 8 indicates that, when N is also to be applied at GS 30, a GS 25 N application should be made when tiller density is below about 1000 m^{-2}. If a farmer decides to make a single spring N application, tiller density can be used to determine whether it is preferable to make a single application at GS 25 (rate based on soil nitrate levels) or at GS 30 (rate based on tissue N levels). Economic analyses indicated that a single GS 30 application based on tissue test results gave higher returns than a single GS 25 application in all experimental fields with more than 800 tillers m^{-2}. Below 800 tillers m^{-2}, a single GS 25 application gave higher returns in most experimental fields. Single-application recommendations in which tiller density is used to determine the timing of the single application and the rate is based on either soil nitrate (for a GS 25 application) or tissue N (for a GS 30 application) increased estimated profit substantially relative to a single fixed-rate early spring application, but gave considerably lower returns than split spring applications (Table 11).

Optimum N application strategy and the associated profit estimate were derived for each site; this value provides a measure of how much room for improvement exists. About three-quarters of the potential economic gain from improving traditional N management at these locations (\$181 - \$108 = \$73 ha^{-1}) was realized by using split spring N applications with the GS 25 application based on tiller density and the GS 30 application based on tissue N content.

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Chapter V

Accounting for spatial yield variability in field experiments increases statistical power

ABSTRACT

Our objective in this research was to evaluate the utility of nearest neighbor analysis in the statistical analysis of a set of field experiments. Parametric statistical techniques evaluate treatment significance in field experiments by comparing variability attributed to treatments to variability attributed to random error. In many experiments, a considerable amount of the variability attributed to random error is actually due to large-scale soil variability that cannot be accounted for by blocking. This variability can, in part, be accounted for by a technique called nearest neighbor analysis, thus reducing the amount of variability attributed to random error; variability attributed to treatments is then larger in comparison, and the statistical significance of treatment effects is increased. Four experiments with fall N treatments on winter wheat (*Triticum aestivum* L.) were analyzed using analysis of variance (ANOVA). According to this analysis, treatment had no significant effect on yield in any of the four experiments. After nearest neighbor analysis was used to remove spatial yield variability from the random error term, ANOVA revealed statistically significant treatment effects in two of the four experiments. Accounting for spatial variability is a practical way to increase the power of ANOVA and accompanying mean separation techniques when analyzing data from replicated field plot experiments.

INTRODUCTION

It has been recognized for a long time that soil spatial variability has a confounding influence on attempts to determine treatment effects using replicated field trials (Mercer and Hall, 1911). While replication is in itself an attempt to account for the existence of soil spatial variability, it is a crude technique given the complex patterns of spatial variability that exist (cf. data from Mercer and Hall (1911) as presented by Ripley (1981), p. 84). Uniformity trials have shown that in many fields there is no way to lay out blocks that will successfully account for spatial yield variability (Mendez, 1970). Many contemporary agricultural field trials examine treatments that are generally expected to have relatively modest effects on yield, e.g. varieties, tillage, pesticides, growth regulators, nitrification inhibitors, and row spacing. Spatial yield variability, if attributed to random error, can mask true treatment effects.

Papadakis (1937) was the first to suggest a statistical approach to this problem. He proposed to use yield residuals from neighboring plots as covariates in the analysis of treatment effect on yield; in effect, a cluster of relatively high-yielding plots is postulated to be the result of a region of relatively favorable soil properties, and a cluster of low-yielding plots the result of unfavorable soil properties. This work substantially forms the basis of what is now termed nearest neighbor analysis. The idea was further discussed and developed by Bartlett (1938, 1978). Wilkinson et al. (1983) showed that the procedure is statistically conservative except when applied iteratively (as has been suggested by several authors). While the nearest neighbor procedure is relatively simple, it appears to have gained little acceptance or use by agricultural scientists in the U.S.

The objectives of this paper are:

1) to illustrate the spatial yield variability that was observed in a set of four field experiments with winter wheat; and
2) to evaluate the statistical significance of treatment effects in these experiments with and without nearest neighbor analysis.

MATERIALS AND METHODS

Data used in the comparisons presented were obtained from a set of four experiments with ten fall N treatments applied to winter wheat in the Coastal Plain of Virginia. Auger borings were used to verify apparent uniformity of soil characteristics as part of the site-selection process. Treatments were sources and times of application of fall N; a uniform rate of urea-ammonium nitrate solution was top-dressed on all plots in the spring. Individual plot yields were measured using a plot combine and corrected to standard moisture content.

Yield residuals for each plot were calculated as the difference between individual plot yield and treatment mean yield for the treatment applied to that plot. Yield residuals were marked on each plot in a map of the experiment, and the map was visually examined for clusters of large positive or large negative residuals. Any distinctive pattern in the residuals was noted.

The nearest neighbor value (estimate of position effect) for each plot was calculated as the mean of the yield residuals of neighboring plots (Papadakis, 1937). Yield residuals and nearest neighbor values were calculated simultaneously using a PC-SAS (SAS Institute, P.O. Box 8000, Cary, NC 27511) macro provided by Dr. David Marx of the University of Nebraska. All immediately adjacent neighboring plots (sides and corners) were used in the calculation of one set of nearest neighbor values; for experiments where some distinctive pattern had been noted in the map of residuals, restricted sets of neighbors suggested by this pattern were used in calculating alternate sets of nearest neighbor values for that experiment. For example, if large positive and large negative residuals tended to appear in "vertical" (as viewed on paper) streaks in the map of residuals, then only "vertically" adjacent plots were used in calculating a set of nearest neighbor values.

Yield data from the experiments were then analyzed for treatment effect on yield using both traditional analysis of variance (ANOVA) and analysis of covariance (ANACOVA) with nearest neighbor estimates of position effect as the covariates. When a set of covariates based on a restricted set of neighbors was suggested by patterns observed in the map of residuals, ANACOVA was run both with this set of covariates and with the set calculated using all eight immediately adjacent neighbors; the set of covariates with the highest F value was then adopted. Computations for ANOVA and ANACOVA were performed on SAS using PROC ANOVA and PROC GLM, respectively; LSMEANS from PROC GLM were used as ANACOVA-corrected estimates of treatment mean yield (SAS Institute, 1985).

RESULTS AND DISCUSSION

Yield residual maps for the four experimental locations are shown in Figure 11. Clusters of large positive and large negative residuals occur at all four locations, violating the assumption of randomness of residuals made by ANOVA. There are an immense number of spatially variable soil properties that might be causing this spatial yield variability. If, in a particular experiment, there is an indication of what the controlling soil property might be, then this property should be measured in each plot and used as a covariate directly (cf. Samra et al., 1992). This is the most straightforward way to deal with spatial yield variability in field experiments. However, in many cases, there is little indication of which spatially variable soil properties will substantially influence yield.

When yield data were analyzed using traditional ANOVA, treatment did not appear to have a significant effect on yield at any of the four experimental locations (Table 12). Blocking effect was significant at all four locations and is included in these traditional ANOVA analyses. Incorporating nearest neighbor values as estimates of position effect substantially increased model R^2, decreased coefficient of variation, and decreased the p-value for treatment effect at all four locations (Table 12). Decreased p-values indicate increased statistical power due to a reduction in the amount of yield variability attributed to random error. Block effect was not significant at any location when nearest neighbor values were considered. At locations one and three, treatment effects on yield were significant when we accounted for position effects using nearest neighbor analysis. Error terms inflated by spatial yield variability masked these

location 1

0.0	-0.3	-0.3	-0.4	-0.3
0.2	0.2	-0.2	-0.7	-0.2
0.0	-0.1	0.4	-0.6	-0.2
-0.2	0.3	0.4	0.0	0.1
0.1	-0.2	0.0	-0.6	-0.3
--	0.3	0.1	-0.4	-0.6
0.3	0.6	0.3	-0.3	0.4
0.8	0.8	0.6	-0.2	0.0

location 2

0.4	0.1	0.6	-0.4	-0.4
0.2	0.5	0.8	0.2	0.0
0.4	-0.1	0.4	-0.2	0.1
0.1	0.1	0.5	0.2	0.1
0.4	0.0	0.0	-0.3	-0.9
0.0	-0.1	-0.3	-0.4	-0.6
0.0	0.0	0.3	-0.5	-0.4
-0.1	0.1	0.2	-0.4	-0.6

location 3

0.5	-0.3	-0.5	-0.3	-0.8
0.4	-0.3	-0.6	-0.3	-0.6
0.3	-0.1	-0.3	-0.8	-0.6
1.0	0.0	-0.2	-0.2	-0.7
1.1	0.4	-0.4	-0.3	-0.5
0.3	0.3	0.2	-0.4	-0.4
0.7	0.2	0.6	-0.3	0.3
1.0	0.4	0.9	0.0	0.2

location 4

1.5	1.1	1.5	0.9	0.5
0.4	-0.6	-0.5	0.1	0.2
-0.1	-0.8	-1.2	0.1	-0.4
0.1	0.2	-1.1	0.3	-0.3
0.2	-0.3	-0.8	-0.5	0.0
0.3	0.3	-0.1	-0.4	-0.4
0.3	0.4	-0.9	-0.8	0.4
-0.4	-0.6	0.1	0.5	0.6

Figure 11. Yield residuals (difference between the individual plot yield and its treatment average in Mg ha^{-1}) plotted on field maps for the four experimental locations. Each rectangle represents an individual plot. A replication consists of two rows of plots. Plots with residuals greater than 0.3 Mg ha^{-1} are shaded; plots with residuals less than -0.3 Mg ha^{-1} are diagonally striped.

Table 12. Statistical analysis of treatment effects on wheat yield with and without nearest neighbor analysis to account for spatial yield variability.

location	statistical procedure					
	traditional ANOVA			nearest neighbor ANACOVA		
	R^2	coefficient of variation	p for treatment	R^2	coefficient of variation	p for treatment
1	0.46	7.5	0.35	0.67	5.7	0.05
2	0.29	10.3	0.98	0.58	7.7	0.39
3	0.35	12.8	0.78	0.88	5.4	0.002
4	0.39	13.8	0.54	0.51	11.9	0.24

treatment effects in normal ANOVA.

Nearest neighbor analysis was spectacularly successful in accounting for yield variability at location three, where it increased R^2 from 0.35 to 0.88; this is due to the large-scale spatial variability implied by the extreme segregation of yield residuals observed at that location (Figure 11). At the other locations, where segregation patterns observed in the residuals are smaller and more complex, yield variability accounted for by nearest neighbor analysis is more modest, but still substantially greater than that accounted for by blocking.

Nearest neighbor analysis not only increased ANOVA treatment significance at locations one and three, it also considerably decreased the values calculated for Fisher's least significant difference at those locations (Table 13). Treatment 9 had the highest estimated yield and was significantly higher yielding than treatments 1, 2, and 8 at both locations. At location three, yield for treatment 9 was significantly higher than for all other treatments. Treatment 9 apparently had a similar beneficial physiological effect on the crop at both locations. While the yields observed for different treatments at experimental locations two and four were not statistically different, neither were they inconsistent with the conclusion that treatment 9 may have had a beneficial effect on wheat yield at those locations.

Table 13. Treatment mean wheat yields with and without nearest neighbor ANACOVA.

	mean yield at location:				mean yield with nearest neighbor ANACOVA at location:			
treatment	1	2	3	4	1	2	3	4
	----------------------	----------------------	----------------------	----------------------Mg	ha^{-1}----------------------	----------------------	----------------------	----------------------
1	4.56	3.56	3.98	4.39	4.69	3.50	4.15	4.23
2	4.88	3.74	4.23	4.75	4.77	3.59	3.99	4.99
3	5.20	3.80	4.04	4.65	5.17	3.88	4.10	4.48
4	4.97	3.87	4.30	4.91	5.08	3.98	4.35	4.73
5	5.10	3.69	4.35	5.07	5.29	3.77	4.18	4.75
6	5.16	3.76	4.07	4.29	5.21	3.82	4.13	4.45
7	5.10	3.68	4.30	4.69	5.00	3.53	4.26	4.83
8	5.06	3.76	4.50	5.27	4.91	3.77	4.34	5.21
9	5.27	3.57	4.67	4.89	5.32	3.73	4.85	5.17
10	5.19	3.74	4.18	5.13	5.10	3.60	4.28	5.21
LSD 0.1†	0.46	0.46	0.66	0.80	0.37	0.35	0.28	0.70
ANOVA significance‡	NS	NS	NS	NS	*	NS	**	NS

†Fisher's least significant difference with alpha=0.1

‡*, ** = significant at alpha=.05 and .01, respectively; NS = not significant

CONCLUSIONS

Considerable position effect on yield occurred at all four experimental locations in this study, judging from the observed patterns of yield residuals. This suggests that such position effects are common.

Nearest neighbor analysis was much superior to blocking in accounting for the observed position effects. No significant treatment effects were detected at any of the four locations using traditional ANOVA with blocking; using nearest neighbor analysis unmasked significant effects at two of the four locations. The agreement between the conclusions from these two locations lends additional support to the validity of those conclusions and thus to the value of using the nearest neighbor technique. Statistical power was increased by the use of this technique.

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Chapter VI

Summary and conclusions

Soil mineral N measurements taken from November through March in soils cropped to winter wheat in the Coastal Plain of Virginia revealed considerable downward movement of soil mineral N within the crop rooting zone (considered to be 1.2 m for purposes of this discussion) and loss of mineral N from the rooting zone. This finding confirms that leaching of mineral N is an important mechanism for loss of N from the crop rooting zone and, presumably, transfer of N from agricultural row cropping systems to ground and surface waters.

Agricultural researchers have, in the past, generally assumed that residual soil N makes no significant contribution to crop N needs in humid climates. This assumption is implicit in the lack of test-based N rate recommendations such as are universally used for all other major crop nutrients. We found a very broad range of soil mineral N levels at different experimental locations in March (when rapid N uptake by the winter wheat crop begins in our climate), due both to variable soil mineral N at planting in the fall and variable rates of loss through the winter. The mineral N content of the rooting zone was strongly correlated with yield gain due to fertilizer N application, indicating that residual mineral N can make a substantial contribution to the N needs of winter wheat in humid climates. This finding is in agreement with research from humid regions of Europe, and demonstrates that there is a pressing need for test-based N rate recommendations for winter wheat (probably for other crops as well) in humid regions of the U.S.

The tissue test-based N rate recommendation system developed by Baethgen and Alley (1989) is the most promising approach in the literature for making field-specific N rate recommendations for wheat, but it had several weaknesses that have been addressed by the research described in this dissertation. Their research utilized a single wheat variety and a small number of soil types in eight experiments in which all cultural operations were performed by researchers. Results from thirty-nine experiments encompassing a broad and representative range of wheat varieties and soil types, and in which all cultural practices other than N fertilizer application were performed by farmers, solidly establish that the recommendation system that they proposed will work in farmer fields. This recommendation system was demonstrated to be both agronomically and environmentally beneficial, increasing estimated profit as well as fertilizer use efficiency. Its effectiveness when organic N sources have been utilized has not been determined and should be regarded as questionable.

Another weakness of the tissue test-based recommendation system is that it requires splitting of spring N fertilizer applications, but provides a field-specific rate recommendation only for the second spring N application. Starting from the hypothesis that the first spring N application functions to stimulate development of additional tillers when tiller density is sub-optimal, we measured optimum rate for the first spring N application in nineteen experiments and showed that it was strongly related to tiller density measured in the same field. This relationship can be used to predict optimum N rate for the first spring N application, and complements the existing tissue test system to provide field-specific rate recommendations for both spring N applications. For reasons discussed in Chapter IV, this system may overestimate the need for early N in late-planted wheat.

Some farmers, however, are unwilling to split spring N applications, either on all or on part of their wheat crop; they cannot use the recommendations from the system described above. Optimum N rate for a single early-spring N application was measured and shown to be correlated to soil nitrate to a 0.9 meter depth. Comparison of recommendations derived from this relationship with recommendations for a single mid-spring N application based on tissue test results showed that, overall, the mid-spring N application was agronomically superior. In fields with low tiller densities, however, a single early-spring application based on a soil nitrate test was preferable. When a single spring N application is to be made, tiller density can be used as a criterion to decide whether to apply N in early or mid-spring; early-spring N application rates can be based on a soil nitrate test, while mid-spring N application rates can be based on a tissue test.

The three field-specific tests described above complement each other to form a flexible N rate recommendation system for winter wheat in Virginia. These tests are probably fairly valid for the mid-Atlantic region as a whole. The concepts used in their development could be applied to adapt them to humid or irrigated regions to which they do not transfer directly, and the powerful basic concept of measuring optimum N rate and regressing it against predictor variables measured in the same field could be applied to the development of field-specific N rate recommendations for other humid-region crops. Such recommendation systems are needed to improve the efficiency and reduce the environmental impact of crop production systems.

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APPENDIX A

SUPPLEMENTAL INFORMATION ON EXPERIMENTAL LOCATIONS

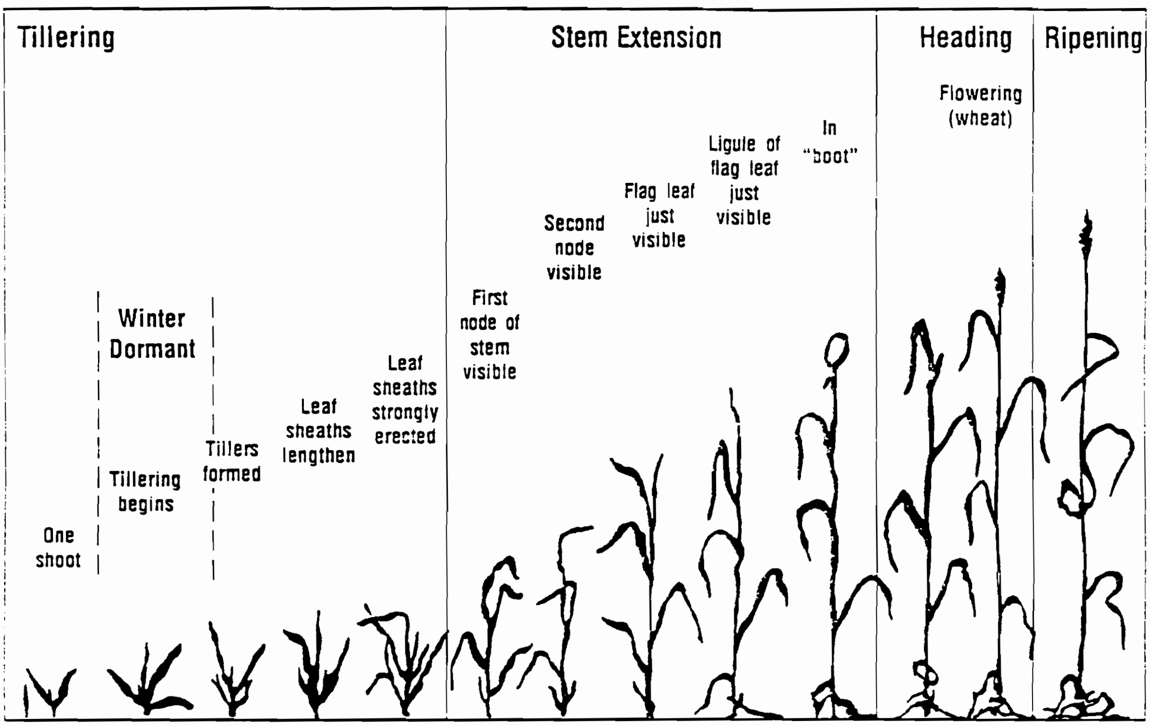
Supplemental information on experimental locations

Location number	County	Cooperating farmer	Farm name
1	Prince George	Courtney Price	Brandon Plantation
2	Caroline	Johnny Davis	Camden Farms
3	Westmoreland	Ferdifax Chandler	Chandler Farm
4	Middlesex	Ronnie Russell	Corbin Hall
5	Amelia	Juan Whittington	Featherstone Farm
6	Westmoreland	Bruce Beahm	Liberty Hall
7	Middlesex	David Taliaferro	Montague Farms
8	Hanover	Ralph Randolph	Randolph Farm
9	King & Queen	Latane Trice	Trice Farm
10	Richmond	Ferdifax Chandler	Chandler Farm
11	Westmoreland	Bruce Beahm	Liberty Hall
12	Essex	David Taliaferro	Montague Farms
13	Prince George	Courtney Price	Brandon Plantation
14	King & Queen	Philip Minor	Minor Farm
15	Prince George	Courtney Price	Brandon Plantation
16	New Kent	Ralph Randolph	Randolph Farm
17	King & Queen	David Taliaferro	Montague Farms
18	Middlesex	David Taliaferro	Montague Farms
19	Westmoreland	Bruce Beahm	Liberty Hall
20	Dinwiddie	Lewis Walker	Roslyn Farm
21	Accomack	Clarence Fitchett	Fitchett Farm
22	Northampton	Roger Byrnes	Byrnes Farm
23	Dinwiddie	Lewis Walker	Roslyn Farm
24	Prince George	Courtney Price	Brandon Plantation
25	New Kent	Ralph Randolph	Randolph Farm
26	Essex	David Taliaferro	Montague Farms
27	Westmoreland	Bruce Beahm	Liberty Hall
28	Accomack	Clarence Fitchett	Fitchett Farm
29	Northampton	Ralph Dodd	Dodd Farm
30	Prince George	Courtney Price	Brandon Plantation
31	Dinwiddie	Lewis Walker	Roslyn Farm
32	Hanover	Ralph Randolph	Randolph Farm
33	Middlesex	David Taliaferro	Montague Farms
34	Middlesex	David Taliaferro	Montague Farms
35	Westmoreland	Bruce Beahm	Liberty Hall
36	Caroline	Johnny Davis	Camden Farms
37	Montgomery	none	Whitethorn Farm
38	Montgomery	none	Whitethorn Farm
39	Giles	none	Agronomy Research
40	Caroline	Johnny Davis	Camden Farms
41	New Kent	Ralph Randolph	Randolph Farm
42	Hanover	Ralph Randolph	Randolph Farm
43	Essex	Charles Otto	Otto Farm
44	Botetourt	James Justice, Jr.	Bluestone Farms
45	Pulaski	Al Smith	Neuhoff Farms

APPENDIX B

GROWTH STAGES IN WHEAT

Growth Stages in Wheat



Growth Stages According to Zadoks

10 20-29 30 31 32 37 39 45 50 58 75-100

Growth Stages According to Feekes

1 2 3 4 5 6 7 8 9 10 10.1 10.5 11

Growth Stages

Zadoks	Feekes	Description
10	1	First leaf through coleoptile
20	2	Main shoot only
25	3	Main shoot and five tillers
30	5	Erect stems
31	6	First node detectable in stem
37	8	Flag leaf just visible
39	9	Flag leaf ligule/collar just visible
45	10	Boot swollen
50	10.1	First spikelet of head visible
60	10.5	Flowering

APPENDIX C

TREATMENT MEAN YIELDS, TEST WEIGHTS, AND LODGING INDICES

Treatment mean yields, test weights, and lodging indices at location 1

treatment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	4.7	58.7	0.9
2	0	34	5.5	58.6	0.9
3	0	68	6.4	59.1	0.2
4	0	102	6.4	58.7	0.6
5	0	136	6.9	58.9	0.6
6	34	0	5.8	59.3	0.2
7	34	34	6.7	59.3	0.2
8	34	68	6.7	59.2	0.2
9	34	102	6.5	58.0	1.8
10	34	136	6.3	56.7	2.6
11	68	0	5.5	59.1	0.2
12	68	34	6.0	58.9	0.2
13	68	68	6.3	59.1	1.4
14	68	102	6.6	58.4	2.4
15	68	136	6.5	58.0	1.8
16	102	0	6.3	59.0	0.2
17	102	34	6.4	59.6	0.2
18	102	68	6.2	56.7	1.8
19	102	102	6.2	57.1	2.8
20	102	136	5.8	55.7	4.8

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 2

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.7	60.0	0.2
2	0	34	3.4	60.4	0.2
3	0	68	5.3	61.6	0.2
4	0	102	5.2	61.6	0.7
5	0	136	5.4	62.0	0.2
6	34	0	3.5	60.4	0.2
7	34	34	4.4	60.8	0.2
8	34	68	5.2	61.7	0.2
9	34	102	5.1	61.4	0.2
10	34	136	5.6	62.4	0.2
11	68	0	4.2	60.4	0.2
12	68	34	5.1	61.3	0.4
13	68	68	5.6	61.8	0.2
14	68	102	5.7	61.9	0.2
15	68	136	5.7	61.8	0.7
16	102	0	4.9	61.2	0.2
17	102	34	5.5	61.3	0.2
18	102	68	5.5	61.7	1.0
19	102	102	5.5	61.8	0.2
20	102	136	5.4	61.9	2.4

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 3

treat-ment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	3.6	57.6	0.2
2	0	34	3.9	57.3	0.2
3	0	68	5.2	58.1	0.2
4	0	102	5.2	58.4	0.2
5	0	136	6.2	59.7	0.2
6	34	0	3.9	58.0	0.2
7	34	34	4.2	57.8	0.2
8	34	68	5.4	58.6	0.2
9	34	102	5.5	59.3	0.2
10	34	136	5.9	59.7	0.6
11	68	0	5.4	58.8	0.2
12	68	34	5.4	58.8	0.2
13	68	68	5.6	59.4	0.2
14	68	102	5.1	58.3	1.0
15	68	136	6.0	59.2	1.8
16	102	0	5.2	58.4	0.4
17	102	34	5.5	59.2	0.2
18	102	68	5.5	59.0	0.6
19	102	102	5.8	58.8	0.4
20	102	136	5.6	59.0	0.9

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 4

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.9	58.5	0.2
2	0	34	4.3	58.4	0.2
3	0	68	5.3	58.5	0.2
4	0	102	5.6	58.8	0.2
5	0	136	5.6	58.3	0.2
6	34	0	4.8	58.5	0.2
7	34	34	5.4	58.6	0.2
8	34	68	5.8	58.2	0.4
9	34	102	5.7	58.9	0.2
10	34	136	5.7	58.4	0.6
11	68	0	4.7	58.4	0.2
12	68	34	5.5	58.3	0.2
13	68	68	6.3	58.6	0.2
14	68	102	6.3	58.5	0.2
15	68	136	6.1	58.6	0.9
16	102	0	5.7	58.8	0.2
17	102	34	5.7	58.5	0.2
18	102	68	6.0	58.9	0.6
19	102	102	5.7	58.2	2.2
20	102	136	5.6	58.0	0.6

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 5

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	4.0	58.1	0.2
2	0	34	5.1	58.6	0.2
3	0	68	5.7	59.2	0.2
4	0	102	5.9	59.3	0.2
5	0	136	6.4	59.6	0.2
6	34	0	5.0	58.4	0.2
7	34	34	5.4	58.3	0.2
8	34	68	5.7	58.9	0.2
9	34	102	6.6	59.6	0.2
10	34	136	7.0	59.6	0.2
11	68	0	5.2	58.6	0.2
12	68	34	5.7	58.7	0.2
13	68	68	6.2	59.0	0.2
14	68	102	6.8	59.6	0.2
15	68	136	6.7	59.6	0.2
16	102	0	5.6	58.8	0.2
17	102	34	6.2	59.0	0.2
18	102	68	6.5	59.4	0.2
19	102	102	6.6	59.5	0.2
20	102	136	6.4	59.2	0.2

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 6

treat-ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	3.0	58.4	0.2
2	0	34	4.2	59.0	0.2
3	0	68	4.9	59.3	0.2
4	0	102	5.6	59.7	0.2
5	0	136	6.4	60.6	0.4
6	34	0	4.4	58.7	0.2
7	34	34	5.1	59.2	0.2
8	34	68	6.2	59.6	0.2
9	34	102	6.2	60.3	0.2
10	34	136	6.3	60.8	0.5
11	68	0	4.4	59.0	0.2
12	68	34	5.5	59.5	0.2
13	68	68	6.5	60.2	0.2
14	68	102	6.4	60.4	0.2
15	68	136	6.3	60.6	0.4
16	102	0	5.7	59.7	0.2
17	102	34	6.3	60.1	0.2
18	102	68	6.4	60.4	0.6
19	102	102	5.9	60.1	3.0
20	102	136	6.7	60.4	1.3

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 7

treatment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	3.0	56.2	0.2
2	0	34	4.3	56.6	0.2
3	0	68	4.8	56.7	0.2
4	0	102	5.2	56.5	0.2
5	0	136	5.9	56.7	0.2
6	34	0	4.7	56.5	0.2
7	34	34	4.9	56.4	0.2
8	34	68	4.9	56.4	0.2
9	34	102	5.8	56.5	0.2
10	34	136	5.7	56.6	0.8
11	68	0	4.7	56.3	0.2
12	68	34	5.4	56.5	0.2
13	68	68	5.5	56.6	0.2
14	68	102	5.7	56.8	0.2
15	68	136	5.8	57.2	0.6
16	102	0	5.1	56.4	0.2
17	102	34	5.8	56.6	0.2
18	102	68	6.0	56.6	0.4
19	102	102	6.0	56.7	0.8
20	102	136	6.0	56.8	1.4

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 8

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	1.4	55.2	0.2
2	0	34	3.3	57.6	0.2
3	0	68	4.3	57.0	0.2
4	0	102	4.4	57.1	0.2
5	0	136	5.2	56.2	0.2
6	34	0	2.8	57.2	0.2
7	34	34	4.1	57.7	0.2
8	34	68	5.2	56.5	0.2
9	34	102	5.1	58.1	0.2
10	34	136	5.4	55.3	0.2
11	68	0	3.8	55.8	0.2
12	68	34	4.7	57.9	0.2
13	68	68	5.6	57.5	0.2
14	68	102	5.7	57.7	0.2
15	68	136	5.8	57.3	0.2
16	102	0	4.6	57.5	0.2
17	102	34	5.4	57.5	0.2
18	102	68	5.8	56.4	0.2
19	102	102	5.8	56.8	0.2
20	102	136	5.7	56.9	0.2

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 9

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	1.8	58.4	0.2
2	0	34	2.6	58.1	0.2
3	0	68	3.2	58.0	0.2
4	0	102	3.6	58.7	0.2
5	0	136	3.4	58.8	0.2
6	34	0	2.7	58.4	0.2
7	34	34	3.6	58.4	0.2
8	34	68	3.4	58.3	0.2
9	34	102	3.9	58.4	0.2
10	34	136	3.9	58.2	1.4
11	68	0	3.0	58.4	0.2
12	68	34	3.3	58.2	0.2
13	68	68	3.7	58.5	0.2
14	68	102	4.0	59.0	0.8
15	68	136	3.9	59.0	0.4
16	102	0	3.2	58.0	0.2
17	102	34	3.9	58.8	0.2
18	102	68	3.5	58.0	0.2
19	102	102	3.5	58.5	1.4
20	102	136	3.2	58.7	1.7

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 10

treat-ment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.5	57.1	0.2
2	0	34	3.0	57.8	0.2
3	0	68	3.9	58.4	0.2
4	0	102	4.6	58.4	0.2
5	0	136	4.6	56.4	0.2
6	34	0	3.1	57.3	0.2
7	34	34	3.9	58.1	0.2
8	34	68	4.4	56.3	0.2
9	34	102	4.4	57.5	0.2
10	34	136	4.4	56.9	0.2
11	68	0	4.1	58.2	0.2
12	68	34	4.6	58.0	0.2
13	68	68	4.8	58.4	0.2
14	68	102	4.5	56.8	0.2
15	68	136	4.3	56.4	0.2
16	102	0	4.2	55.7	0.2
17	102	34	4.7	58.0	0.2
18	102	68	4.6	56.5	0.2
19	102	102	4.4	55.6	0.2
20	102	136	4.2	56.0	0.2

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 11

treatment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.6	57.9	0.2
2	0	34	4.0	58.6	0.2
3	0	68	4.8	58.1	0.2
4	0	102	5.8	57.9	0.2
5	0	136	5.9	59.8	0.2
6	34	0	3.8	58.0	0.2
7	34	34	5.0	58.1	0.2
8	34	68	5.9	58.8	0.2
9	34	102	5.9	59.4	0.2
10	34	136	6.3	58.8	0.2
11	68	0	4.6	58.3	0.2
12	68	34	5.7	58.8	0.2
13	68	68	5.8	59.4	0.2
14	68	102	6.0	59.4	0.2
15	68	136	5.7	59.0	0.2
16	102	0	5.4	58.8	0.2
17	102	34	5.5	59.4	0.2
18	102	68	6.1	59.0	0.2
19	102	102	5.9	58.9	0.2
20	102	136	5.5	58.5	0.2

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 12

treat-ment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.8	55.5	0.2
2	0	34	4.6	55.6	0.2
3	0	68	5.5	56.2	0.4
4	0	102	5.3	57.0	0.4
5	0	136	5.8	56.7	2.4
6	34	0	3.5	53.8	0.2
7	34	34	5.7	54.2	0.2
8	34	68	6.1	54.9	0.6
9	34	102	5.7	56.2	0.4
10	34	136	5.5	56.2	3.8
11	68	0	4.6	55.8	0.2
12	68	34	6.1	55.8	0.2
13	68	68	6.1	56.2	1.6
14	68	102	5.8	56.1	2.8
15	68	136	5.5	55.5	4.3
16	102	0	5.8	55.7	0.2
17	102	34	5.8	55.0	1.1
18	102	68	5.6	55.3	2.1
19	102	102	5.1	55.8	2.4
20	102	136	4.8	55.6	5.4

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 13

treat- ment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	4.7	58.8	0.2
2	0	34	5.8	59.2	0.2
3	0	68	5.9	58.8	0.2
4	0	102	6.5	58.1	0.2
5	0	136	6.6	59.6	0.2
6	34	0	5.1	58.2	0.2
7	34	34	5.8	59.2	0.2
8	34	68	6.1	59.1	0.2
9	34	102	6.5	59.6	0.2
10	34	136	6.3	57.9	0.2
11	68	0	5.8	58.9	0.2
12	68	34	6.0	58.7	0.2
13	68	68	6.3	58.8	0.2
14	68	102	5.7	59.2	0.2
15	68	136	5.5	59.5	0.2
16	102	0	5.5	59.6	0.2
17	102	34	6.1	59.2	0.2
18	102	68	5.2	58.8	0.2
19	102	102	5.6	59.3	0.2
20	102	136	5.3	59.6	0.2

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 14

treat-ment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	0.9	57.8	0.2
2	0	34	2.2	57.2	0.2
3	0	68	2.5	56.2	0.2
4	0	102	2.8	56.1	0.2
5	0	136	2.4	56.0	0.2
6	34	0	1.9	57.4	0.2
7	34	34	2.4	56.8	0.2
8	34	68	3.0	56.2	0.2
9	34	102	2.8	56.0	0.2
10	34	136	2.2	55.3	0.2
11	68	0	2.6	57.3	0.2
12	68	34	2.8	56.8	0.2
13	68	68	3.0	56.2	0.2
14	68	102	2.7	55.6	0.2
15	68	136	2.2	55.0	0.2
16	102	0	2.4	56.4	0.2
17	102	34	2.7	56.2	0.2
18	102	68	2.6	55.5	0.2
19	102	102	2.1	55.1	0.2
20	102	136	2.0	54.1	0.2

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 15

treat-ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	5.4	61.4	0.2
2	0	34	6.2	62.5	0.2
3	0	68	6.1	62.3	0.2
4	0	102	7.1	61.8	1.1
5	0	136	6.8	61.7	1.1
6	34	0	4.9	62.1	0.2
7	34	34	6.2	62.5	0.8
8	34	68	6.4	62.3	0.7
9	34	102	6.9	61.4	0.5
10	34	136	6.5	60.6	1.4
11	68	0	6.5	62.2	0.5
12	68	34	6.4	61.4	1.0
13	68	68	6.8	62.2	1.8
14	68	102	6.2	58.8	3.9
15	68	136	6.3	60.6	3.7
16	102	0	6.6	61.4	0.8
17	102	34	6.6	62.0	0.2
18	102	68	6.4	60.6	3.0
19	102	102	5.8	60.6	1.9
20	102	136	6.4	60.1	4.8

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 16

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	3.1	57.7	0.2
2	0	34	3.4	56.4	0.2
3	0	68	4.9	57.1	0.2
4	0	102	5.5	56.6	0.2
5	0	136	5.6	56.0	0.2
6	34	0	3.6	57.2	0.2
7	34	34	4.4	57.6	0.2
8	34	68	5.6	55.9	0.2
9	34	102	5.6	56.6	0.2
10	34	136	5.8	56.4	0.4
11	68	0	4.2	56.4	0.2
12	68	34	4.9	57.5	0.2
13	68	68	5.2	57.2	0.4
14	68	102	5.8	53.5	1.0
15	68	136	5.3	53.6	1.0
16	102	0	4.8	57.1	0.2
17	102	34	5.6	55.9	0.4
18	102	68	5.1	56.6	0.5
19	102	102	5.4	55.2	0.9
20	102	136	5.7	55.2	2.4

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 17

treat-ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.3	53.8	0.2
2	0	34	2.1	53.6	0.2
3	0	68	2.7	51.9	0.6
4	0	102	2.6	47.1	1.0
5	0	136	2.6	46.3	1.0
6	34	0	2.6	54.6	0.2
7	34	34	2.7	50.6	0.6
8	34	68	2.1	46.9	4.0
9	34	102	2.3	47.2	5.1
10	34	136	2.1	43.8	4.3
11	68	0	2.2	53.3	0.9
12	68	34	2.4	50.2	2.5
13	68	68	2.2	46.2	5.4
14	68	102	2.1	44.5	4.1
15	68	136	2.1	45.9	5.8
16	102	0	2.6	51.9	0.9
17	102	34	2.6	50.1	2.1
18	102	68	2.1	49.0	4.8
19	102	102	1.9	46.0	4.4
20	102	136	1.9	45.1	5.2

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 18

treat-ment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	1.7	56.2	0.2
2	0	34	2.5	54.6	0.2
3	0	68	3.2	56.7	0.2
4	0	102	3.6	57.2	0.2
5	0	136	3.5	55.1	0.4
6	34	0	2.5	55.0	0.2
7	34	34	3.2	54.7	0.2
8	34	68	3.7	56.2	0.2
9	34	102	3.8	56.8	0.2
10	34	136	3.8	55.4	1.0
11	68	0	3.4	57.1	0.2
12	68	34	3.6	56.7	0.2
13	68	68	3.9	57.0	0.6
14	68	102	4.0	56.4	1.7
15	68	136	3.6	57.2	1.6
16	102	0	3.8	57.5	0.2
17	102	34	3.5	55.2	0.2
18	102	68	3.9	57.1	1.6
19	102	102	3.9	56.5	2.2
20	102	136	3.6	56.4	2.4

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 19

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.4	58.2	0.2
2	0	34	3.3	57.6	0.4
3	0	68	3.2	56.2	1.8
4	0	102	4.3	57.8	2.3
5	0	136	5.4	57.6	2.1
6	34	0	2.9	57.5	0.2
7	34	34	3.7	57.2	0.6
8	34	68	4.8	57.2	1.0
9	34	102	5.7	57.1	2.2
10	34	136	6.0	58.2	3.9
11	68	0	4.8	57.5	0.8
12	68	34	5.5	57.8	1.2
13	68	68	5.7	58.0	3.1
14	68	102	6.4	58.5	5.0
15	68	136	6.1	57.4	7.4
16	102	0	5.2	57.5	1.9
17	102	34	5.8	57.8	3.7
18	102	68	6.2	57.8	5.0
19	102	102	5.6	58.8	5.4
20	102	136	5.3	56.8	7.7

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 20

treat-ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.3	56.9	0.2
2	0	34	3.3	58.4	0.2
3	0	68	3.9	56.8	0.2
4	0	102	4.4	57.6	0.2
5	0	136	4.4	54.3	0.2
6	34	0	2.9	57.4	0.2
7	34	34	3.8	59.9	0.2
8	34	68	4.2	57.2	0.2
9	34	102	4.6	58.6	0.2
10	34	136	4.4	57.2	1.2
11	68	0	3.9	59.3	0.2
12	68	34	4.3	59.0	1.0
13	68	68	4.7	59.2	1.7
14	68	102	4.8	56.6	2.1
15	68	136	4.6	53.8	2.4
16	102	0	4.1	60.7	0.2
17	102	34	3.9	59.2	1.0
18	102	68	4.6	59.4	2.4
19	102	102	4.3	56.8	3.4
20	102	136	4.3	56.7	3.6

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 21

treatment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.5	58.4	0.2
2	0	56	4.5	57.9	0.2
3	0	112	5.2	57.6	0.2
4	0	168	6.0	58.0	1.0
5	28	0	3.7	58.2	0.2
6	28	56	5.0	57.8	0.2
7	28	112	5.8	58.3	0.4
8	28	168	6.5	57.8	4.0
9	56	0	4.4	58.1	0.2
10	56	56	5.9	58.2	1.0
11	56	112	5.7	58.4	0.7
12	56	168	6.3	58.1	5.0
13	112	0	5.5	58.2	0.2
14	112	56	6.4	58.1	3.4
15	112	112	6.2	58.2	3.9
16	112	168	6.0	57.1	5.2
17	168	0	6.1	58.2	0.2
18	168	56	6.2	58.3	3.6
19	168	112	6.3	58.2	4.1
20	168	168	6.2	56.8	6.8

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 22

treatment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	1.5	56.1	0.2
2	0	56	3.1	56.2	0.2
3	0	112	3.3	56.3	2.2
4	0	168	3.4	53.8	5.2
5	28	0	2.4	56.5	0.2
6	28	56	3.6	56.0	2.8
7	28	112	3.6	56.5	3.0
8	28	168	3.8	56.5	6.5
9	56	0	3.4	56.0	2.4
10	56	56	3.7	55.6	3.8
11	56	112	4.0	56.7	4.8
12	56	168	3.6	54.8	5.0
13	112	0	3.5	57.0	3.0
14	112	56	3.7	56.7	5.3
15	112	112	3.6	57.4	6.5
16	112	168	3.8	55.3	6.4
17	168	0	3.8	56.7	1.9
18	168	56	3.8	56.4	6.8
19	168	112	3.7	56.8	6.8
20	168	168	3.4	54.2	8.5

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 23

treat-ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.5	54.5	0.2
2	0	56	3.6	53.5	1.5
3	0	112	4.2	53.0	5.2
4	0	168	4.3	52.8	7.0
5	28	0	3.0	53.9	0.2
6	28	56	3.8	53.0	4.3
7	28	112	4.4	52.1	6.8
8	28	168	4.4	50.0	8.1
9	56	0	3.6	52.6	2.5
10	56	56	4.0	51.9	6.3
11	56	112	4.0	51.3	7.4
12	56	168	4.0	50.4	7.9
13	112	0	4.0	52.2	5.4
14	112	56	4.2	51.7	6.1
15	112	112	4.2	50.9	7.4
16	112	168	4.2	50.3	7.7
17	168	0	4.3	50.9	6.1
18	168	56	4.2	51.0	7.4
19	168	112	4.3	51.6	7.2
20	168	168	3.8	49.5	8.3

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 24

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	4.8	54.4	0.6
2	0	56	4.9	53.4	2.9
3	0	112	4.5	52.6	5.6
4	0	168	4.4	52.6	7.0
5	28	0	5.2	54.2	1.3
6	28	56	4.6	52.4	6.0
7	28	112	3.6	51.2	7.4
8	28	168	3.7	51.0	5.8
9	56	0	4.6	53.4	4.0
10	56	56	3.6	51.8	5.9
11	56	112	3.4	51.2	4.9
12	56	168	2.3	49.4	7.0
13	112	0	3.4	50.3	3.6
14	112	56	3.1	51.2	5.4
15	112	112	2.5	49.4	5.5
16	112	168	2.7	50.6	5.2
17	168	0	3.8	53.0	3.2
18	168	56	3.2	51.5	3.9
19	168	112	2.9	51.5	5.0
20	168	168	2.6	59.8	5.0

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 25

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	1.5	58.6	0.2
2	0	56	2.8	58.1	0.2
3	0	112	2.9	58.2	0.2
4	0	168	3.0	59.1	0.2
5	28	0	2.6	58.7	0.2
6	28	56	3.7	58.3	0.2
7	28	112	4.1	59.3	1.1
8	28	168	3.8	58.7	2.6
9	56	0	4.0	58.0	0.5
10	56	56	4.2	58.8	2.7
11	56	112	4.4	59.1	4.6
12	56	168	3.7	58.3	5.0
13	112	0	3.8	58.0	1.3
14	112	56	4.6	58.8	3.9
15	112	112	4.4	57.7	4.8
16	112	168	4.1	57.1	4.8
17	168	0	4.2	58.5	4.3
18	168	56	4.2	57.6	5.2
19	168	112	4.2	57.5	5.6
20	168	168	3.7	57.4	7.0

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 26

treatment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	4.4	55.8	0.2
2	0	56	4.7	51.0	8.1
3	0	112	4.6	51.3	8.1
4	0	168	4.6	48.8	8.6
5	28	0	4.9	53.9	0.9
6	28	56	5.0	51.6	6.9
7	28	112	4.2	58.7	8.6
8	28	168	3.8	48.6	9.0
9	56	0	5.0	53.3	6.0
10	56	56	4.6	51.0	9.0
11	56	112	3.8	47.4	9.0
12	56	168	3.4	48.3	9.0
13	112	0	4.9	51.3	7.9
14	112	56	4.4	50.3	9.0
15	112	112	4.0	48.3	8.6
16	112	168	3.4	47.0	7.6
17	168	0	4.4	48.9	8.6
18	168	56	3.6	49.2	9.0
19	168	112	3.1	45.1	9.0
20	168	168	3.4	44.7	9.0

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 27

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.4	59.0	0.2
2	0	56	4.3	59.8	0.2
3	0	112	4.5	59.2	0.2
4	0	168	5.8	60.8	0.2
5	28	0	3.1	58.8	0.2
6	28	56	4.6	59.9	0.2
7	28	112	5.3	60.3	0.2
8	28	168	5.9	60.4	1.5
9	56	0	4.2	58.9	0.2
10	56	56	5.0	60.4	0.2
11	56	112	5.2	60.8	1.0
12	56	168	5.3	60.1	2.7
13	112	0	5.0	60.1	0.2
14	112	56	5.4	60.8	0.5
15	112	112	4.8	60.2	3.1
16	112	168	4.5	58.2	3.6
17	168	0	5.2	60.7	1.0
18	168	56	4.5	59.4	3.6
19	168	112	5.2	60.0	3.7
20	168	168	4.6	58.3	4.6

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 28

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	3.1	60.4	1.9
2	0	56	4.6	60.9	2.9
3	0	112	5.7	60.3	4.3
4	0	168	6.0	61.2	5.8
5	28	0	3.5	61.8	0.2
6	28	56	4.4	61.8	3.4
7	28	112	5.6	61.9	4.5
8	28	168	5.9	61.2	5.8
9	56	0	4.0	60.6	3.0
10	56	56	5.0	61.3	3.6
11	56	112	5.4	61.5	5.0
12	56	168	5.9	60.4	6.5
13	112	0	4.4	61.5	2.4
14	112	56	5.2	62.3	4.7
15	112	112	5.7	62.3	5.8
16	112	168	5.6	59.2	7.2
17	168	0	5.2	61.9	3.2
18	168	56	5.4	61.9	5.2
19	168	112	5.5	61.2	6.5
20	168	168	5.4	59.0	7.2

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 29

treat-ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.9	59.9	0.2
2	0	56	3.6	57.8	0.2
3	0	112	4.2	58.0	0.2
4	0	168	4.1	56.8	1.8
5	28	0	3.1	58.9	0.2
6	28	56	3.9	57.2	0.7
7	28	112	4.4	57.8	1.6
8	28	168	4.2	56.6	2.1
9	56	0	3.6	59.4	0.2
10	56	56	4.4	57.8	1.6
11	56	112	5.0	58.0	1.6
12	56	168	5.0	57.6	2.9
13	112	0	4.1	59.3	0.2
14	112	56	4.8	59.4	1.9
15	112	112	5.3	59.0	2.6
16	112	168	4.8	56.2	3.9
17	168	0	4.8	58.5	2.8
18	168	56	5.2	58.3	3.7
19	168	112	5.2	58.5	4.0
20	168	168	4.3	56.0	5.4

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 30

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	6.0	59.8	0.2
2	0	56	6.0	60.2	3.0
3	0	112	5.9	58.7	5.3
4	0	168	6.0	59.1	6.4
5	28	0	6.2	60.2	0.8
6	28	56	5.9	59.4	4.5
7	28	112	5.6	60.2	5.7
8	28	168	5.4	58.4	5.8
9	56	0	6.2	60.2	1.2
10	56	56	5.8	60.6	3.5
11	56	112	5.8	59.4	5.4
12	56	168	5.6	58.8	6.4
13	112	0	5.7	59.3	4.3
14	112	56	5.6	60.6	5.9
15	112	112	5.2	59.4	5.6
16	112	168	5.6	59.0	5.9
17	168	0	5.6	59.8	4.8
18	168	56	5.4	59.6	5.2
19	168	112	5.6	59.4	5.8
20	168	168	5.6	59.2	5.6

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 31

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	3.1	60.0	0.2
2	0	56	4.0	58.0	0.2
3	0	112	4.6	58.2	0.8
4	0	168	5.3	57.7	0.5
5	28	0	3.2	58.4	0.4
6	28	56	4.8	57.1	0.2
7	28	112	5.3	58.5	0.6
8	28	168	5.3	57.5	0.6
9	56	0	3.7	59.7	0.2
10	56	56	4.9	58.1	0.2
11	56	112	5.4	58.4	0.9
12	56	168	5.6	58.1	3.1
13	112	0	4.8	59.2	0.4
14	112	56	5.2	59.6	0.6
15	112	112	5.4	58.8	2.2
16	112	168	5.4	56.4	4.5
17	168	0	5.3	58.3	0.4
18	168	56	5.4	58.6	3.2
19	168	112	5.5	59.1	4.6
20	168	168	5.4	56.2	5.0

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 32

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	5.5	60.4	0.2
2	0	56	6.0	59.2	0.2
3	0	112	5.6	56.2	0.2
4	0	168	5.6	56.4	0.2
5	28	0	6.0	59.3	0.2
6	28	56	6.0	58.6	0.2
7	28	112	6.0	56.6	0.2
8	28	168	5.3	54.8	0.2
9	56	0	6.0	60.4	0.2
10	56	56	5.9	58.9	0.2
11	56	112	6.0	57.4	0.2
12	56	168	5.4	54.5	0.2
13	112	0	5.4	58.9	1.2
14	112	56	5.3	56.8	2.0
15	112	112	5.1	55.6	1.5
16	112	168	4.9	53.4	2.5
17	168	0	5.9	58.6	0.4
18	168	56	5.4	56.0	1.7
19	168	112	5.0	54.9	2.3
20	168	168	4.8	51.4	2.4

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 33

treat-ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	3.6	59.3	0.2
2	0	56	5.4	59.8	0.2
3	0	112	5.6	60.7	0.2
4	0	168	6.1	61.0	0.3
5	28	0	4.3	59.2	0.2
6	28	56	5.8	60.7	0.2
7	28	112	6.1	60.6	0.2
8	28	168	6.4	60.3	0.4
9	56	0	5.6	60.3	0.2
10	56	56	6.0	60.2	0.2
11	56	112	6.0	60.8	1.2
12	56	168	5.8	60.6	1.6
13	112	0	5.9	61.0	0.3
14	112	56	6.0	60.7	3.0
15	112	112	6.2	60.8	3.2
16	112	168	5.7	60.8	4.0
17	168	0	5.6	61.0	0.8
18	168	56	5.5	59.8	5.2
19	168	112	5.5	58.9	7.3
20	168	168	5.2	59.5	5.3

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 34

treat-ment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.0	60.0	0.2
2	0	56	3.6	59.2	0.2
3	0	112	4.5	58.9	0.2
4	0	168	4.8	58.1	0.2
5	28	0	2.9	60.2	0.2
6	28	56	4.3	60.2	0.2
7	28	112	4.7	59.8	0.2
8	28	168	4.9	59.3	2.8
9	56	0	3.5	60.4	0.2
10	56	56	4.4	60.0	0.2
11	56	112	5.1	60.9	0.2
12	56	168	5.2	59.0	7.6
13	112	0	4.2	59.8	0.2
14	112	56	5.0	60.7	1.8
15	112	112	4.4	60.3	2.0
16	112	168	4.6	58.8	9.0
17	168	0	5.1	60.8	2.8
18	168	56	4.6	59.2	6.4
19	168	112	4.4	56.5	9.0
20	168	168	4.7	58.5	8.8

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 35

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.4	60.4	0.2
2	0	56	4.3	62.0	0.2
3	0	112	4.8	62.4	0.2
4	0	168	5.6	62.5	0.2
5	28	0	2.9	60.5	0.2
6	28	56	4.5	61.8	0.2
7	28	112	5.0	62.7	0.2
8	28	168	5.4	62.6	0.2
9	56	0	3.2	61.1	0.2
10	56	56	4.9	62.5	0.2
11	56	112	5.1	62.6	0.2
12	56	168	5.4	62.0	0.2
13	112	0	4.0	61.3	0.2
14	112	56	4.8	62.2	0.2
15	112	112	5.2	62.2	0.2
16	112	168	5.1	62.1	0.2
17	168	0	4.6	62.9	0.2
18	168	56	5.0	62.4	0.2
19	168	112	4.7	61.2	0.2
20	168	168	4.6	61.3	0.2

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 36

treat-ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	5.9	61.1	0.2
2	0	56	6.3	61.8	0.6
3	0	112	6.2	61.5	1.3
4	0	168	6.4	61.2	2.3
5	28	0	5.8	61.7	1.3
6	28	56	6.2	61.5	2.9
7	28	112	6.0	61.9	2.1
8	28	168	6.2	59.8	4.0
9	56	0	6.1	59.5	0.4
10	56	56	6.2	60.5	4.1
11	56	112	6.0	60.8	3.4
12	56	168	6.0	59.4	4.9
13	112	0	6.2	60.1	3.0
14	112	56	6.2	59.2	2.5
15	112	112	5.8	59.0	4.8
16	112	168	5.8	60.3	4.6
17	168	0	5.3	60.1	3.9
18	168	56	5.8	59.7	4.3
19	168	112	5.3	59.6	5.3
20	168	168	5.6	58.4	4.8

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 37

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	5.7	59.4	0.2
2	0	56	6.3	60.5	1.3
3	0	112	6.6	60.6	3.8
4	0	168	6.3	59.7	4.0
5	28	0	6.3	60.1	2.2
6	28	56	6.2	59.8	3.2
7	28	112	6.4	60.5	4.4
8	28	168	6.3	58.8	5.6
9	56	0	6.3	60.1	2.4
10	56	56	6.5	60.4	5.0
11	56	112	6.4	59.3	4.8
12	56	168	6.0	59.2	5.8
13	112	0	6.2	60.2	4.0
14	112	56	5.3	59.3	4.9
15	112	112	6.4	58.5	5.8
16	112	168	5.4	59.4	5.5
17	168	0	6.2	60.3	4.9
18	168	56	5.6	59.5	5.5
19	168	112	5.3	59.0	5.9
20	168	168	5.6	58.9	5.6

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 38

treat- ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	6.4	60.0	0.3
2	0	56	7.2	61.0	1.7
3	0	112	7.6	59.9	4.6
4	0	168	6.7	60.0	4.9
5	28	0	6.8	60.4	1.3
6	28	56	7.1	60.9	1.4
7	28	112	6.6	60.6	4.2
8	28	168	6.6	59.0	6.5
9	56	0	6.8	61.3	2.0
10	56	56	6.9	60.3	3.8
11	56	112	6.8	60.4	4.3
12	56	168	6.6	58.8	7.1
13	112	0	6.7	61.1	3.4
14	112	56	5.8	59.6	7.0
15	112	112	6.2	59.9	5.9
16	112	168	6.1	59.6	6.3
17	168	0	6.4	59.6	7.0
18	168	56	6.2	59.4	7.1
19	168	112	5.2	59.6	6.7
20	168	168	5.6	59.4	6.8

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 39

treat-ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.9	60.9	0.2
2	0	56	5.3	59.7	0.2
3	0	112	4.7	57.5	0.2
4	0	168	7.0	60.9	0.2
5	28	0	3.4	60.6	0.2
6	28	56	5.2	58.9	0.2
7	28	112	6.0	59.4	0.2
8	28	168	6.8	58.8	0.5
9	56	0	4.5	59.8	0.2
10	56	56	6.2	59.6	0.2
11	56	112	7.1	60.0	0.3
12	56	168	5.8	56.7	0.6
13	112	0	5.8	58.6	0.3
14	112	56	6.2	59.0	0.4
15	112	112	6.0	59.2	2.3
16	112	168	5.7	58.7	3.5
17	168	0	6.6	58.0	0.4
18	168	56	5.8	58.2	3.3
19	168	112	6.2	58.6	4.7
20	168	168	4.8	54.5	4.0

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 40

treat-ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	1.3	60.8	0.2
2	0	34	2.7	61.6	0.2
3	0	68	3.0	60.7	0.2
4	0	102	3.8	61.6	0.2
5	0	136	3.5	61.6	0.2
6	34	0	2.3	61.6	0.2
7	34	34	3.8	61.8	0.2
8	34	68	4.0	61.1	0.2
9	34	102	4.4	61.8	0.2
10	34	136	4.1	61.6	0.2
11	68	0	3.4	61.3	0.2
12	68	34	3.6	62.0	0.2
13	68	68	4.2	62.2	0.2
14	68	102	4.5	62.0	0.2
15	68	136	3.4	61.8	0.2
16	102	0	3.6	61.6	0.2
17	102	34	4.3	61.5	0.2
18	102	68	4.2	61.6	0.2
19	102	102	4.2	60.8	0.2
20	102	136	3.8	59.9	0.2

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 41

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	5.5	61.5	0.4
2	0	34	4.8	61.7	0.8
3	0	68	4.8	61.9	1.8
4	0	102	4.7	61.6	1.4
5	0	136	5.1	61.3	3.2
6	34	0	5.1	61.6	0.4
7	34	34	5.8	62.6	0.9
8	34	68	4.5	61.8	2.0
9	34	102	4.5	61.8	2.9
10	34	136	3.6	61.3	2.4
11	68	0	5.3	62.0	2.8
12	68	34	4.3	62.7	3.4
13	68	68	4.5	61.3	4.6
14	68	102	4.2	62.0	3.9
15	68	136	3.2	59.4	3.2
16	102	0	4.4	61.6	1.8
17	102	34	4.0	60.5	3.0
18	102	68	3.5	60.6	3.6
19	102	102	3.4	59.5	2.6
20	102	136	3.2	58.3	2.7

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 42

treat-ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	3.8	60.0	0.2
2	0	34	4.3	60.9	0.2
3	0	68	5.1	59.0	0.2
4	0	102	5.1	59.6	0.2
5	0	136	5.7	61.1	0.2
6	34	0	4.4	58.4	0.2
7	34	34	4.7	61.4	0.2
8	34	68	5.5	58.8	0.2
9	34	102	5.9	57.6	0.2
10	34	136	5.7	59.6	0.2
11	68	0	5.1	61.0	0.2
12	68	34	5.6	60.2	0.2
13	68	68	5.5	60.3	0.2
14	68	102	5.9	58.4	0.2
15	68	136	5.7	59.1	0.2
16	102	0	5.6	60.7	0.2
17	102	34	5.3	58.2	0.2
18	102	68	5.6	60.5	0.2
19	102	102	5.3	59.2	0.2
20	102	136	5.4	59.1	0.2

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 43

treatment number	N rate at GS 25†	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	3.2	56.2	0.2
2	0	34	4.1	56.4	0.2
3	0	68	5.1	56.9	0.2
4	0	102	5.5	57.3	1.2
5	0	136	5.5	57.7	5.1
6	34	0	4.2	56.3	0.2
7	34	34	4.8	56.4	0.4
8	34	68	6.1	56.9	1.8
9	34	102	5.7	58.1	4.4
10	34	136	6.1	57.5	5.4
11	68	0	4.8	56.4	0.2
12	68	34	5.4	56.8	1.6
13	68	68	6.2	55.9	4.2
14	68	102	5.2	57.0	5.7
15	68	136	5.2	56.7	6.3
16	102	0	5.1	56.7	0.2
17	102	34	5.5	57.0	3.4
18	102	68	5.6	55.8	5.0
19	102	102	5.5	56.8	7.2
20	102	136	5.5	56.4	6.8

†GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 44

treat-ment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	3.1	52.2	0.2
2	0	34	2.7	52.8	9.0
3	0	68	2.8	52.6	9.0
4	0	102	3.0	52.2	9.0
5	0	136	2.8	52.2	9.0
6	34	0	3.2	54.4	9.0
7	34	34	2.8	50.0	9.0
8	34	68	2.8	53.3	9.0
9	34	102	2.8	53.2	9.0
10	34	136	3.0	52.3	9.0
11	68	0	2.8	53.9	9.0
12	68	34	2.9	53.4	9.0
13	68	68	3.0	54.2	9.0
14	68	102	3.0	53.6	9.0
15	68	136	2.7	53.3	9.0
16	102	0	2.8	53.6	9.0
17	102	34	2.5	54.2	9.0
18	102	68	2.6	52.7	9.0
19	102	102	2.6	50.7	9.0
20	102	136	2.5	54.1	9.0

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

Treatment mean yields, test weights, and lodging indices at location 45

treatment number	N rate at GS 25[†]	N rate at GS 30	mean yield	mean test weight	mean lodging index
	kg N ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	lb bu^{-1}	
1	0	0	2.3	53.8	0.2
2	0	34	3.0	54.4	0.2
3	0	68	3.4	54.1	1.0
4	0	102	3.1	54.2	1.7
5	0	136	2.6	54.0	4.0
6	34	0	2.4	55.0	0.2
7	34	34	3.1	55.6	0.2
8	34	68	3.2	54.0	1.4
9	34	102	3.0	52.6	2.6
10	34	136	2.6	50.8	6.2
11	68	0	2.6	55.0	0.2
12	68	34	3.4	55.2	0.6
13	68	68	3.0	53.6	2.2
14	68	102	1.9	50.6	6.9
15	68	136	2.4	50.9	7.6
16	102	0	3.6	54.1	0.9
17	102	34	3.0	54.8	2.4
18	102	68	2.2	51.3	7.6
19	102	102	2.0	51.7	8.1
20	102	136	1.5	49.9	9.0

[†]GS 25 = Zadoks growth stage 25 (spring greenup)
GS 30 = Zadoks growth stage 30 (pre-jointing)

APPENDIX D

SOIL MINERAL N MEASURED IN LATE JANUARY/EARLY FEBRUARY

Soil mineral N measured in late January/early February

location	cumulative NO_3^--N to: 30 cm depth	60 cm depth	90 cm depth	120 cm depth	cumulative NH_4^+-N to: 30 cm depth	60 cm depth	90 cm depth	120 cm depth
	kg N ha^{-1}							
1	18	69	118	151	4	20	31	40
2	2	3	12	53	2	2	4	8
3	11	34	69	86	9	16	25	28
4	4	19	71	114	10	15	19	22
5	25	68	106	147	7	25	45	57
6	2	4	17	32	4	7	10	12
7	4	29	74	112	7	11	16	19
8	2	11	34	46	7	9	11	12
9	1	2	18	67	6	6	9	9
10	6	19	30	37	9	12	12	14
11	3	4	6	8	9	11	12	12
12	3	6	9	17	11	22	24	24
13	7	11	22	37	16	20	24	32
14	3	5	7	11	6	8	10	10
15	12	52	87	114	7	7	7	18
16	2	4	7	11	13	13	13	13
17	3	8	26	43	12	12	12	12
18	0	0	9	22	10	10	10	10
19	0	6	26	44	9	9	9	13
20	4	7	13	22	13	13	15	15
21	11	30	48	60	9	12	17	20
22	8	19	28	34	12	17	20	23
23	21	40	58	85	20	26	32	38
24	30	78	111	137	13	20	28	49
25	4	13	54	96	9	13	21	27
26	32	144	166	186	16	20	25	29
27	4	9	21	28	12	16	19	21
28	16	41	NA†	NA	44	119	NA	NA
29	3	12	25	NA	10	15	19	NA
30	26	94	126	NA	4	11	16	NA
31	20	95	NA	NA	59	NA	NA	NA
32	2	6	66	NA	3	9	14	NA
33‡	28	64	85	NA	13	20	25	NA
34‡	12	36	57	NA	7	15	19	NA
35‡	10	44	58	NA	7	13	17	NA
36‡	25	111	146	NA	9	16	19	NA
37 to 45	NA	NA	NA	NA	NA	NA	NA	NA

†NA = data not available
‡sampled in December

APPENDIX E

WHEAT TISSUE N CONTENT AT GROWTH STAGE 30

Wheat tissue N content at growth stage 30.

location	wheat tissue N content at GS 30 when N applied at GS 25 was (kg ha^{-1}): 0	34	68	102
	----------g N kg^{-1} tissue----------			
1	36.1	39.4	45.2	47.9
2	23.1	29.2	32.2	33.9
3	27.5	29.1	33.5	38.3
4	25.2	30.6	35.3	38.8
5	27.1	29.3	33.0	37.4
6	23.4	29.9	34.0	37.4
7	22.0	26.6	29.0	32.9
8	23.1	26.0	29.5	34.9
9	20.8	31.2	34.5	38.5
10	28.1	35.9	40.7	45.2
11	20.4	25.1	30.3	32.6
12	19.8	27.8	31.3	37.1
13	25.6	29.6	34.7	37.6
14	23.0	39.8	46.7	52.3
15	32.3	38.6	43.0	44.6
16	20.0	25.1	30.7	34.7
18	21.9	35.7	42.0	50.0
19	22.9	27.0	37.2	44.3
20	21.5	25.4	34.1	36.1
40-45	NA†	NA	NA	NA

†NA = data not available

Wheat tissue N content at growth stage 30.

location	wheat tissue N content at GS 30 when N applied at GS 25 was (kg ha^{-1}):				
	0	28	56	112	168
	---g N kg^{-1} tissue---				
21	22.7	35.3	41.0	53.8	54.6
22	25.2	36.0	52.4	56.5	58.1
23	29.2	36.5	50.3	57.2	61.1
24	33.9	40.8	46.9	56.9	59.8
25	17.6	22.3	29.0	41.6	50.8
26	33.3	36.2	45.0	53.3	61.2
27	21.3	27.4	35.2	49.6	57.8
28	26.3	28.7	33.5	35.1	42.0
29	25.8	29.3	31.0	37.1	46.0
30	39.3	41.1	40.2	49.2	49.1
31	23.5	29.2	30.9	41.3	44.1
32	29.7	28.8	34.2	46.7	53.5
33	22.4	24.7	30.5	32.4	39.2
34	23.6	26.1	30.1	38.3	46.0
35	19.7	21.6	24.3	28.3	36.6
36	29.8	31.2	32.7	36.6	38.9
37	28.0	29.5	31.8	35.9	38.3
38	29.1	30.7	31.3	35.7	42.1
39	17.8	20.5	23.7	30.9	35.7

APPENDIX F

TILLER DENSITY AND POTENTIALLY MINERALIZABLE N MEASUREMENTS

Tiller density and mineralizable soil N for experiments conducted in 1989-1990, 1990-1991, and 1991-1992.

location	tiller density	potentially mineralizable N
	tillers m^{-2}	kg ha^{-1}
1	1070	22
2	1530	23
3	970	24
4	810	29
5	970	66
6	1030	14
7	1280	29
8	790	25
9	880	19
10	670	46
11	830	34
12	750	39
13	950	76
14	370	24
15	900	55
16	990	47
17	860	NA
18	760	40
19	800	34
20	920	58
40	710	23
41	1080	94
42	1010	51
43	720	57
44	940	52
45	580	45

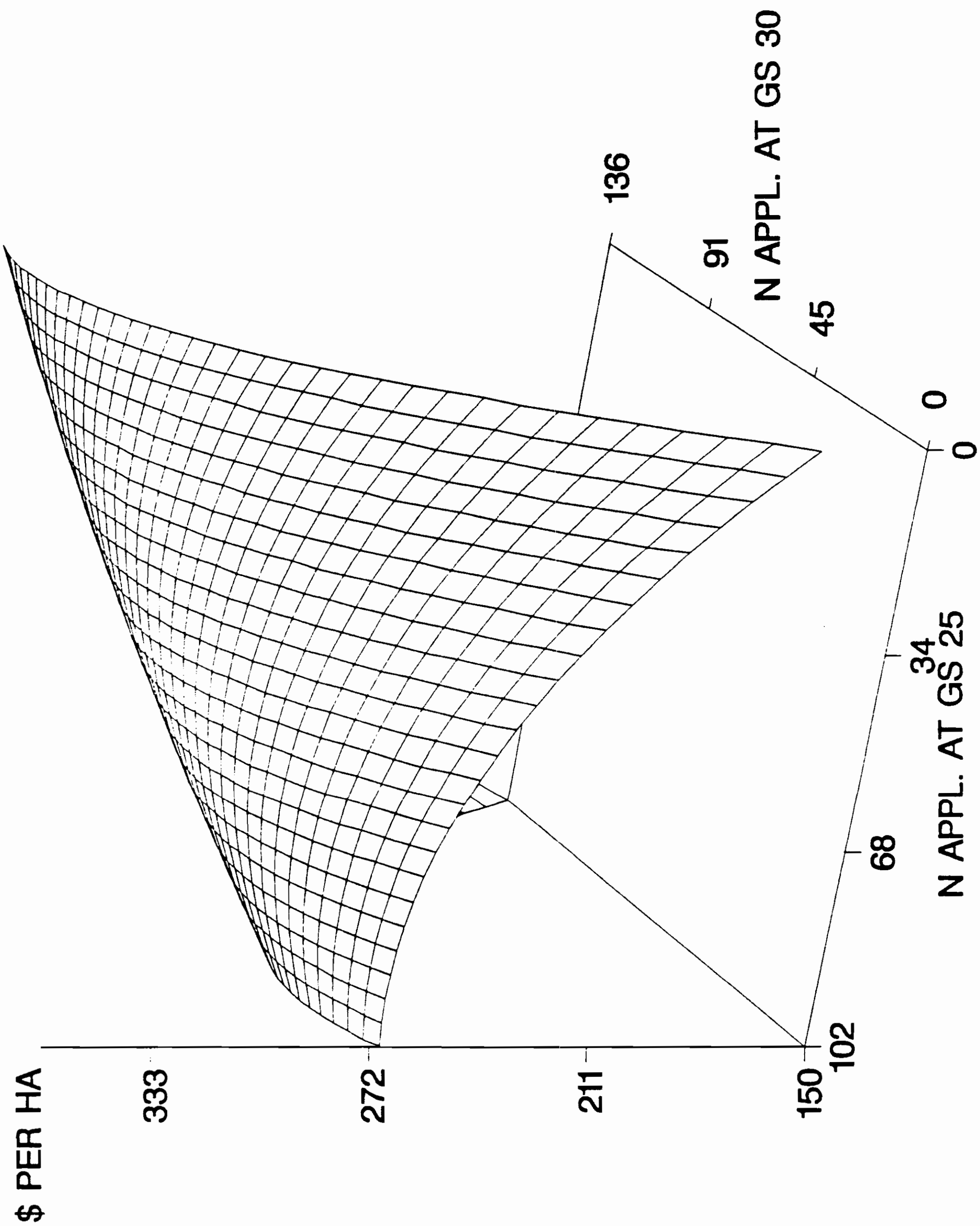
APPENDIX G

RESPONSE SURFACES DESCRIBING ESTIMATED PROFIT AS A FUNCTION OF N APPLICATION RATE AT GROWTH STAGE 25 AND AT GROWTH STAGE 30

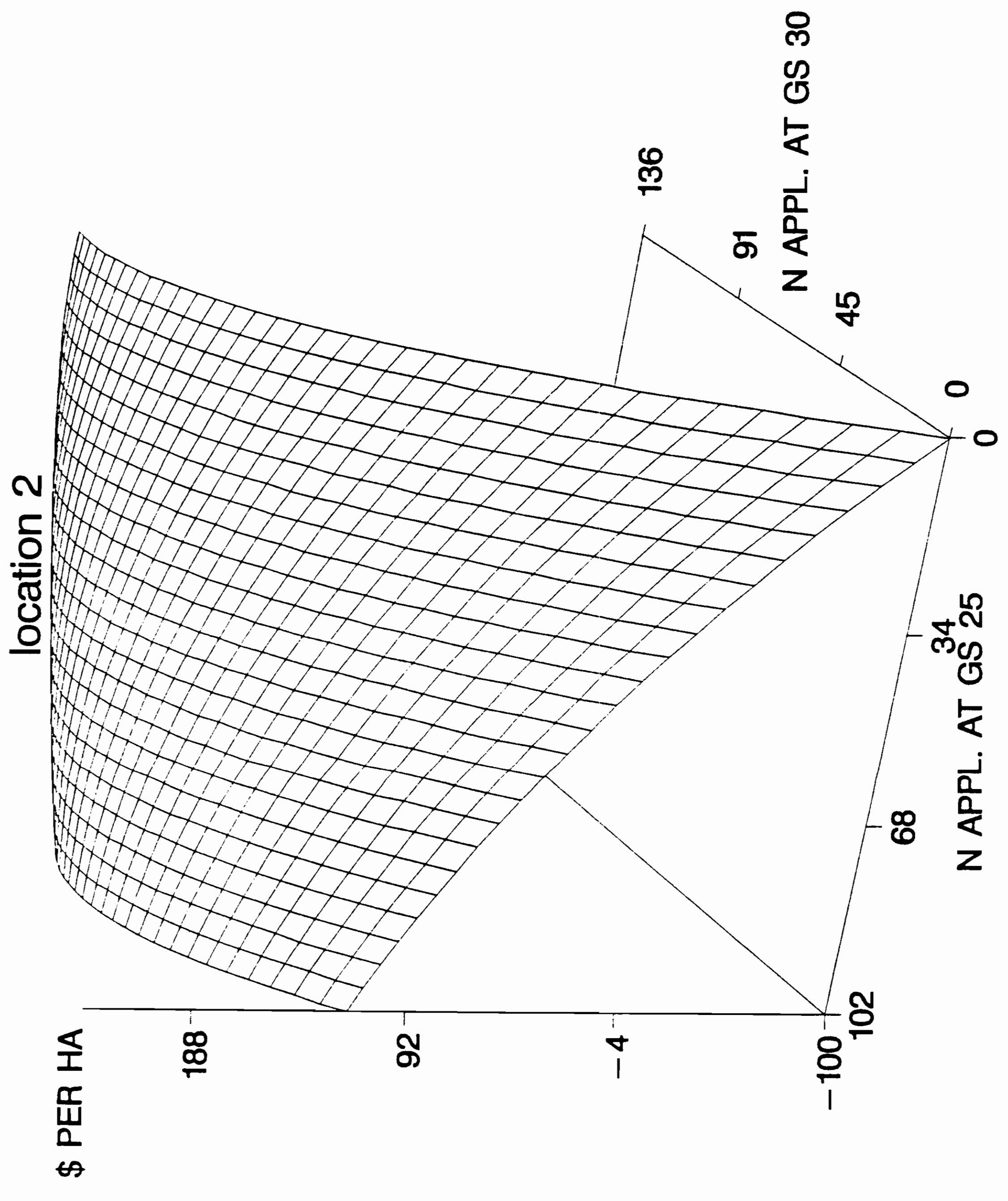
Equations for estimated profit ($ ha^{-1}) quadratic response surfaces (N rates in kg ha^{-1})

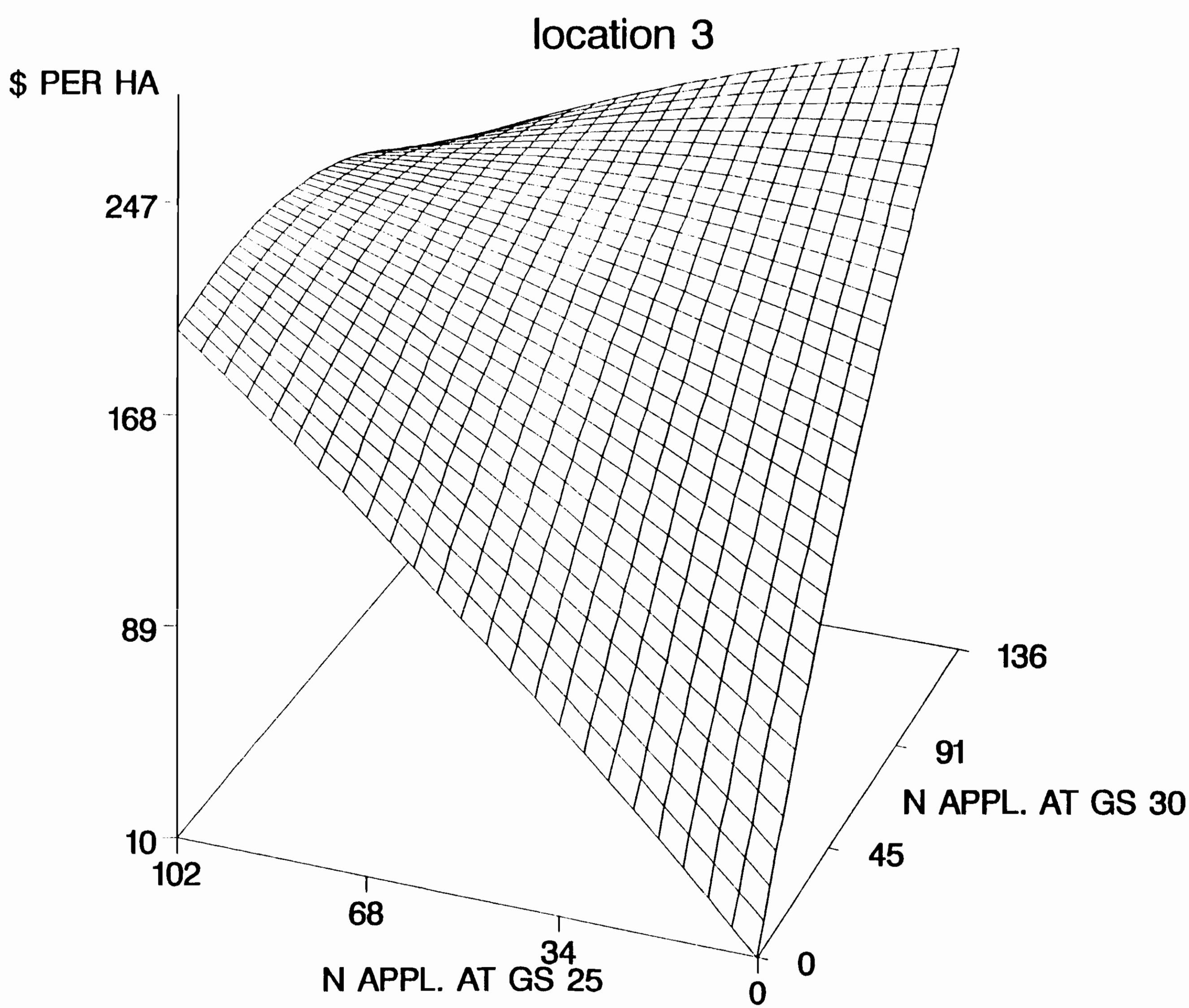
	equation coefficient for:						response
location	inter-cept	N25	N30	N25^2	N25*N30	N30^2	response surface R^2
1	178	1.96	2.61	-.0105	-.0195	-.0110	.32
2	-100	3.02	4.32	-.0086	-.0210	-.0171	.65
3	10	2.13	2.37	-.0026	-.0192	-.0046	.51
4	-18	4.03	3.83	-.0201	-.0200	-.0166	.48
5	80	2.24	2.66	-.0092	-.0122	-.0076	.47
6	-38	3.42	3.80	-.0095	-.0214	-.0113	.63
7	0	2.25	2.49	-.0051	-.0146	-.0072	.37
8	-208	4.09	5.17	-.0119	-.0197	-.0200	.88
9	-188	3.25	2.59	-.0204	-.0149	-.0118	.57
10	-175	2.26	2.66	-.0076	-.0169	-.0114	.62
11	-146	3.64	3.95	-.0133	-.0250	-.0142	.78
12	-116	3.43	4.83	-.0146	-.0273	-.0246	.56
13	82	1.18	1.97	-.0087	-.0173	-.0086	.49
14	-291	2.35	2.52	-.0150	-.0159	-.0153	.66
15	256	1.03	2.61	+.0031	-.0249	-.0096	.33
16	-29	2.91	3.69	-.0141	-.0185	-.0112	.60
17	-96	-0.81	-0.36	+.0056	-.0108	+.0001	.58
18	-179	3.12	2.84	-.0130	-.0183	-.0117	.65
19	-173	6.98	3.87	-.0294	-.0306	-.0086	.66
20	-110	3.18	3.31	-.0161	-.0182	-.0131	.52
21	-37	3.42	3.29	-.0085	-.0161	-.0084	.78
22	-154	2.12	1.84	-.0079	-.0099	-.0075	.53
23	-50	0.86	1.39	-.0019	-.0089	-.0052	.46
24	291	-4.19	-2.15	+.0144	+.0008	+.0033	.80
25	-167	3.90	2.14	-.0166	-.0085	-.0105	.57
26	223	-0.92	-1.71	-.0011	-.0019	+.0024	.74
27	-53	2.68	2.78	-.0078	-.0183	-.0064	.56
28	3	1.05	2.87	-.0008	-.0122	-.0075	.65
29	-70	2.23	2.35	-.0073	-.0067	-.0109	.39
30	379	-1.49	-1.63	+.0019	+.0033	+.0032	.75
31	-33	2.11	2.59	-.0049	-.0113	-.0075	.63
32	345	-0.50	-0.07	-.0009	-.0043	-.0033	.55
33	106	2.95	2.38	-.0130	-.0126	-.0081	NA
34	-107	2.53	2.77	-.0070	-.0161	-.0076	.65
35	-82	1.81	3.53	-.0048	-.0138	-.0104	.78
36	561	0.55	1.71	-.0080	-.0018	-.0133	.68
37	476	-0.85	-0.05	-.0016	-.0048	-.0024	.65
38	379	-0.31	-0.13	-.0023	-.0045	-.0012	.60
39	-29	3.70	4.43	-.0090	-.0256	-.0122	.44
40	-272	3.36	3.72	-.0155	-.0177	-.0185	.48
41	138	-1.02	-1.24	-.0040	-.0058	+.0010	.69
42	-30	2.08	1.53	-.0084	-.0166	-.0042	.32
43	-78	2.79	2.98	-.0147	-.0190	-.0132	.45
44	-134	-0.43	-1.20	-.0056	+.0026	+.0030	.55
45	-173	0.88	1.43	-.0062	-.0211	-.0113	.70

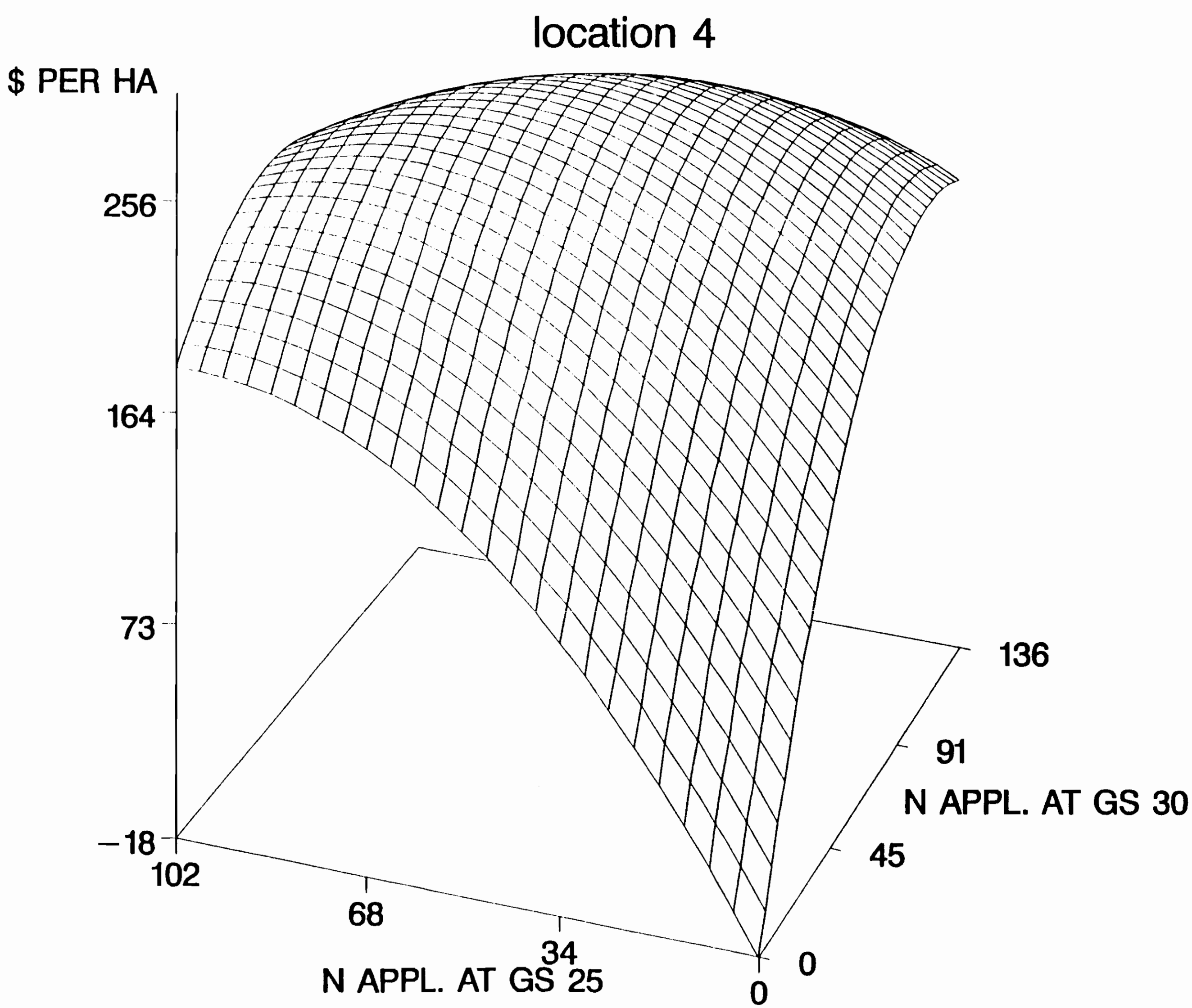
Quadratic response surface equations presented on the preceding page were calculated using PROC RSREG in SAS (SAS Institute, Cary, NC) from estimated profit values calculated for each of the individual plots in an experiment. Approximate current wheat prices in the harvest year were used in making these calculations: \$128 Mg^{-1} in 1987-1988, 1988-1989, and 1989-1990; \$100 Mg^{-1} in 1990-1991; and \$120 Mg^{-1} in 1991-1992. Approximate current N price was also used, and in all years was \$0.48 kg^{-1} N. Increased harvest cost due to slowed combining was estimated, in \$ ha^{-1}, as $(\text{lodging index})^2/1.6$; this estimate agrees well with data collected by Dr. Dan Brann in Cerone evaluation trials.



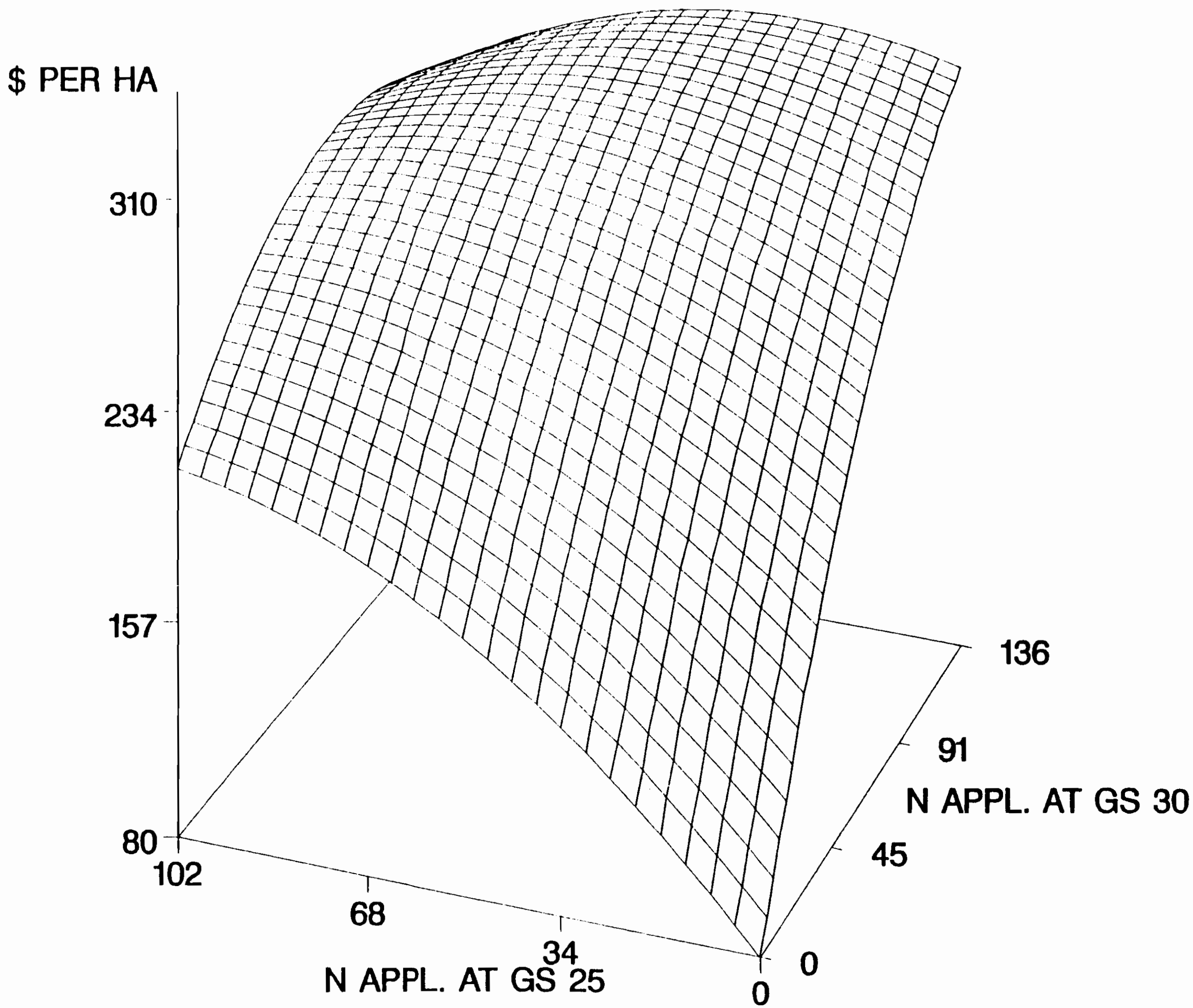
location 1
$ PER HA
333
272
211
150
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

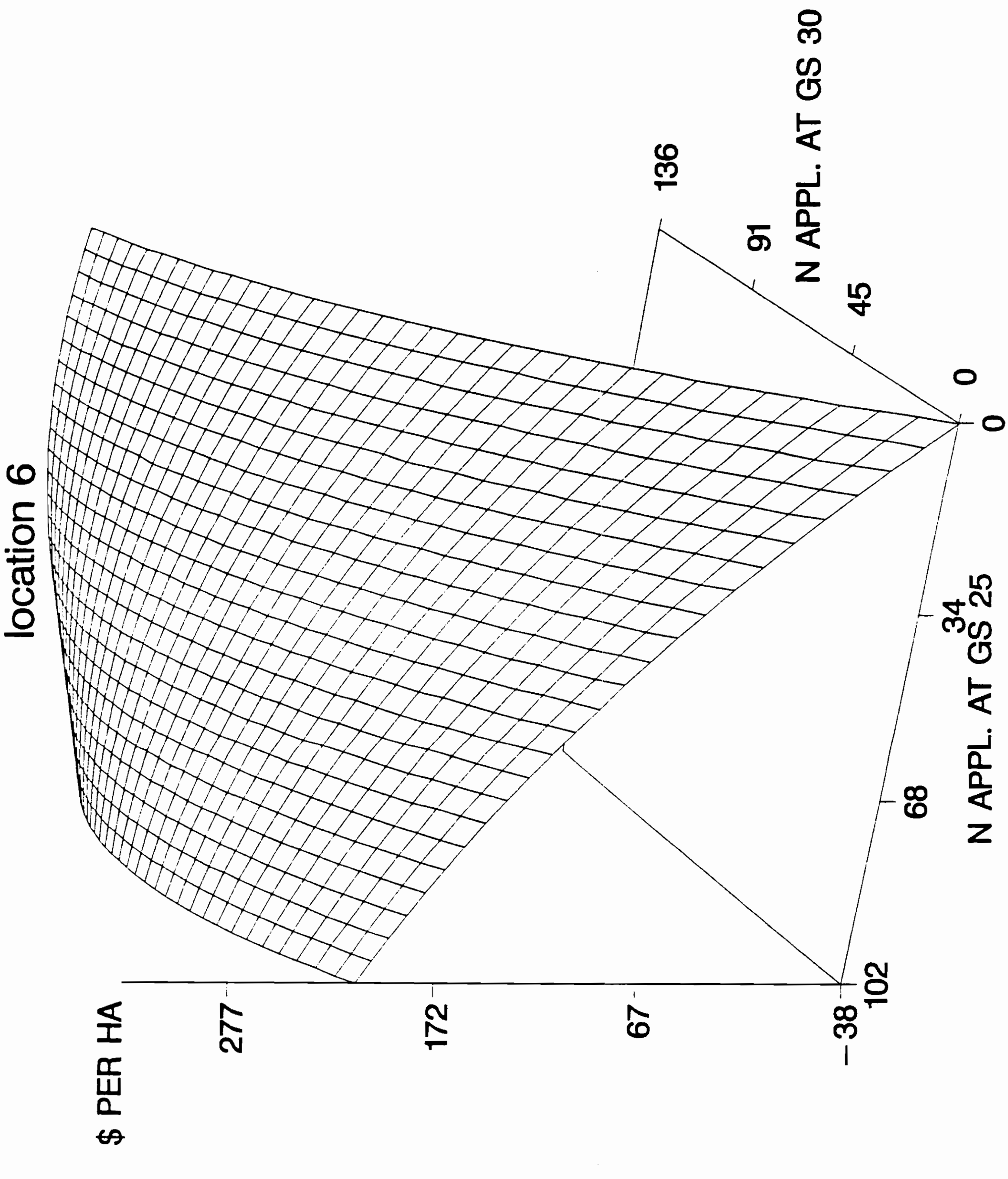

location 2
$ PER HA
188
92
-4
-100
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30


location 3
$ PER HA
247
168
89
10
102
68
34
N APPL. AT GS 25
0
0
45
91
136
N APPL. AT GS 30


location 4
$ PER HA
256
164
73
−18
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

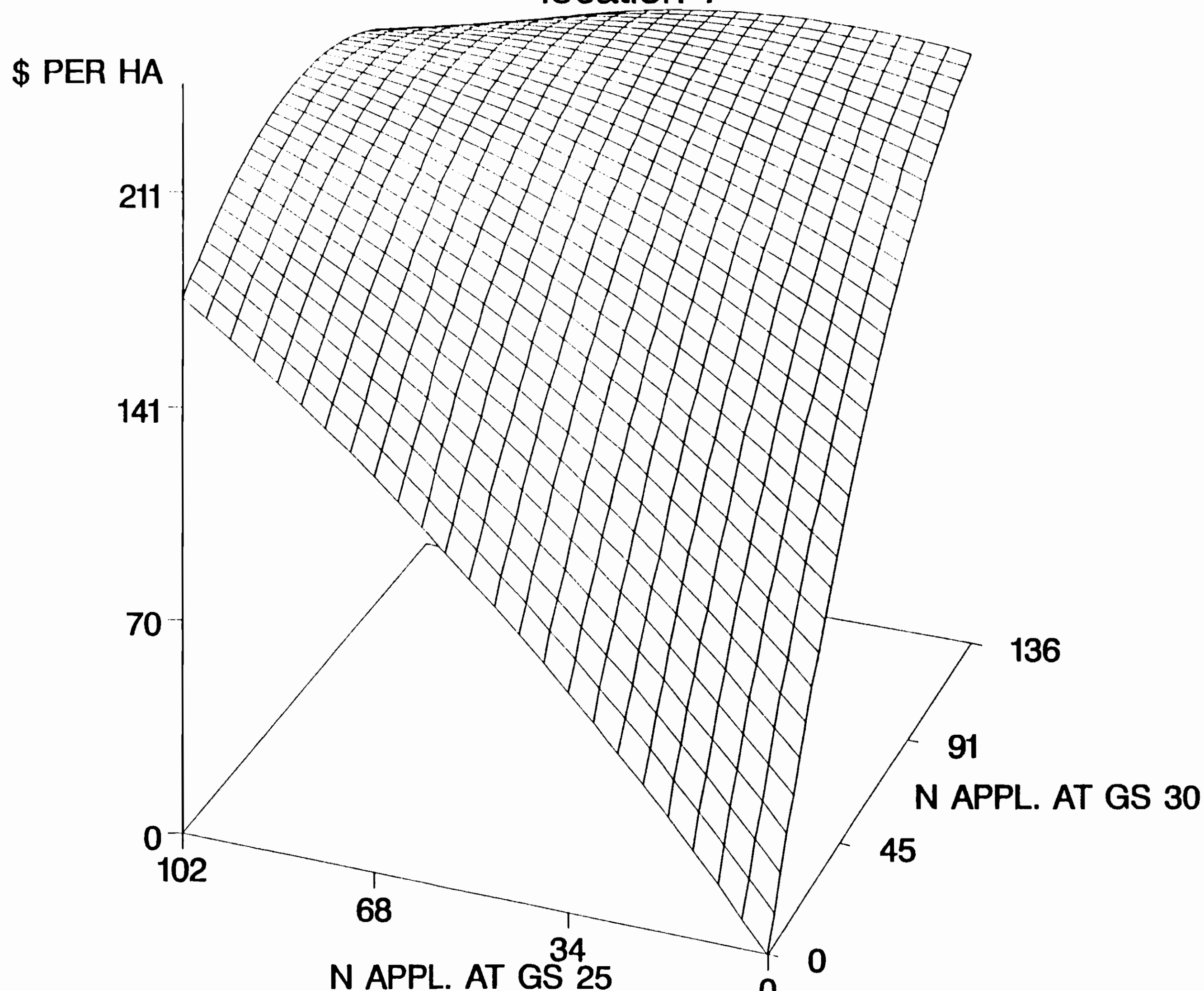
location 5

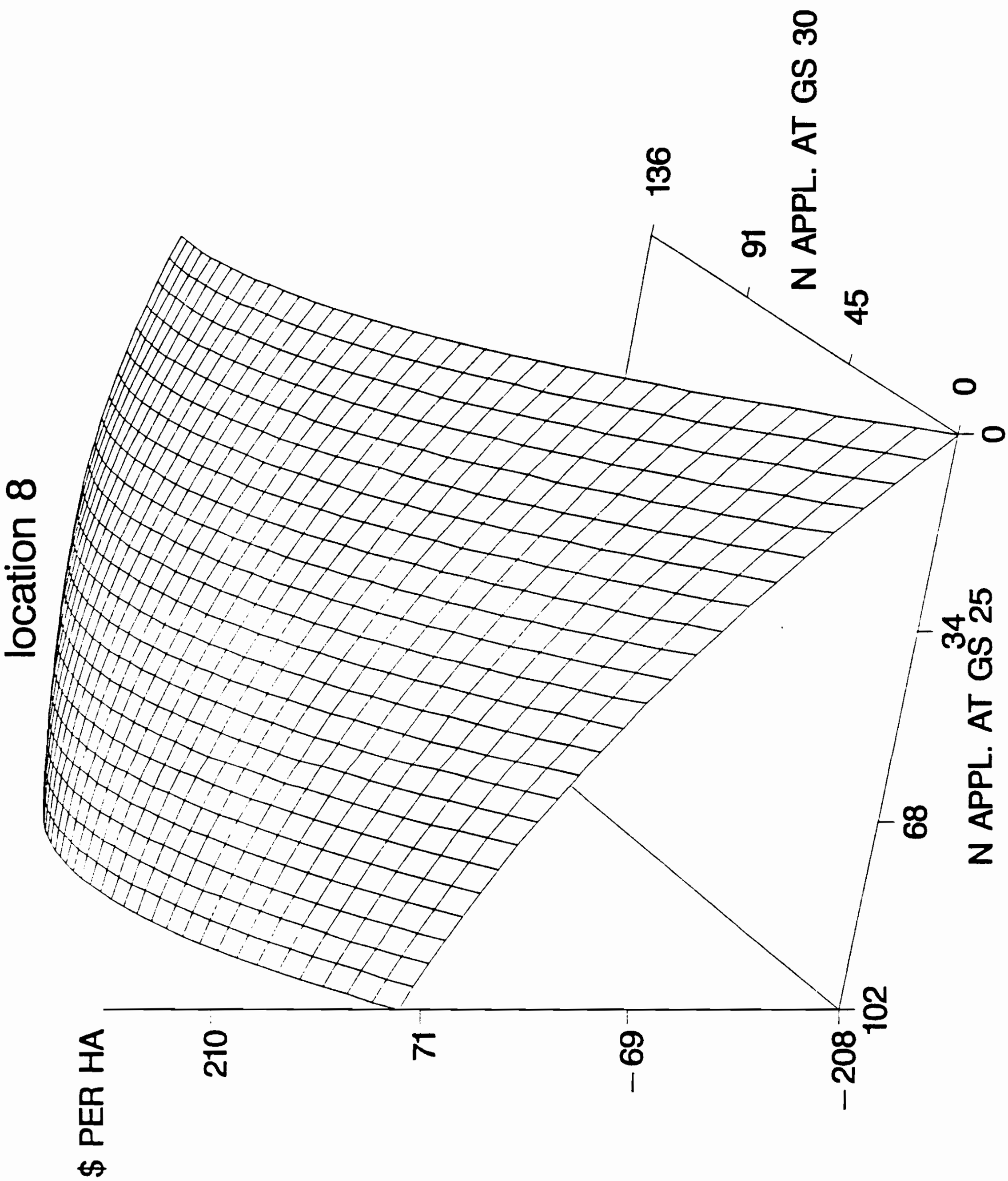

$ PER HA
310
234
157
80
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

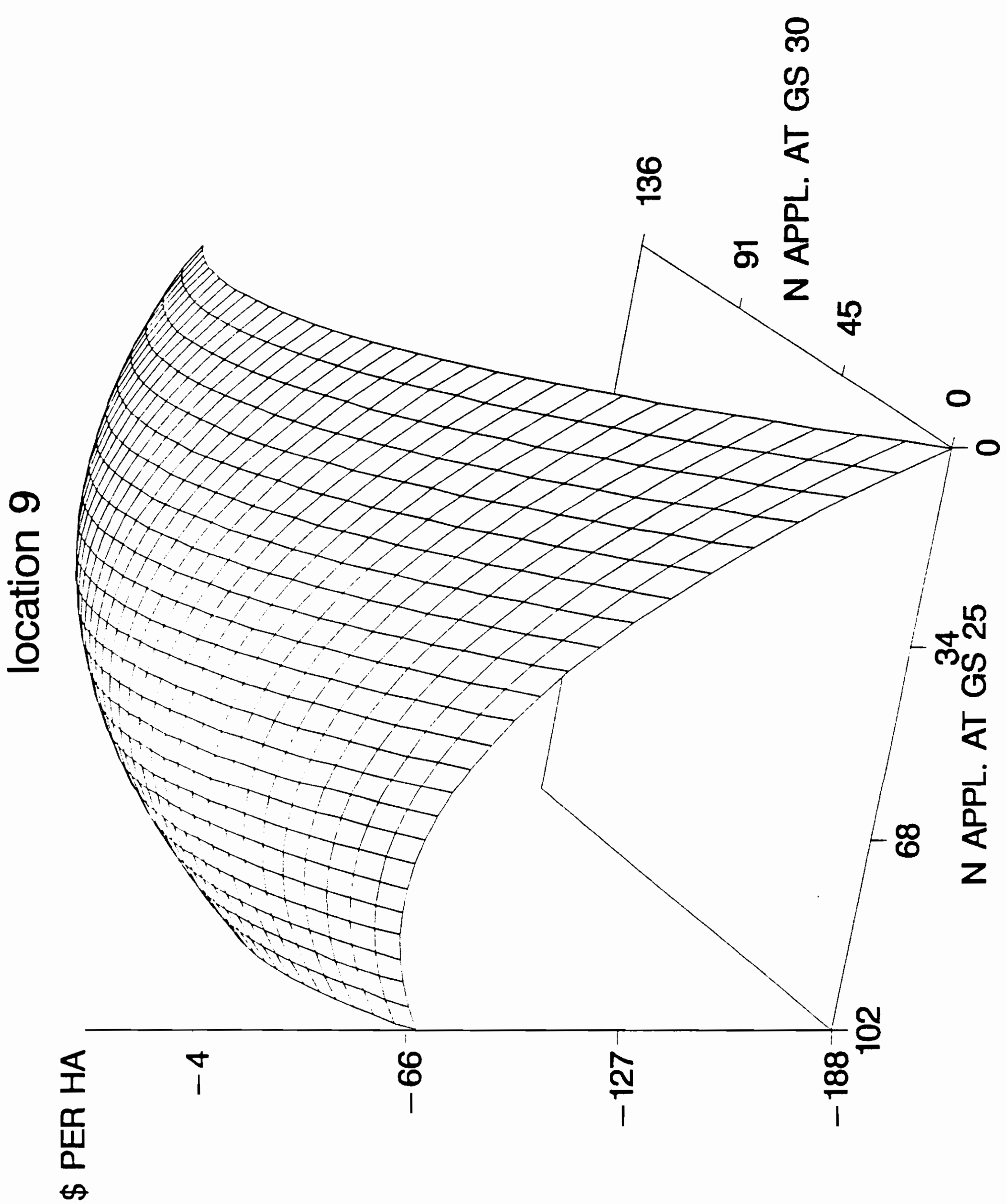


location 6
$ PER HA
277
172
67
−38
102
68
34
0
N APPL. AT GS 25
136
91
45
0
N APPL. AT GS 30

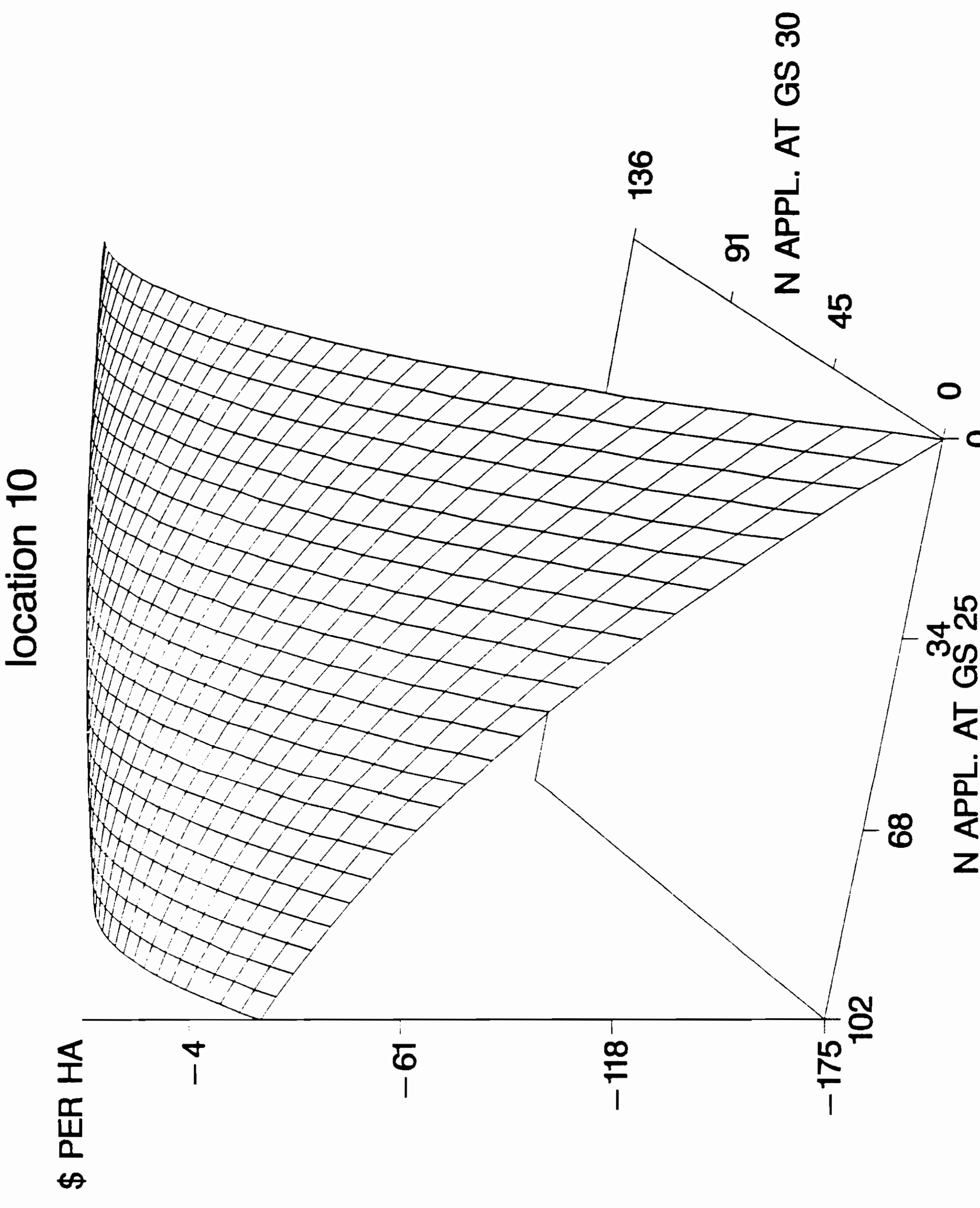
location 7

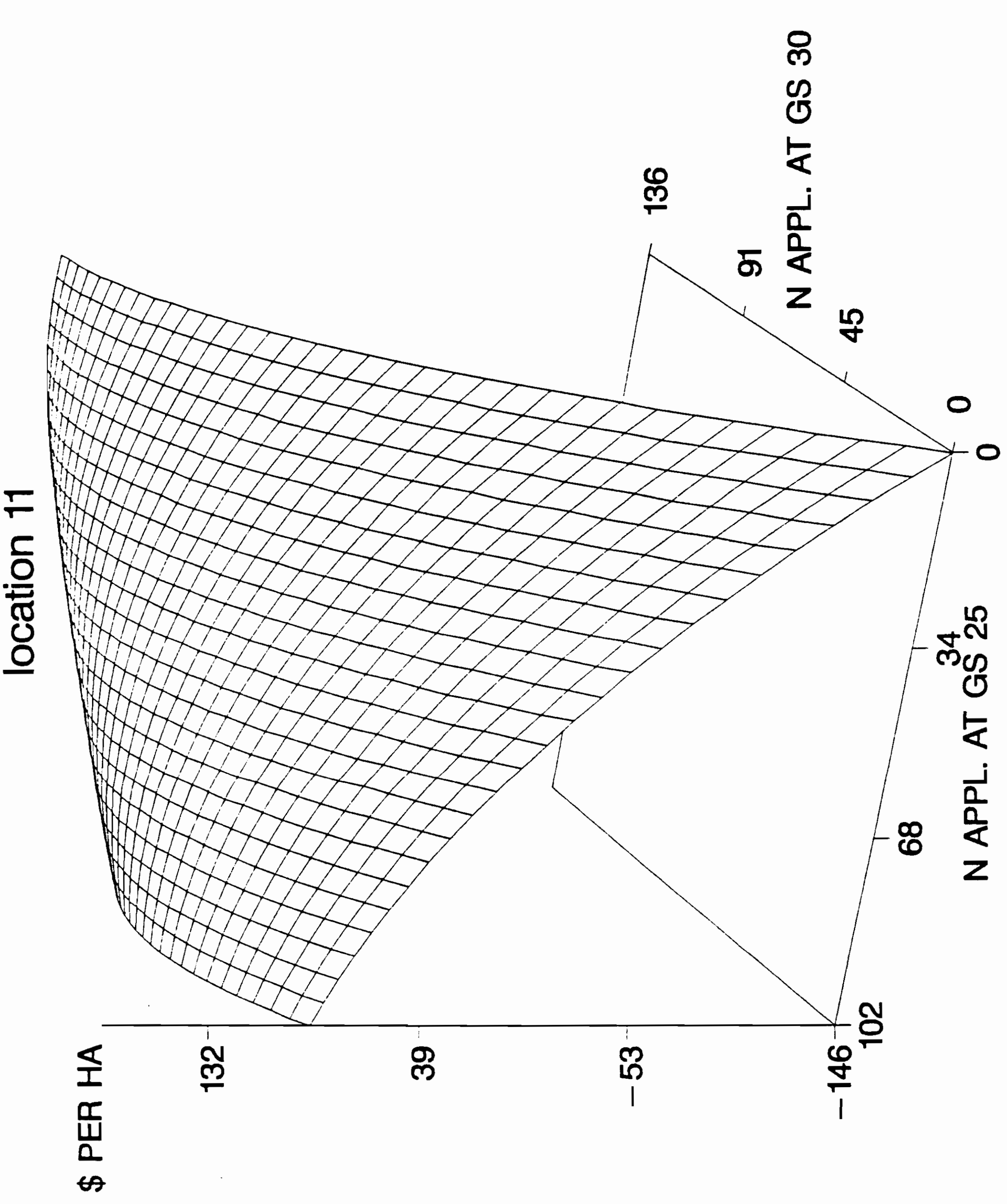

$ PER HA
211
141
70
0
102
68
34
N APPL. AT GS 25
0
0
45
91
136
N APPL. AT GS 30


location 8
$ PER HA
210
71
−69
−208
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

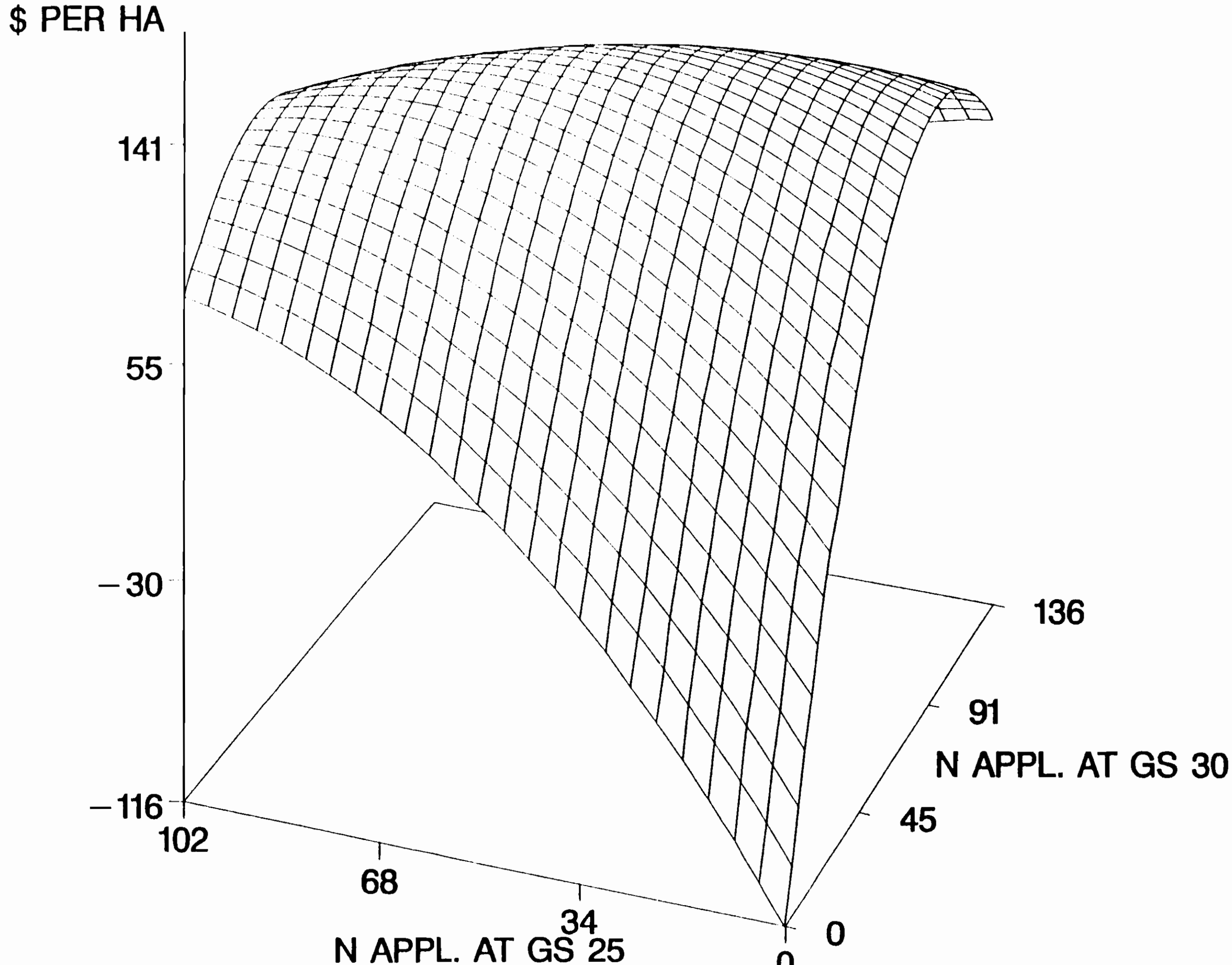


location 9
$ PER HA
-4
-66
-127
-188
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

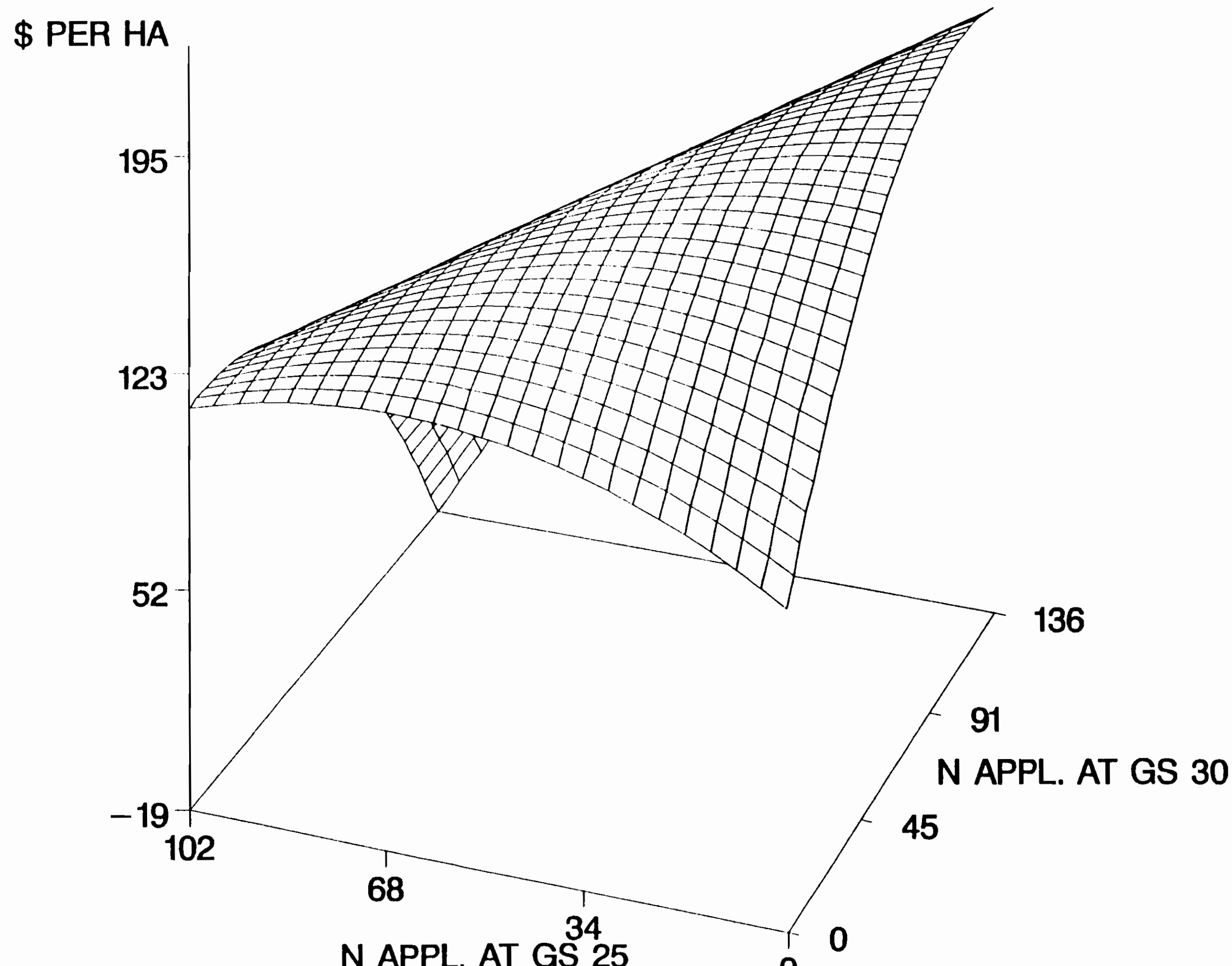

location 10
$ PER HA
-4
-61
-118
-175
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30


location 11
$ PER HA
132
39
−53
−146
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

location 12

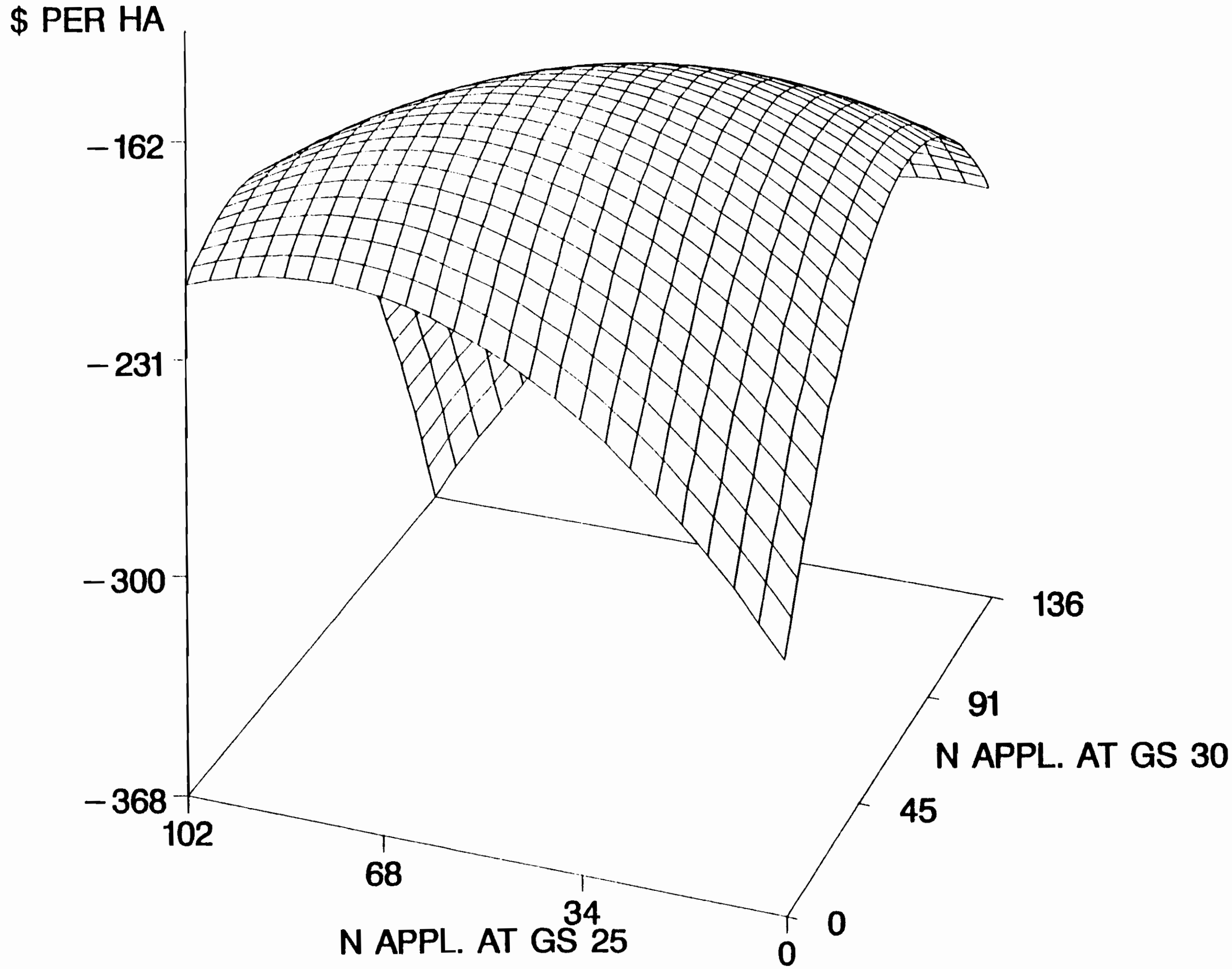

$ PER HA
141
55
-30
-116
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

location 13



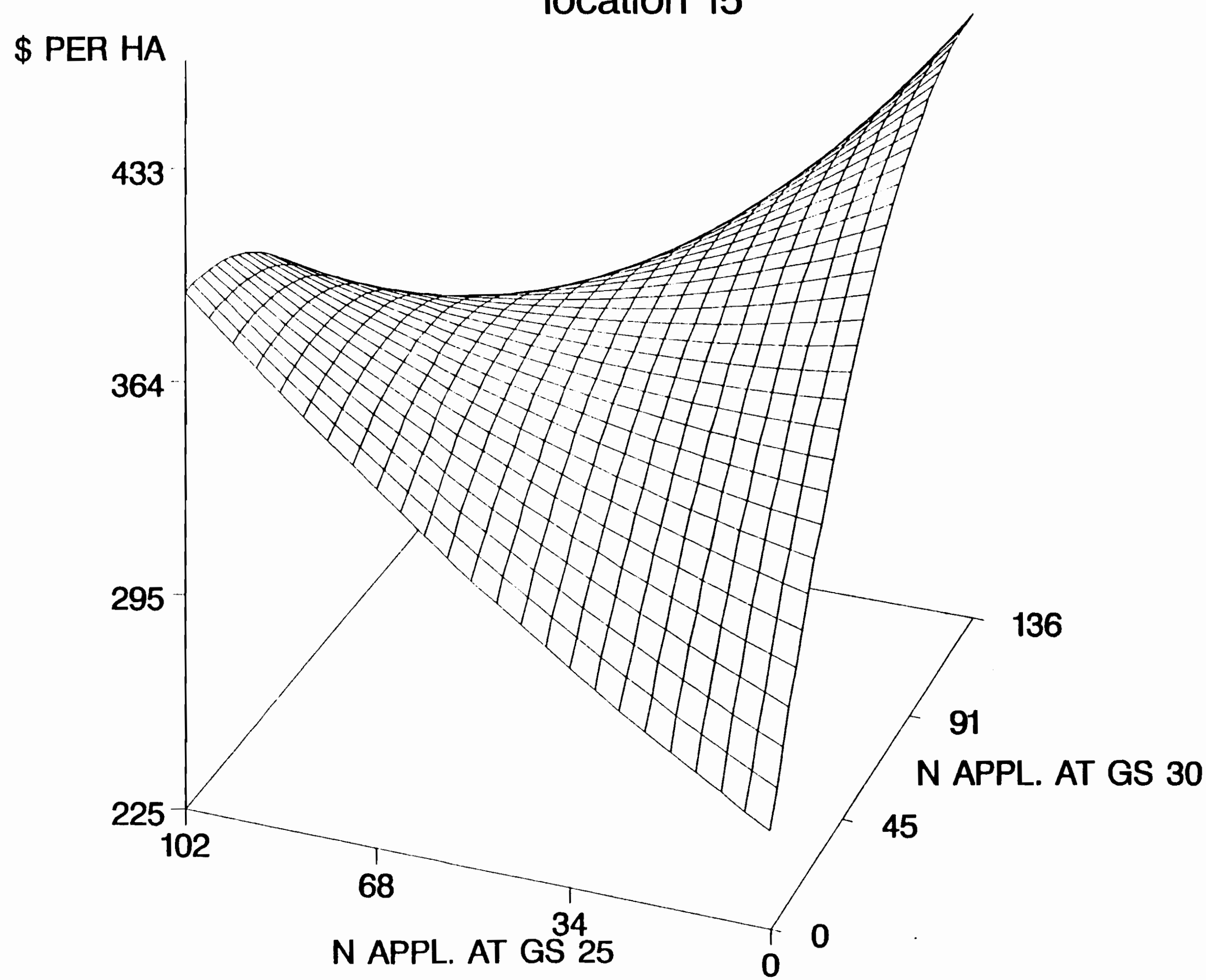
$ PER HA
195
123
52
−19
102
68
34
N APPL. AT GS 25
0
0
45
N APPL. AT GS 30
91
136

location 14

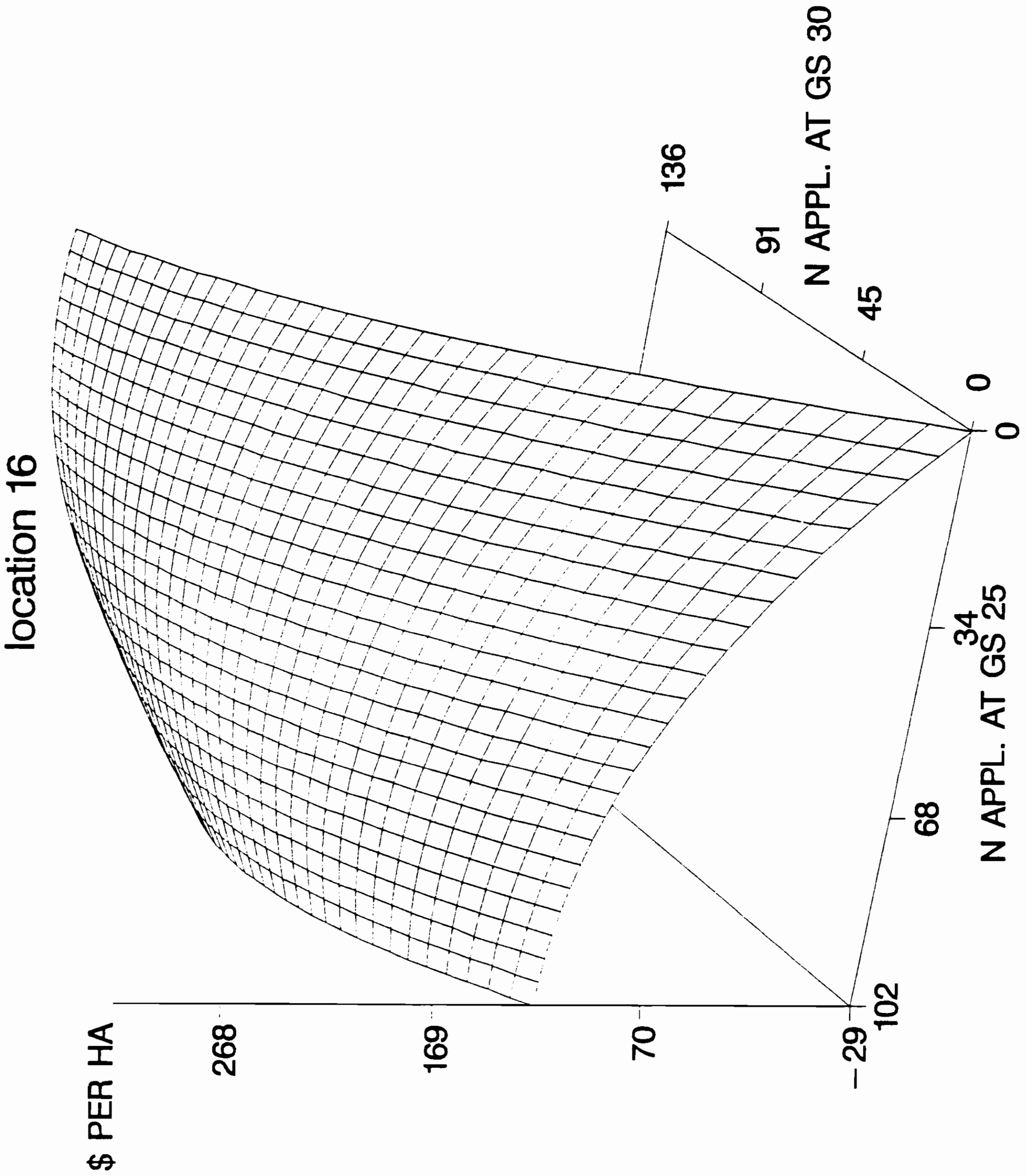


$ PER HA
−162
−231
−300
−368
102
68
34
0
N APPL. AT GS 25
136
91
45
0
N APPL. AT GS 30

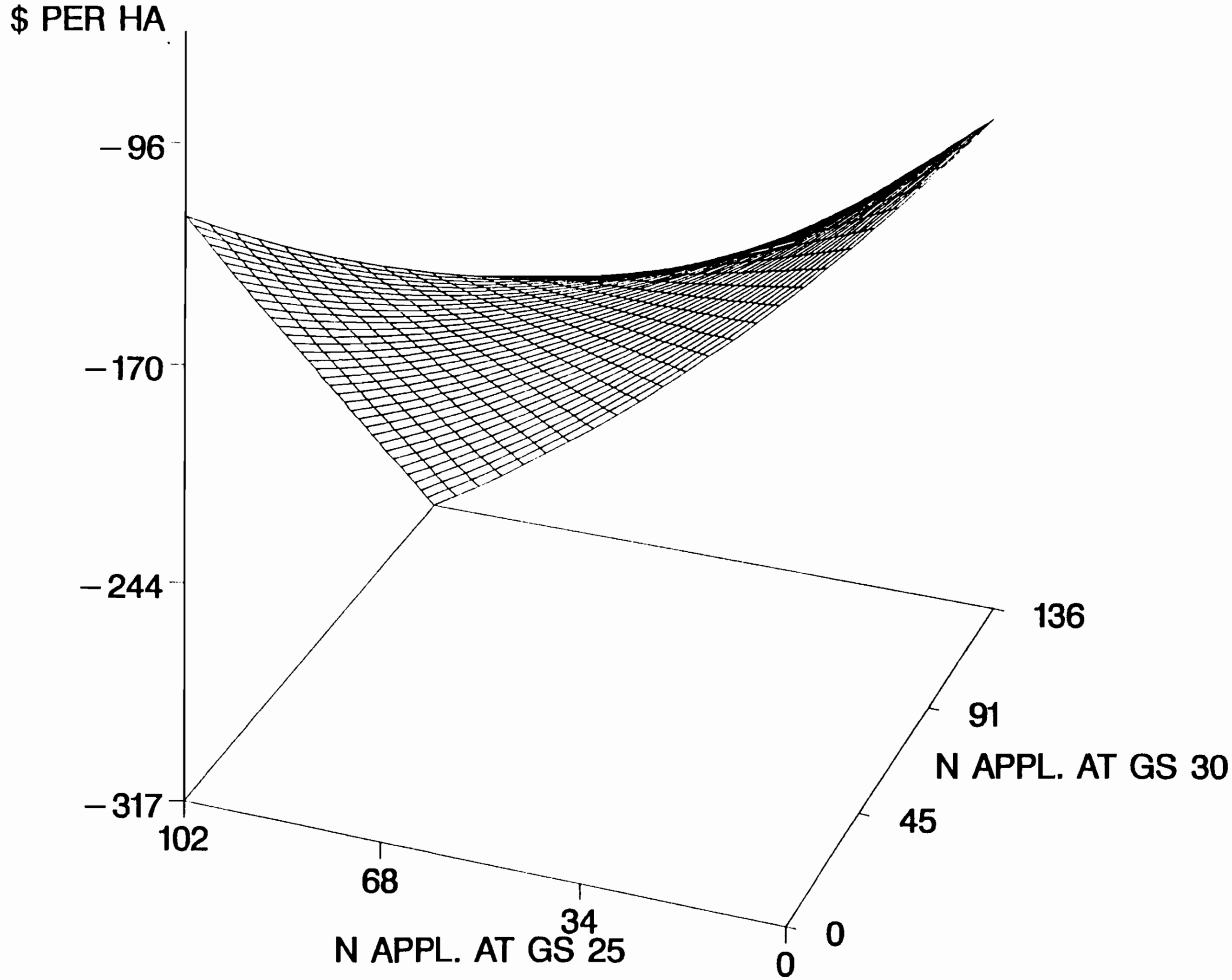
location 15



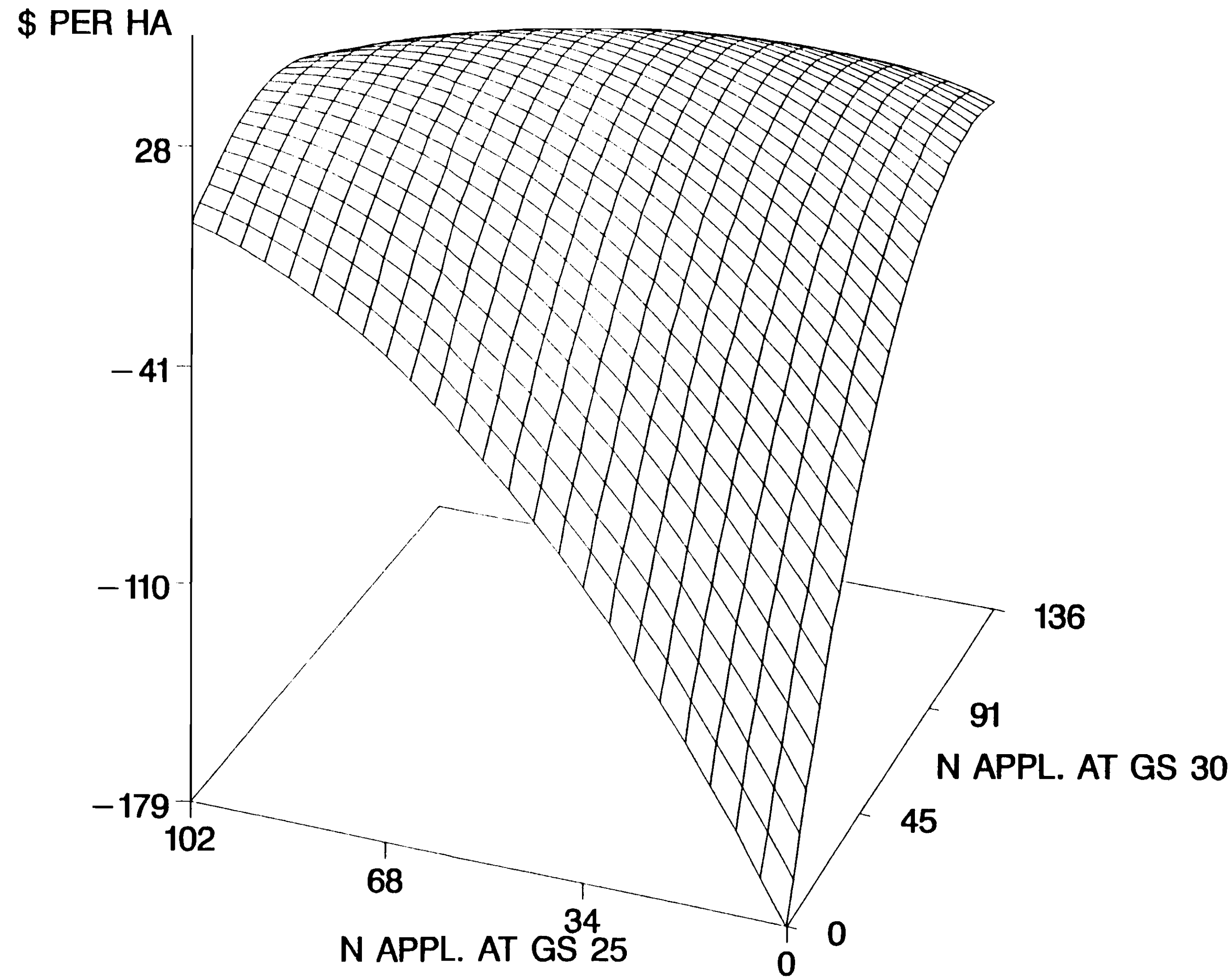
$ PER HA
433
364
295
225
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30


location 16
$ PER HA
268
169
70
−29
102
68
34
25
N APPL. AT GS 25
0
0
45
91
136
N APPL. AT GS 30

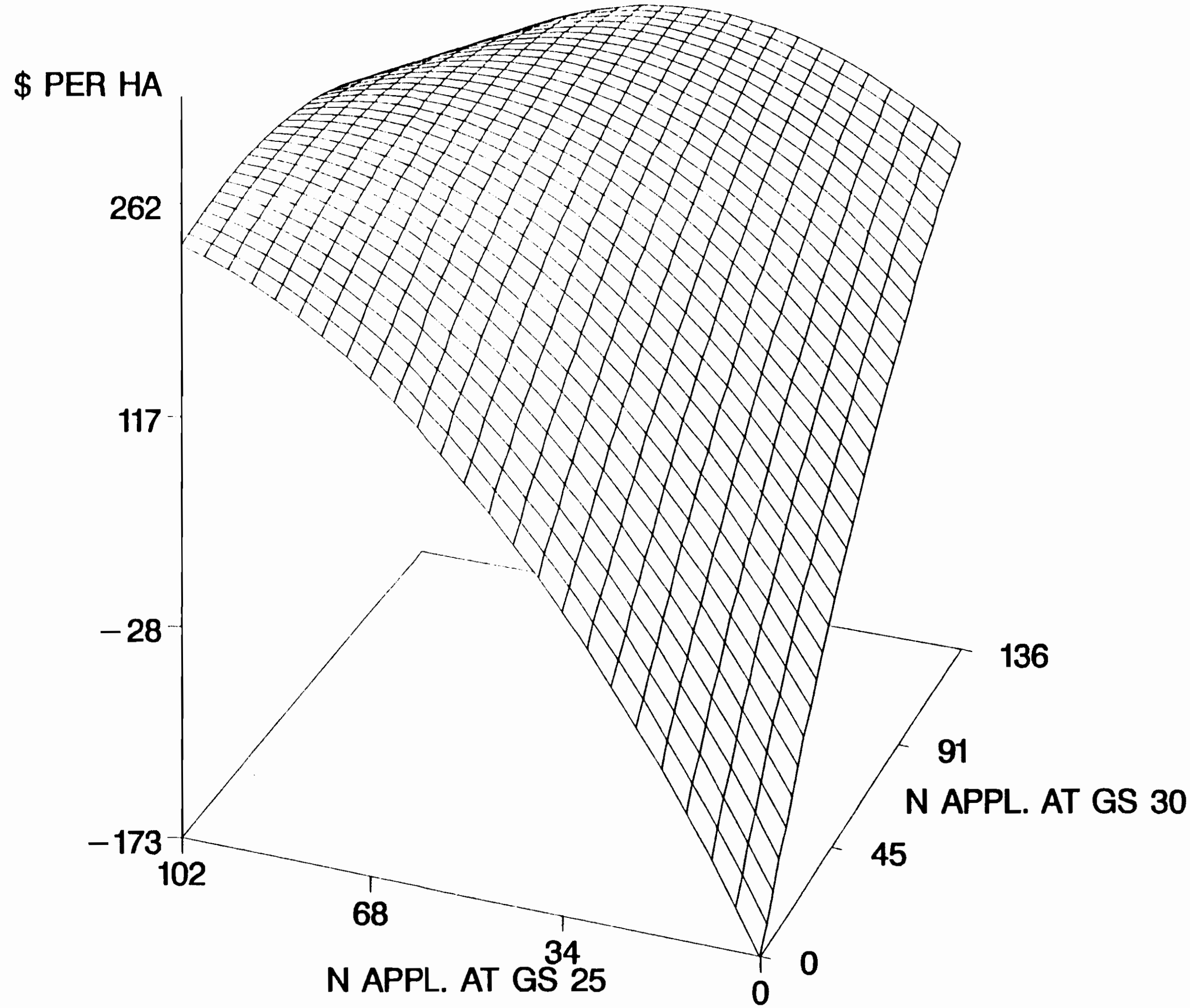
location 17


$ PER HA
-96
-170
-244
-317
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

location 18

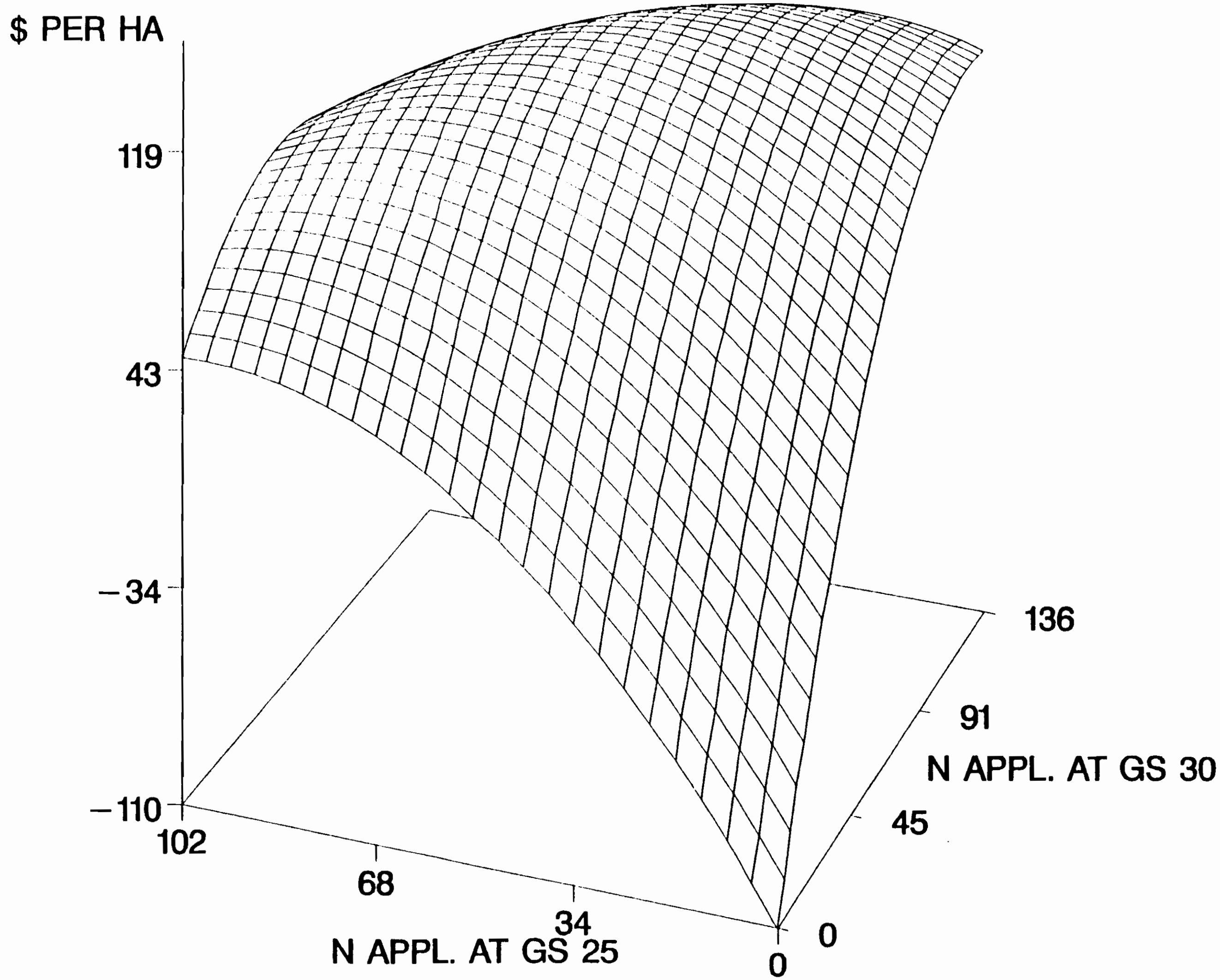

$ PER HA
28
-41
-110
-179
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

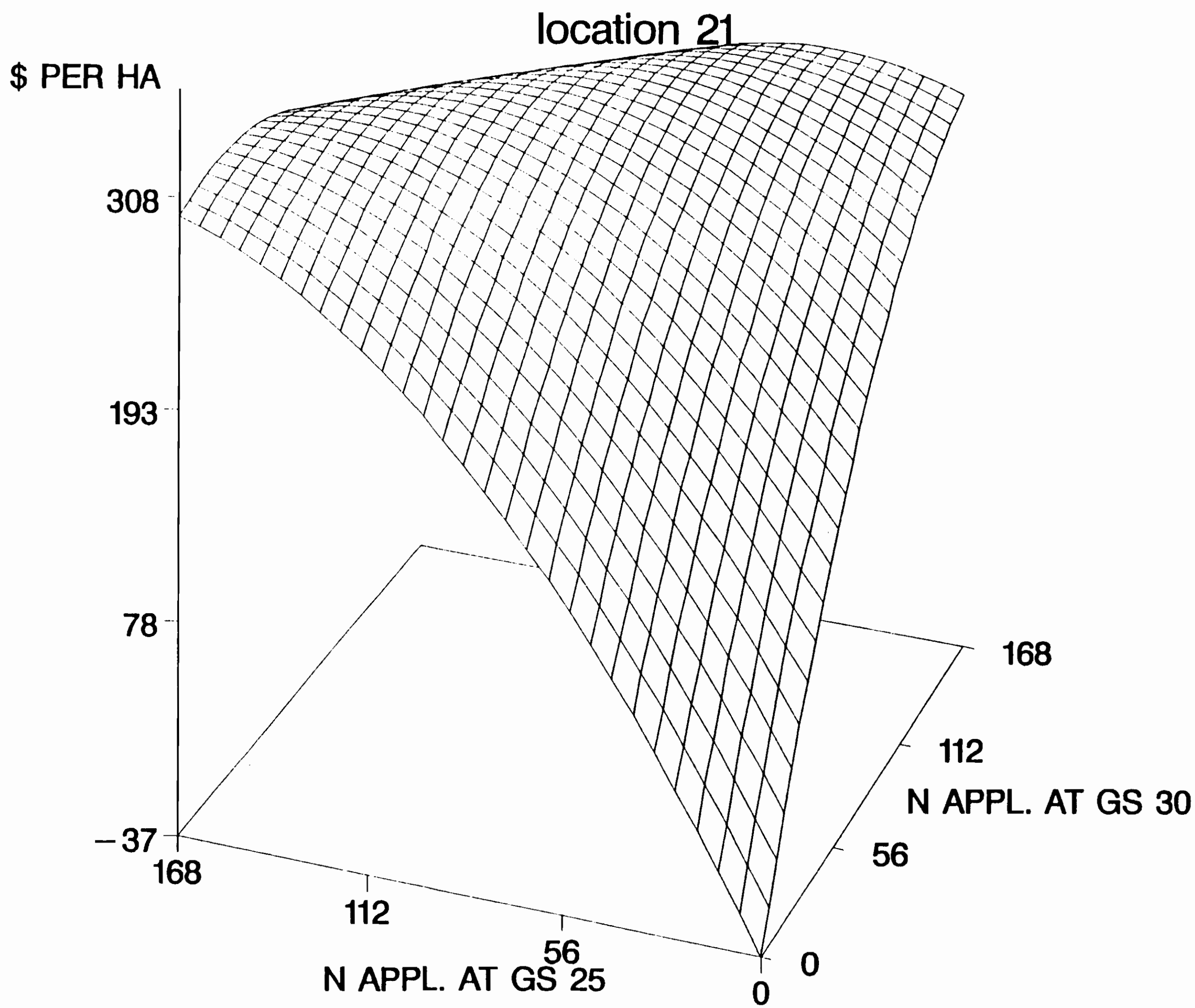
location 19



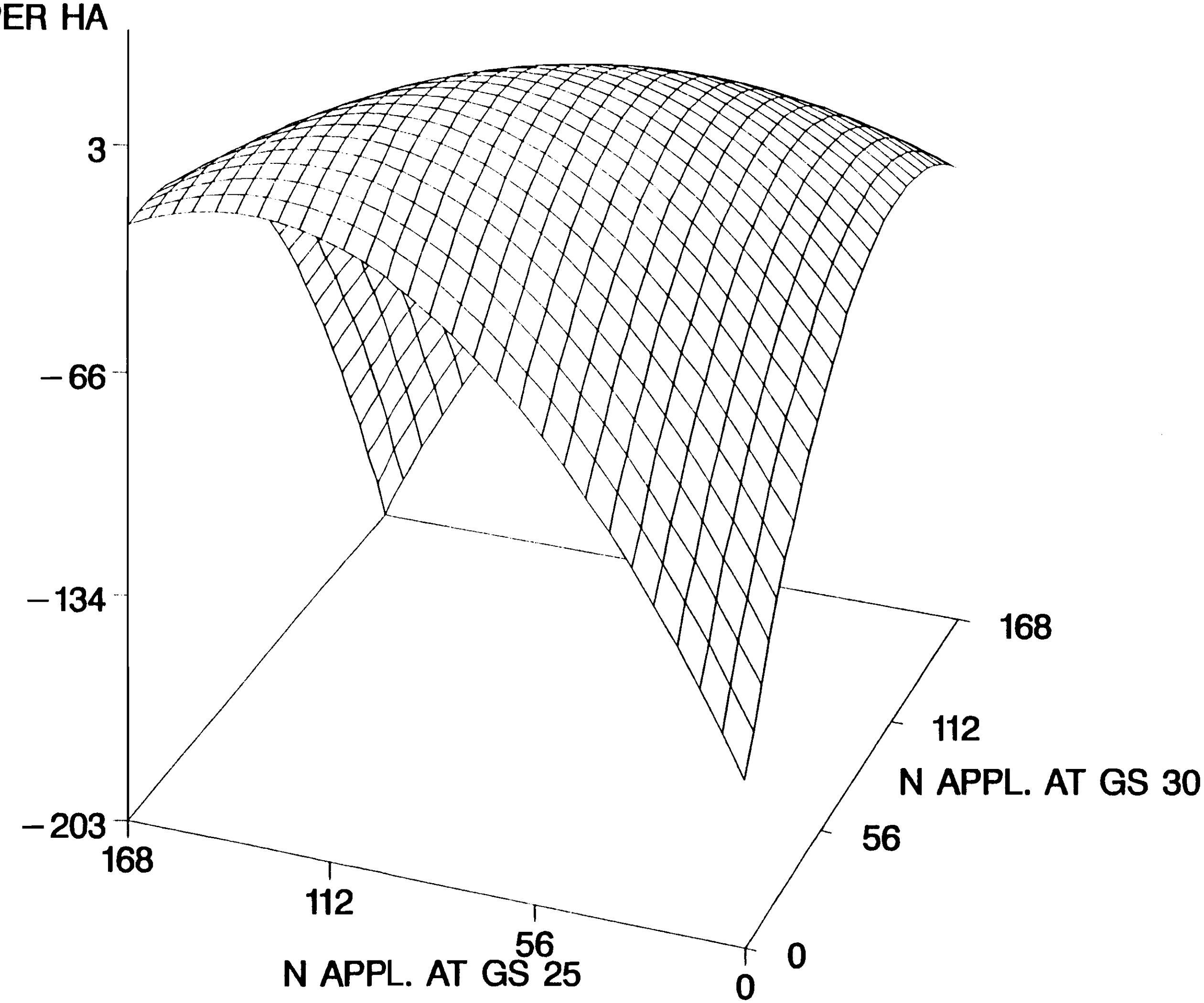
$ PER HA
262
117
−28
−173
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

location 20


$ PER HA
119
43
-34
-110
102
68
34
N APPL. AT GS 25
0
0
45
91
136
N APPL. AT GS 30

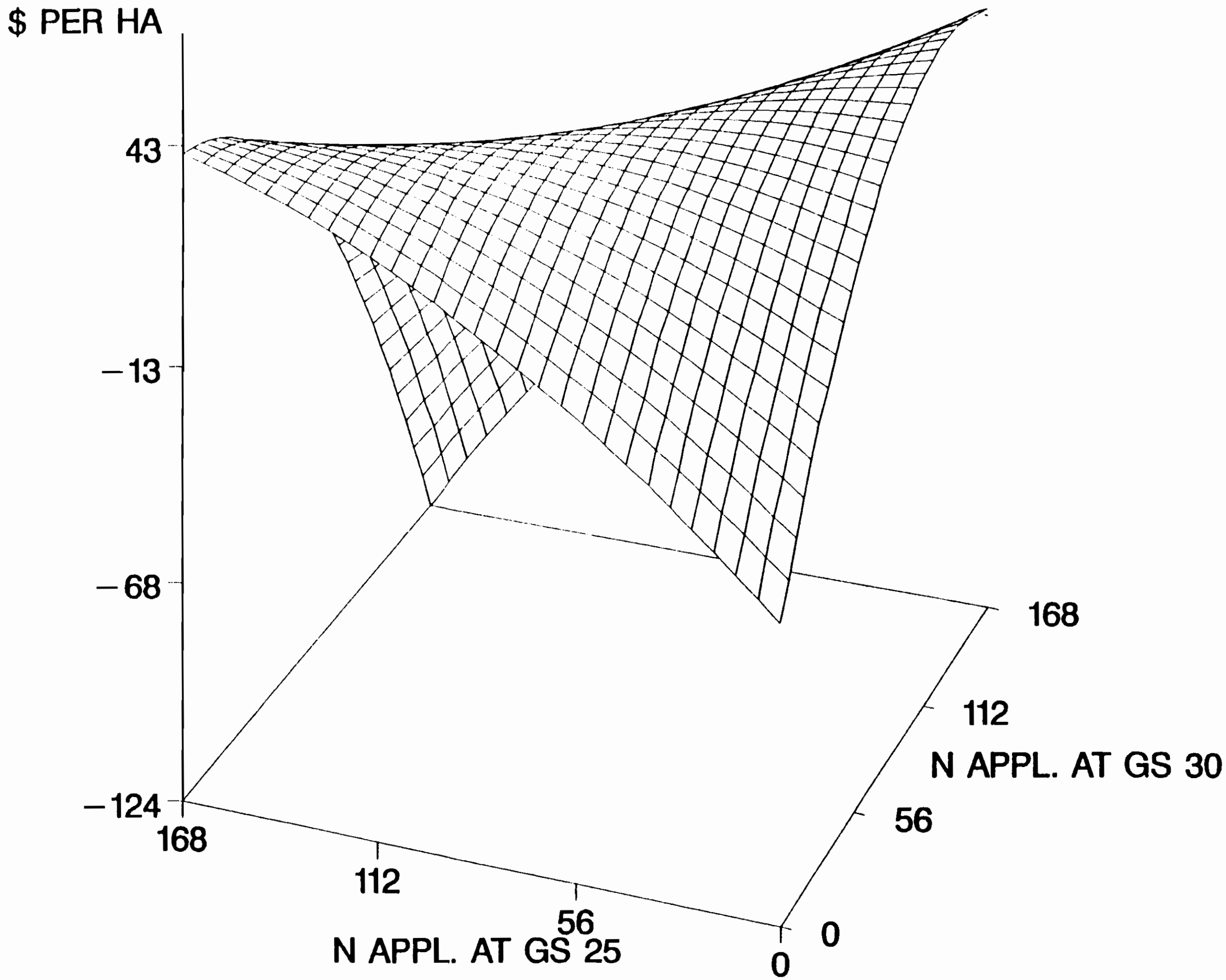

location 21
$ PER HA
308
193
78
-37
168
112
56
0
N APPL. AT GS 25
0
56
112
168
N APPL. AT GS 30

location 22



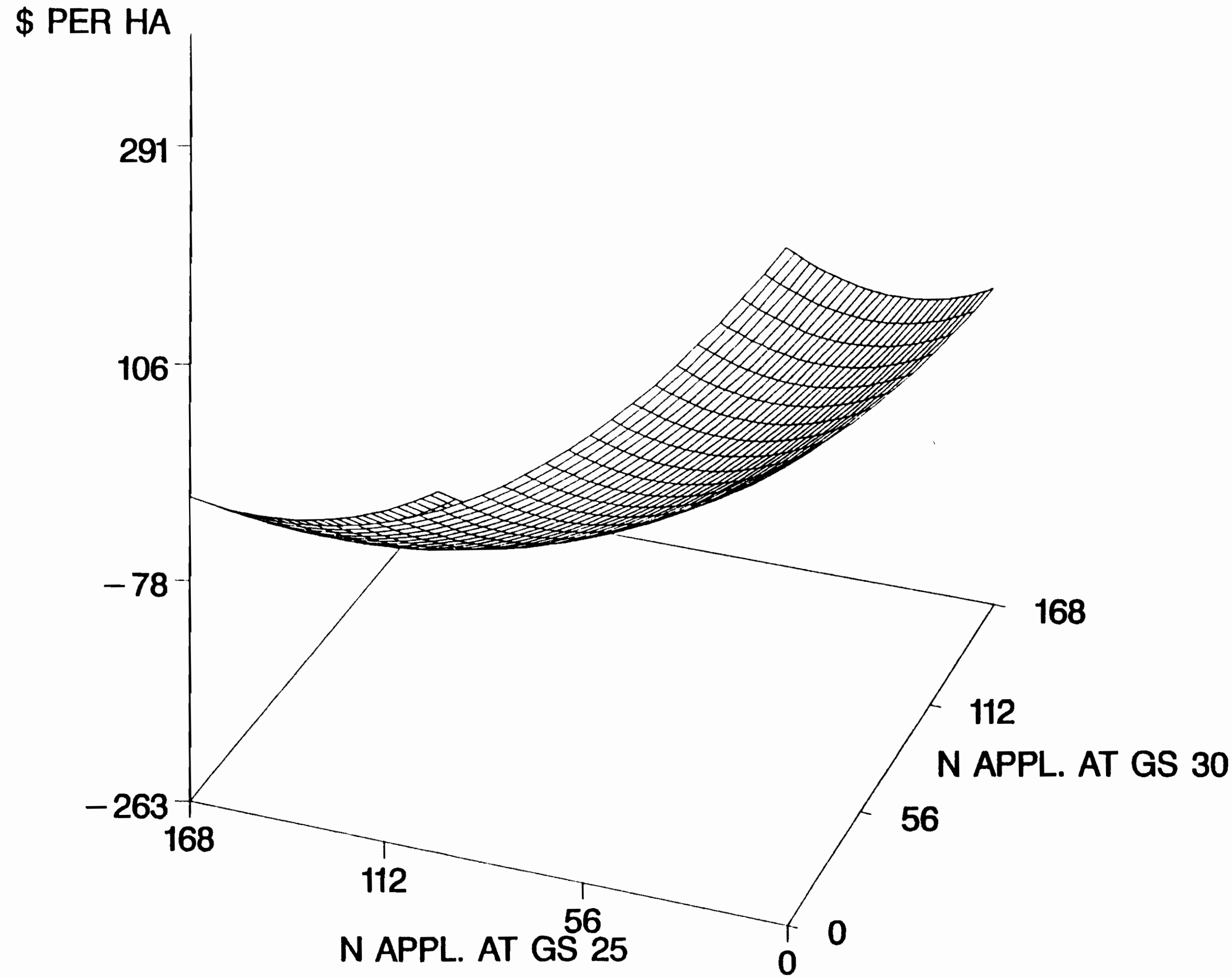
$ PER HA
3
−66
−134
−203
168
112
56
0
N APPL. AT GS 25
0
56
112
168
N APPL. AT GS 30

location 23



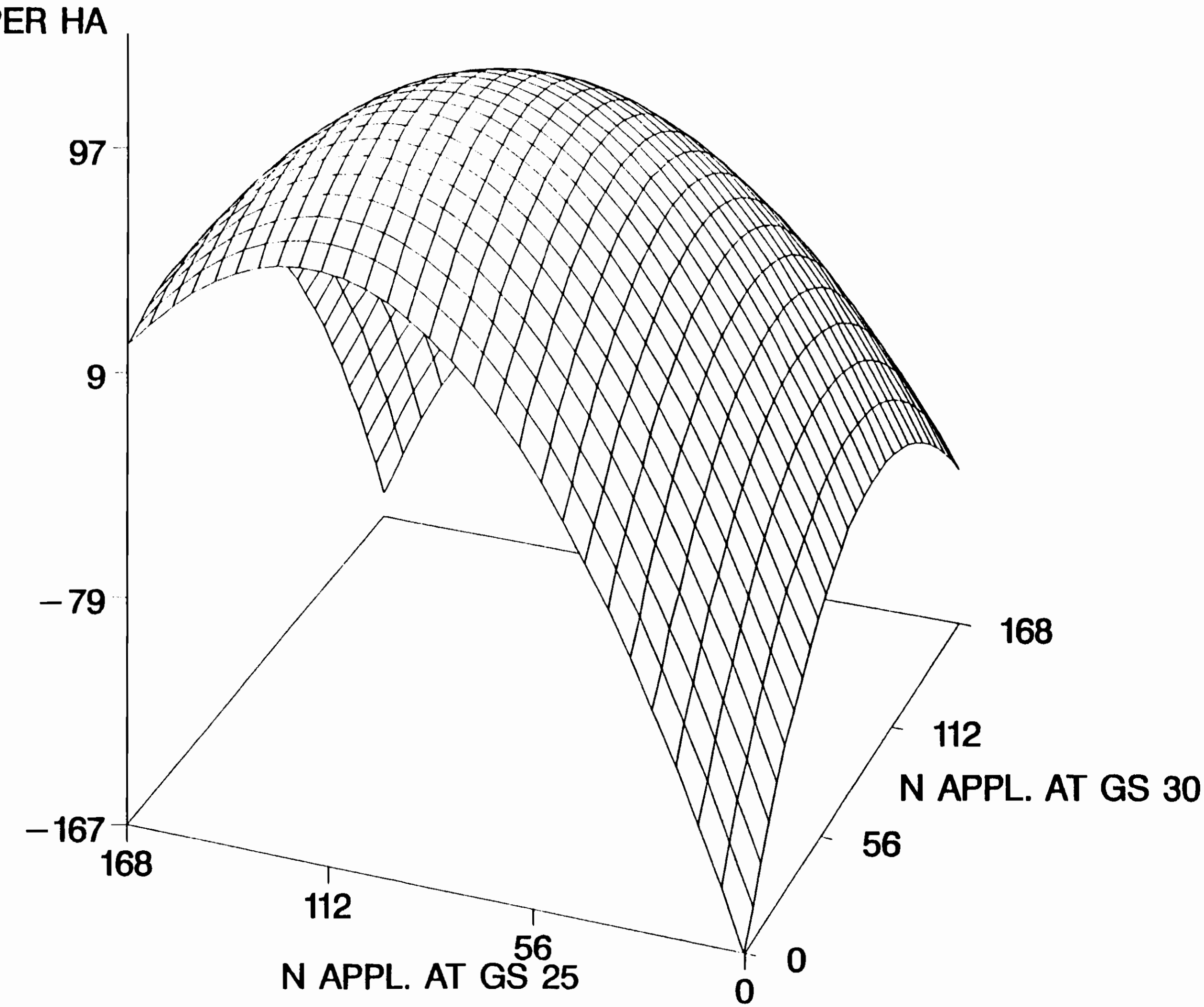
$ PER HA
43
−13
−68
−124
168
112
56
0
N APPL. AT GS 25
168
112
56
0
N APPL. AT GS 30

location 24



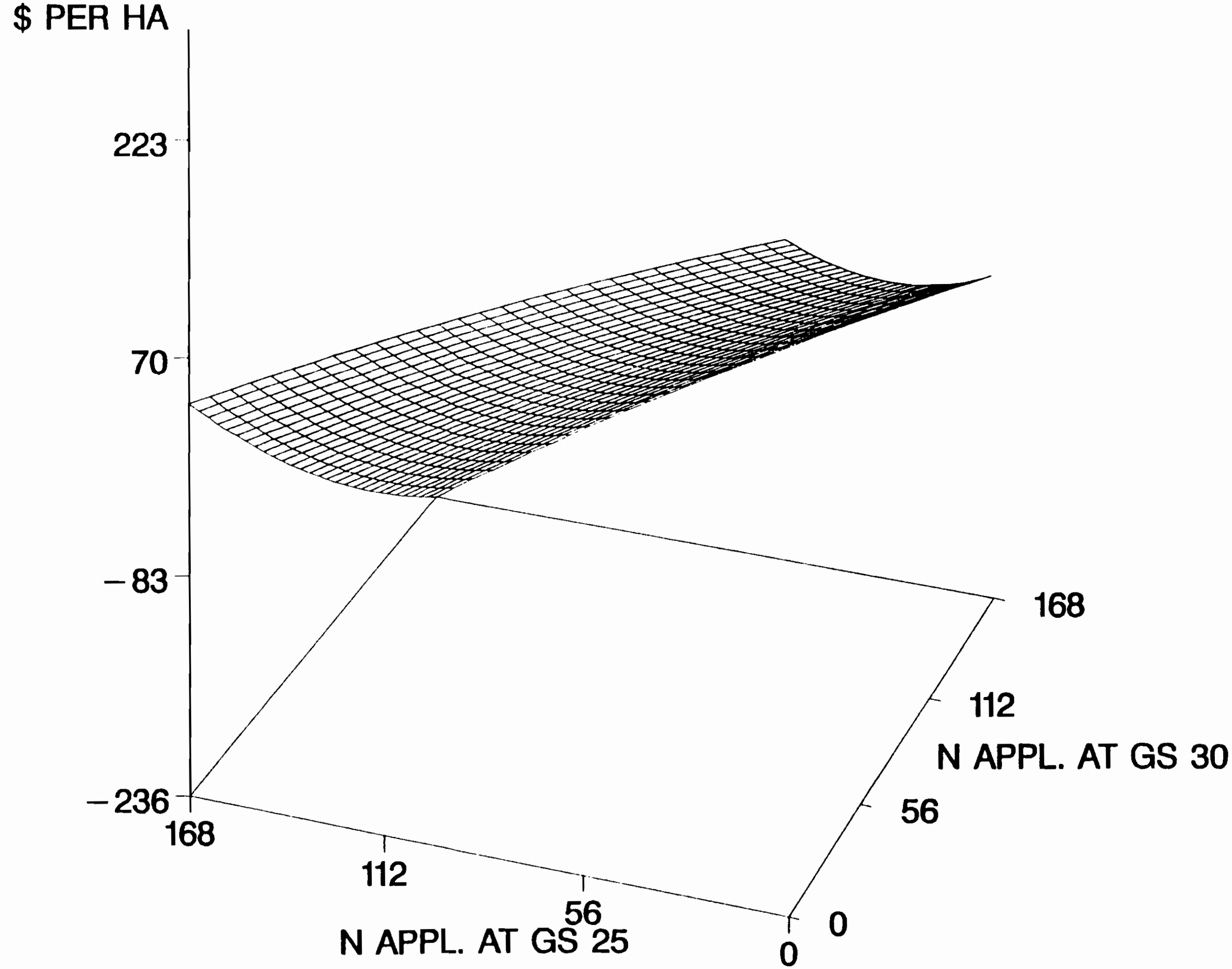
$ PER HA
291
106
-78
-263
168
112
56
0
N APPL. AT GS 25
168
112
56
0
N APPL. AT GS 30

location 25

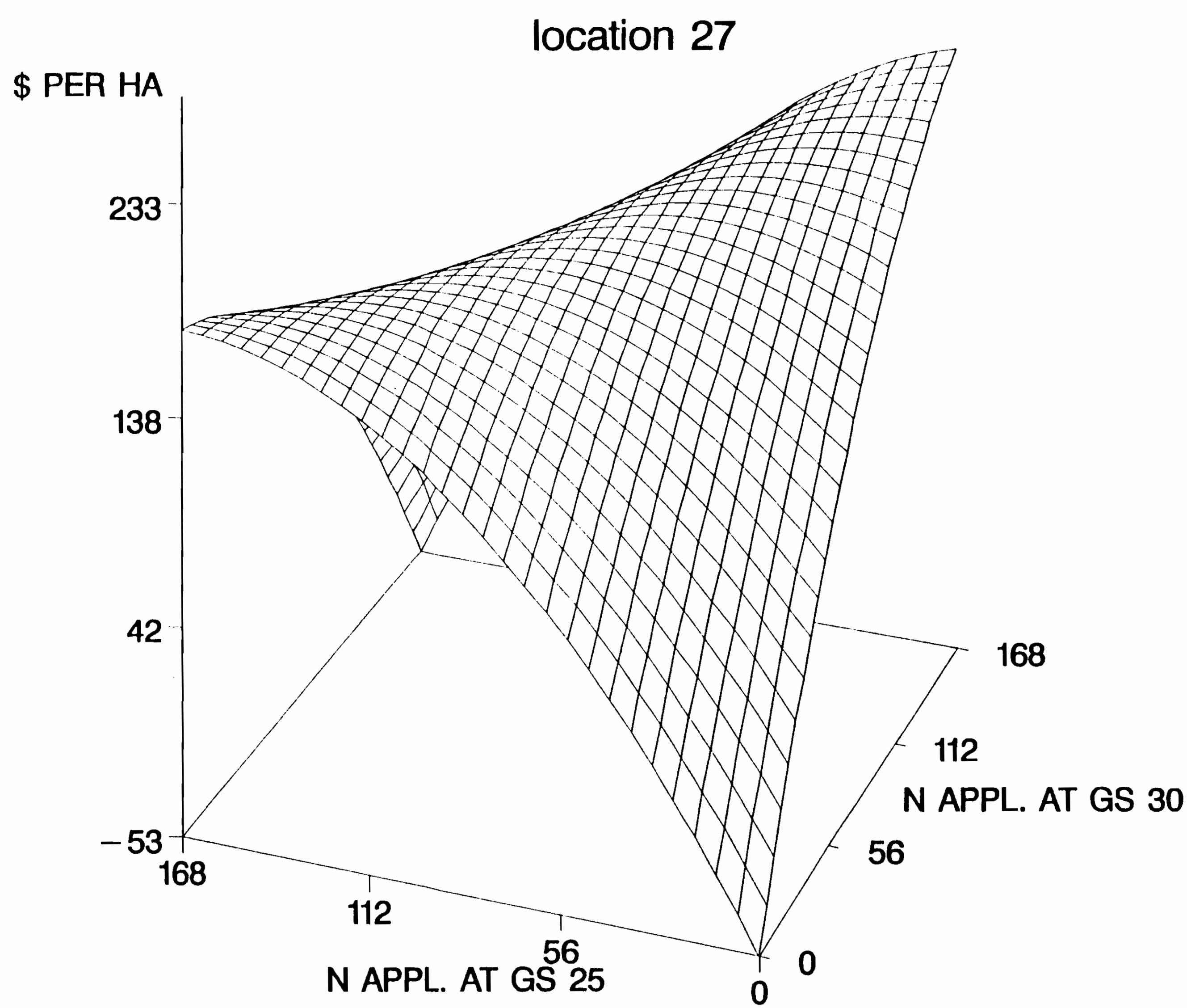


$ PER HA
97
9
−79
−167
168
112
56
N APPL. AT GS 25
0
0
56
112
168
N APPL. AT GS 30

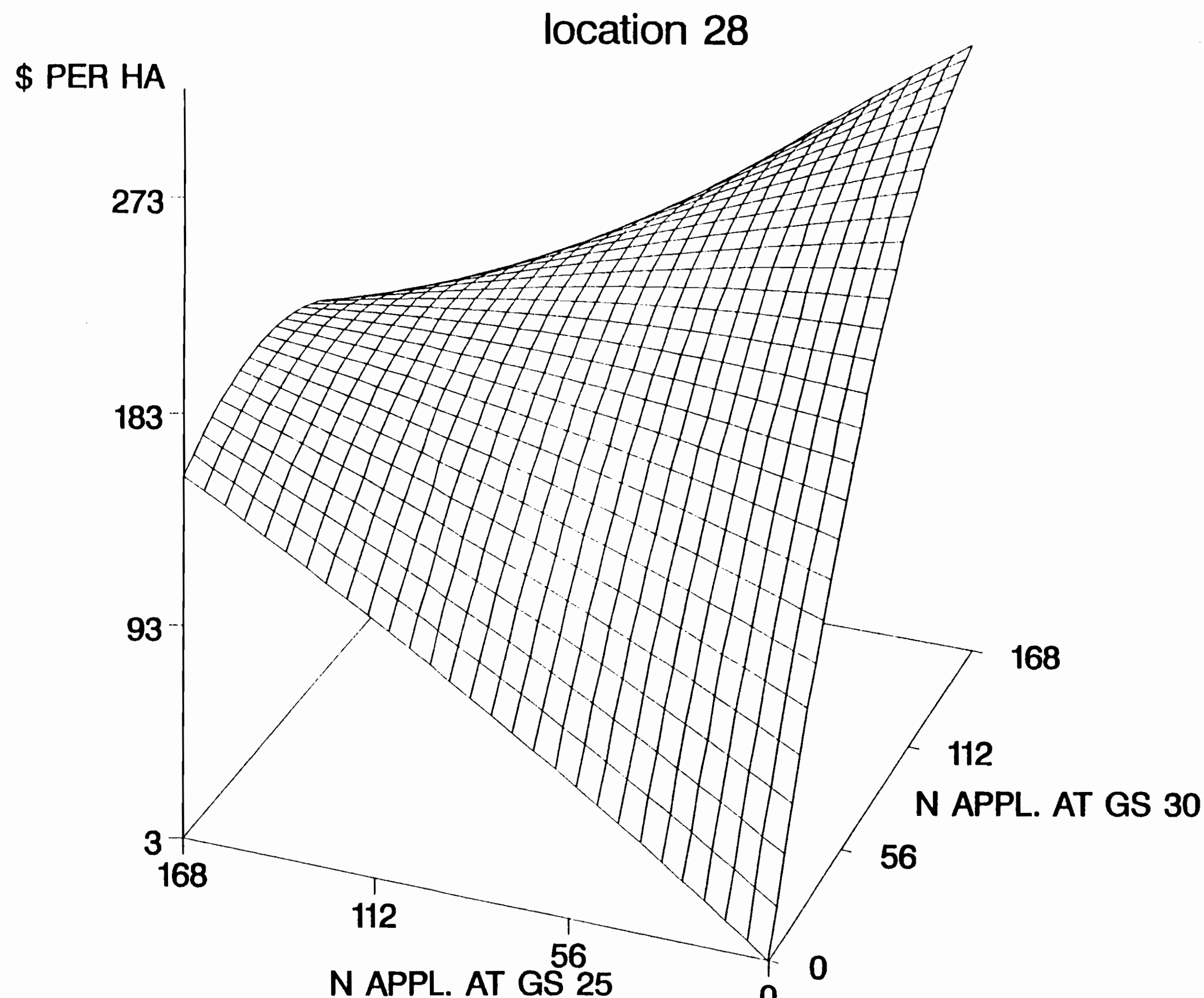
location 26



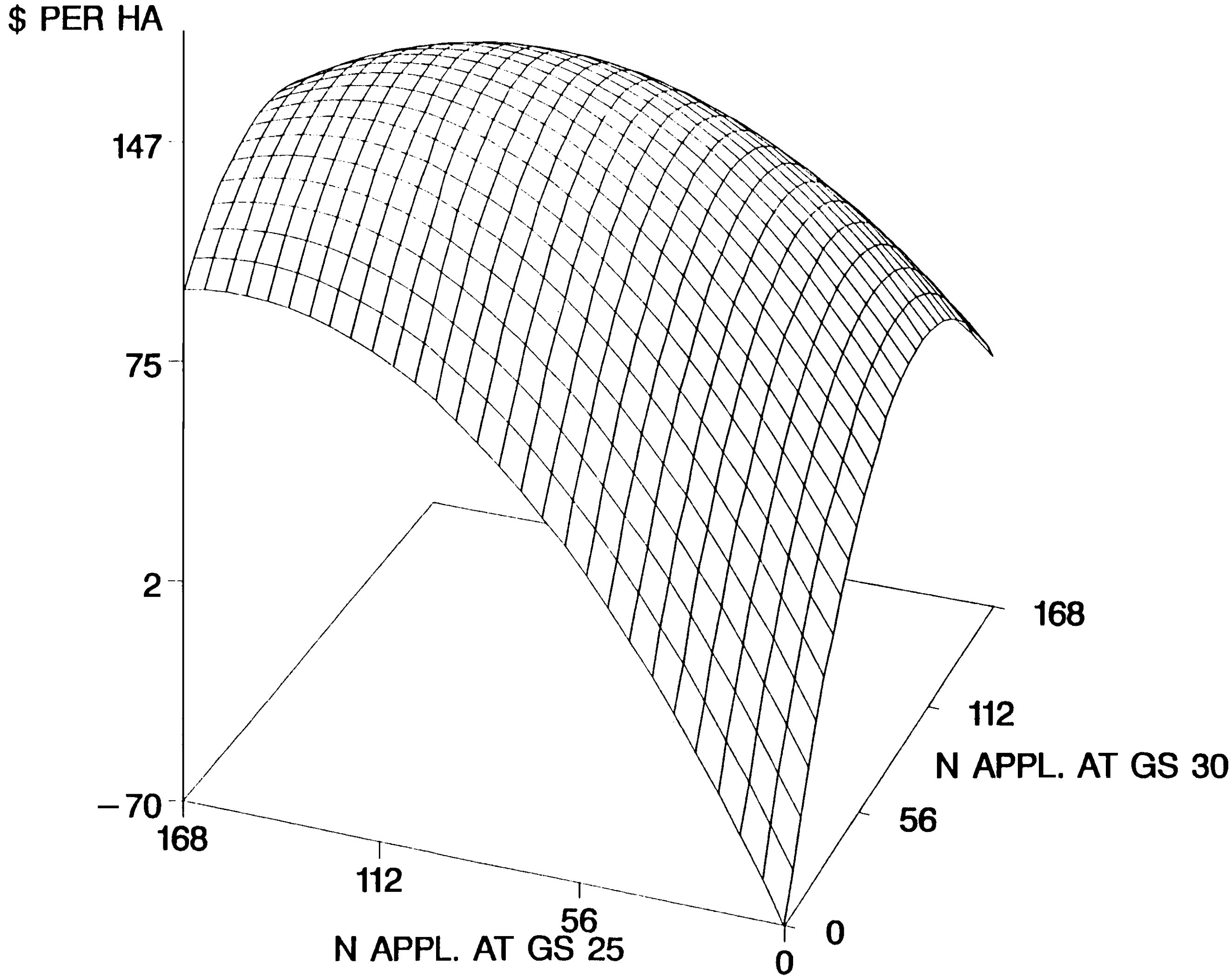
$ PER HA
223
70
−83
−236
168
112
56
N APPL. AT GS 25
0
0
56
N APPL. AT GS 30
112
168



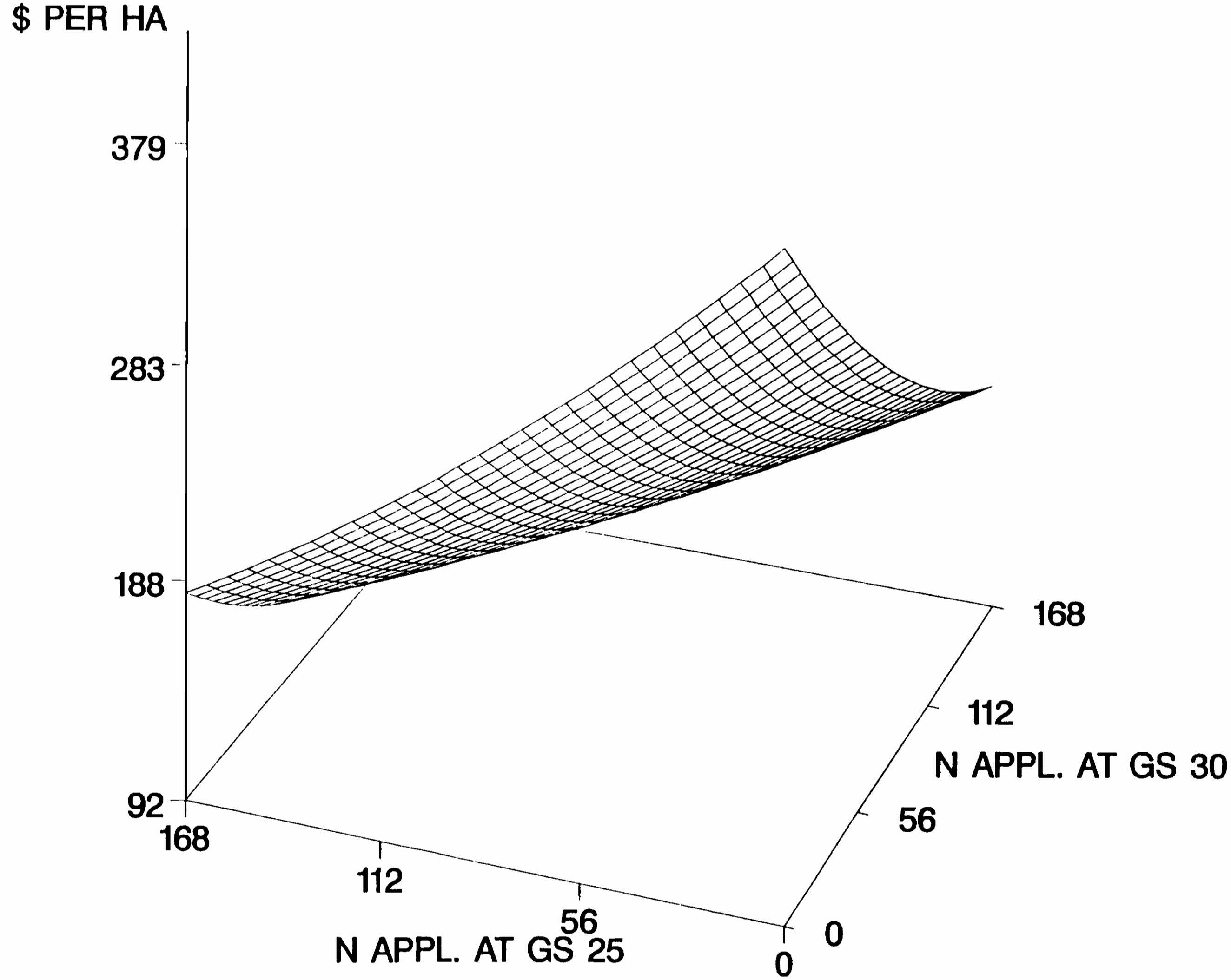
location 27
$ PER HA
233
138
42
−53
168
112
56
0
N APPL. AT GS 25
0
56
112
168
N APPL. AT GS 30

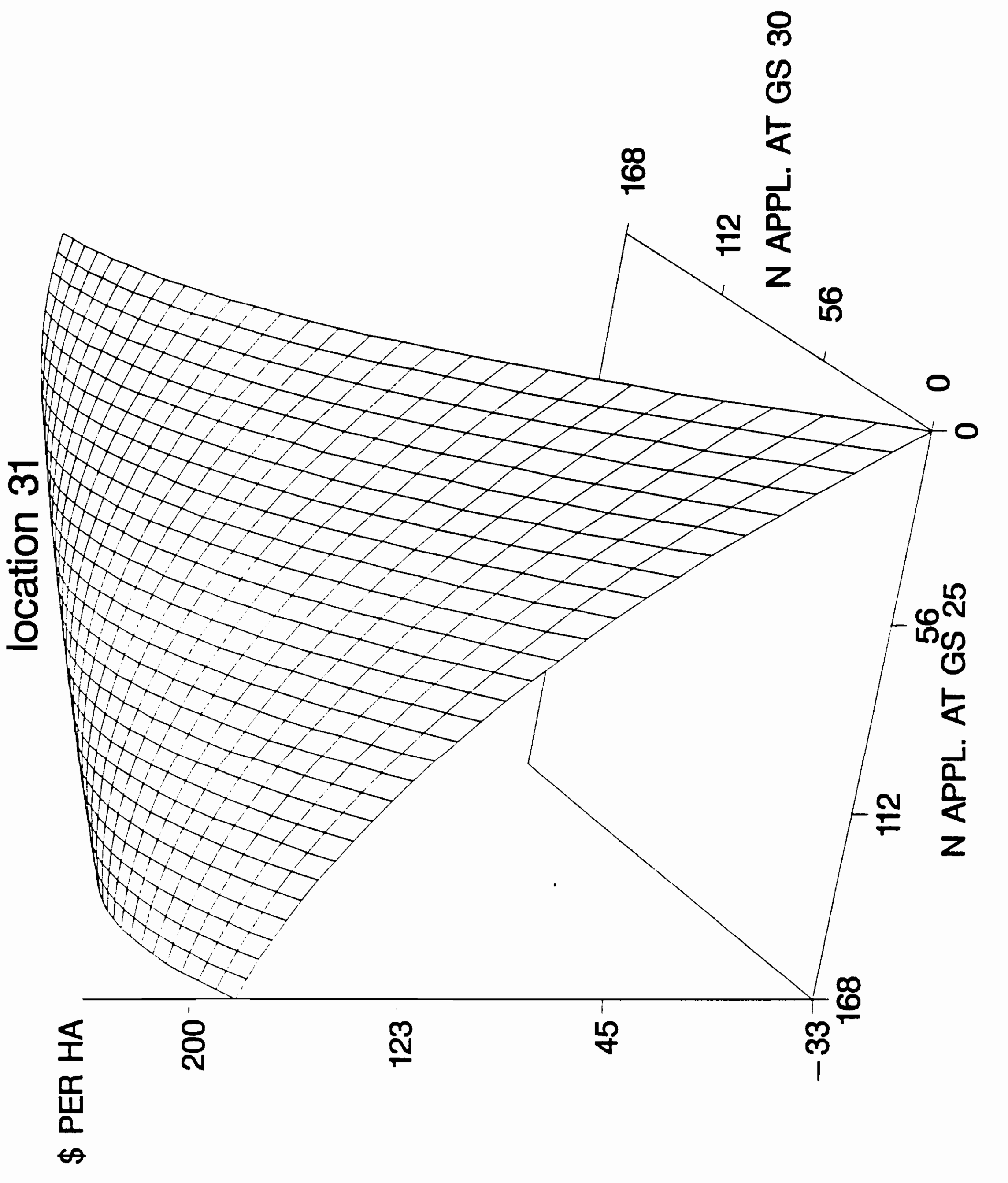

location 28
$ PER HA
273
183
93
3
168
112
56
N APPL. AT GS 25
0
0
56
112
168
N APPL. AT GS 30

location 29

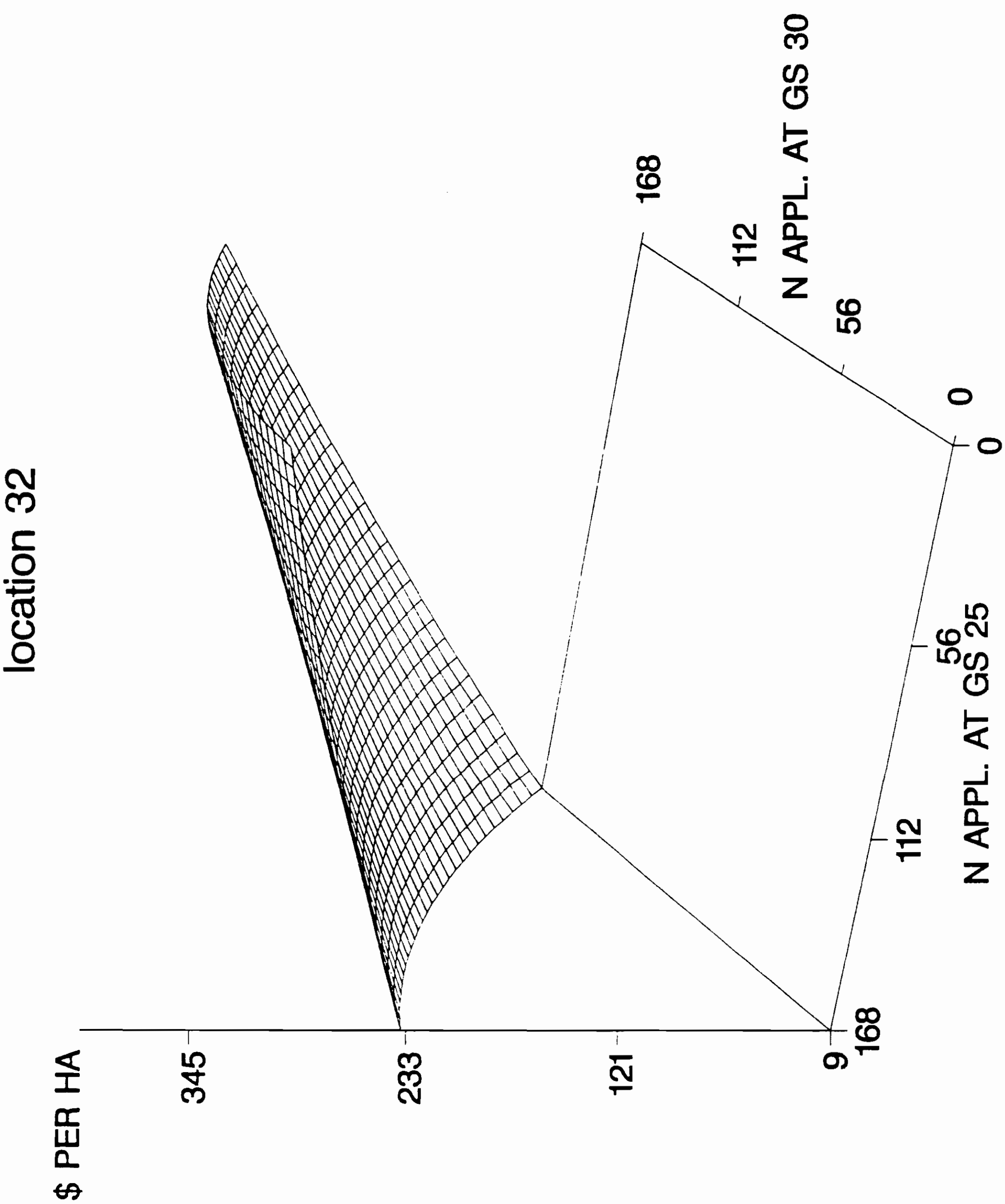

$ PER HA
147
75
2
−70
168
112
56
0
N APPL. AT GS 25
168
112
56
0
N APPL. AT GS 30

location 30

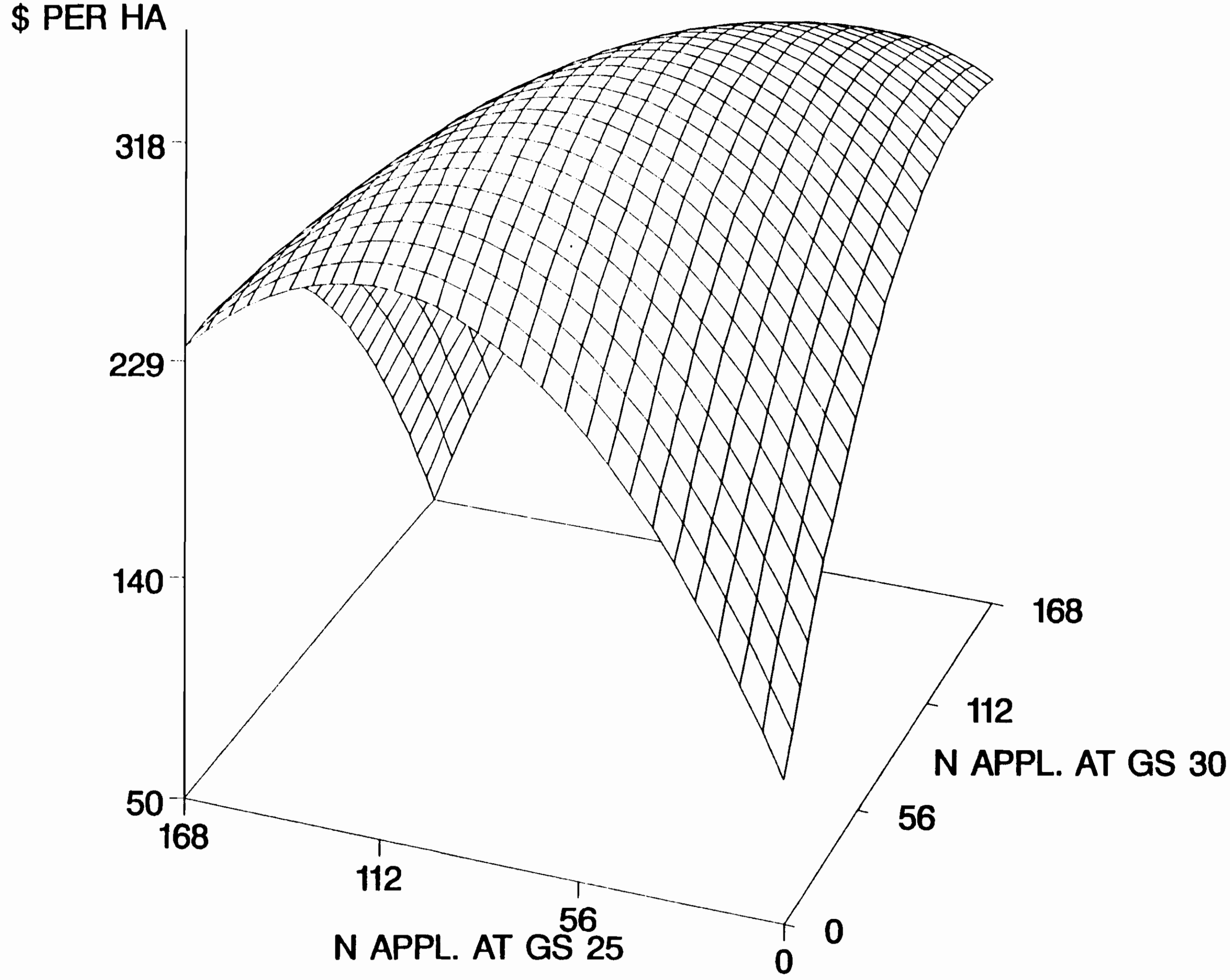

$ PER HA
379
283
188
92
168
112
56
0
N APPL. AT GS 25
168
112
56
0
N APPL. AT GS 30



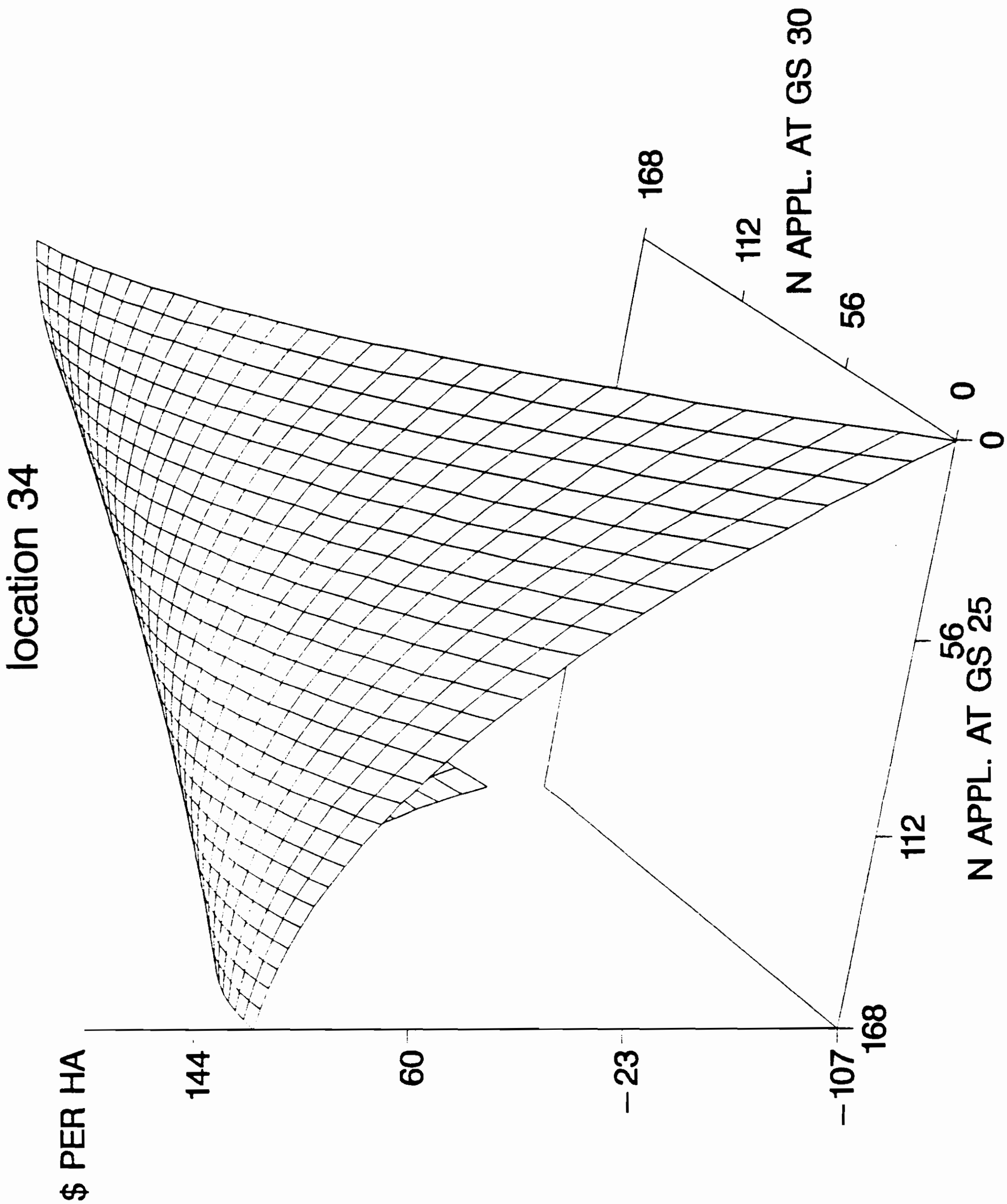
location 31
$ PER HA
200
123
45
−33
168
112
56
0
N APPL. AT GS 25
168
112
56
0
N APPL. AT GS 30


location 32
$ PER HA
345
233
121
9
168
112
56
0
N APPL. AT GS 25
168
112
56
0
N APPL. AT GS 30

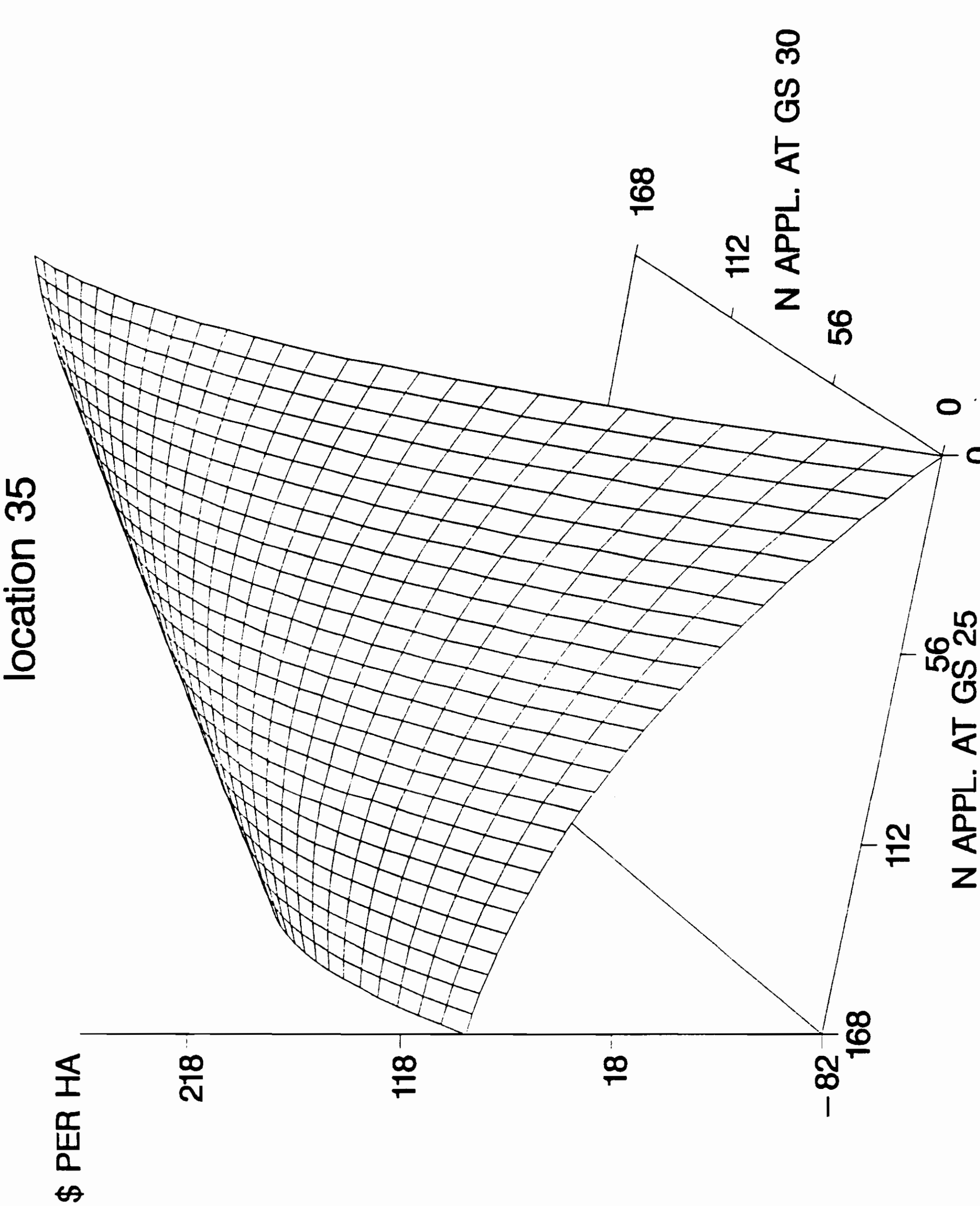
location 33



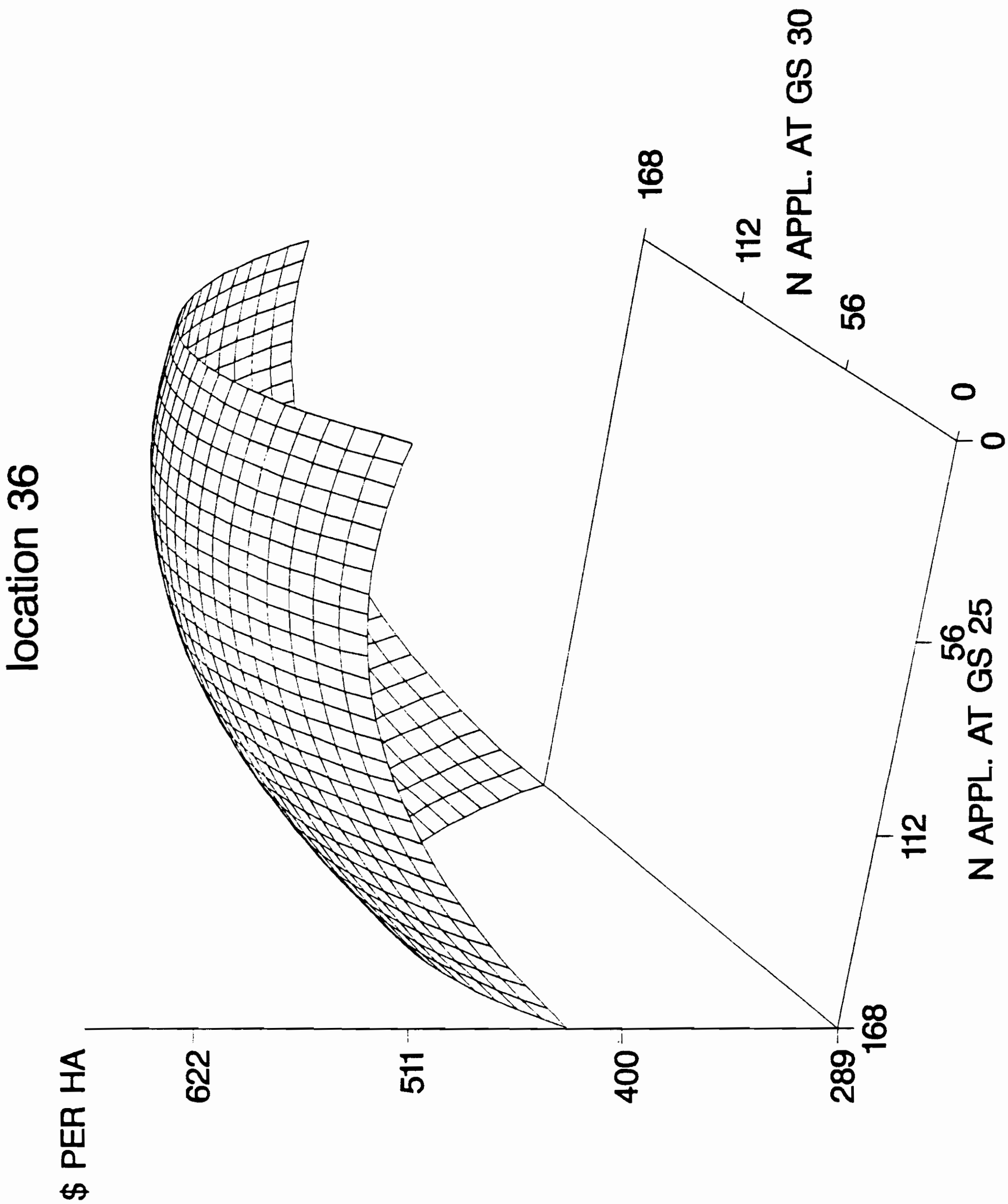
$ PER HA
318
229
140
50
168
112
56
0
N APPL. AT GS 25
168
112
56
0
N APPL. AT GS 30



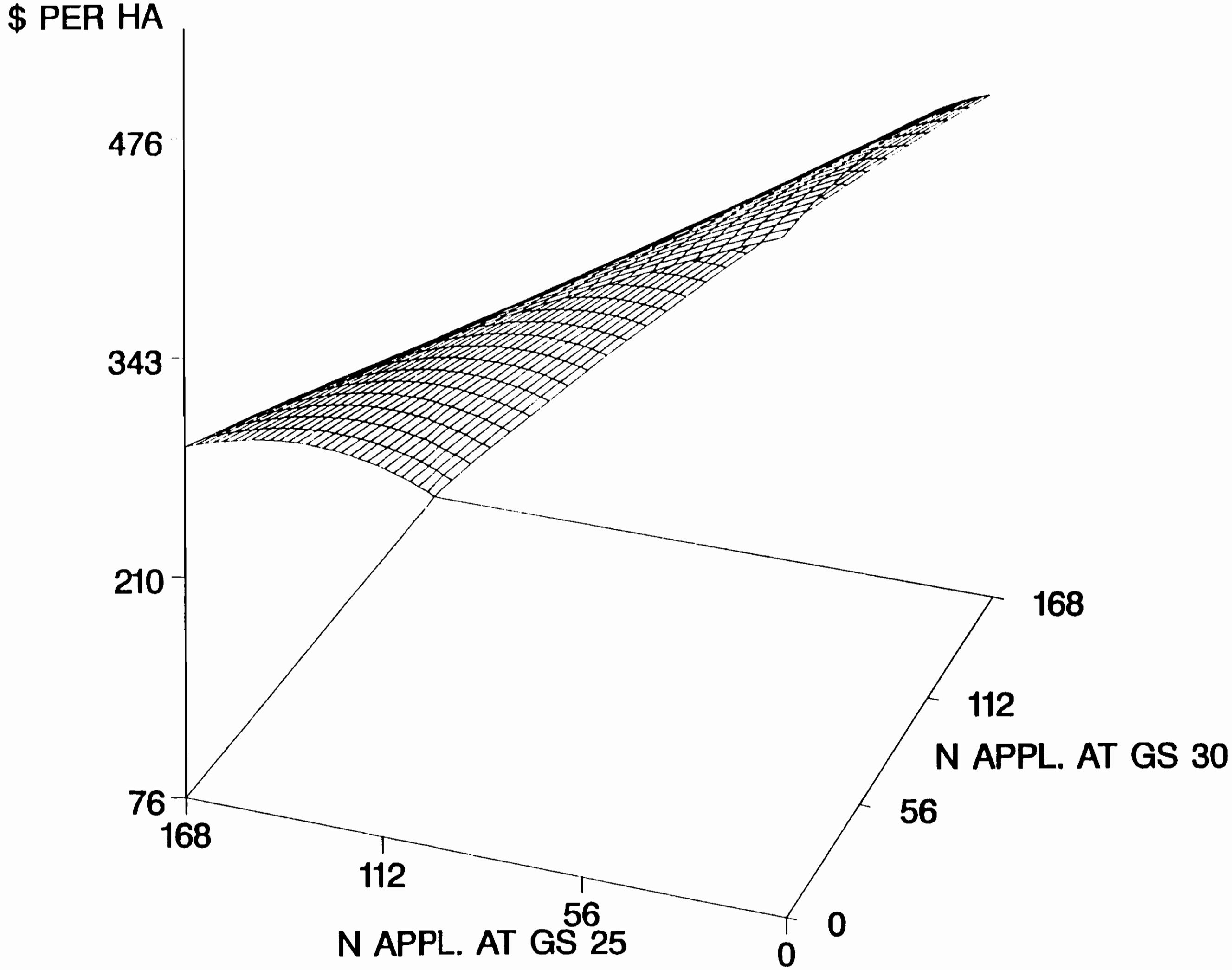
location 34
$ PER HA
144
60
−23
−107
168
112
56
0
N APPL. AT GS 25
N APPL. AT GS 30



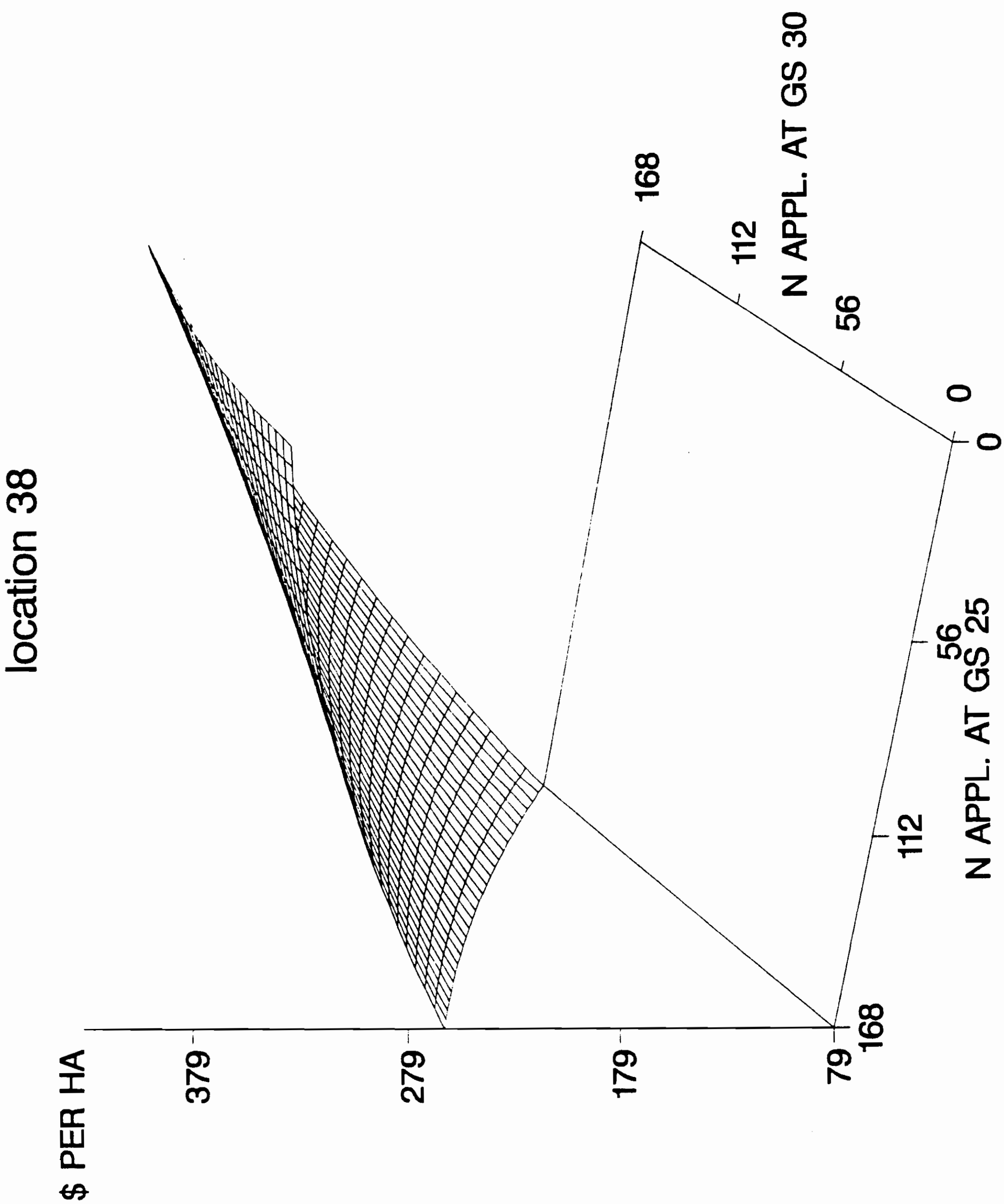
location 35
$ PER HA
218
118
18
−82
168
112
56
0
N APPL. AT GS 25
N APPL. AT GS 30


location 36
$ PER HA
622
511
400
289
168
112
56
0
N APPL. AT GS 25
168
112
56
0
N APPL. AT GS 30

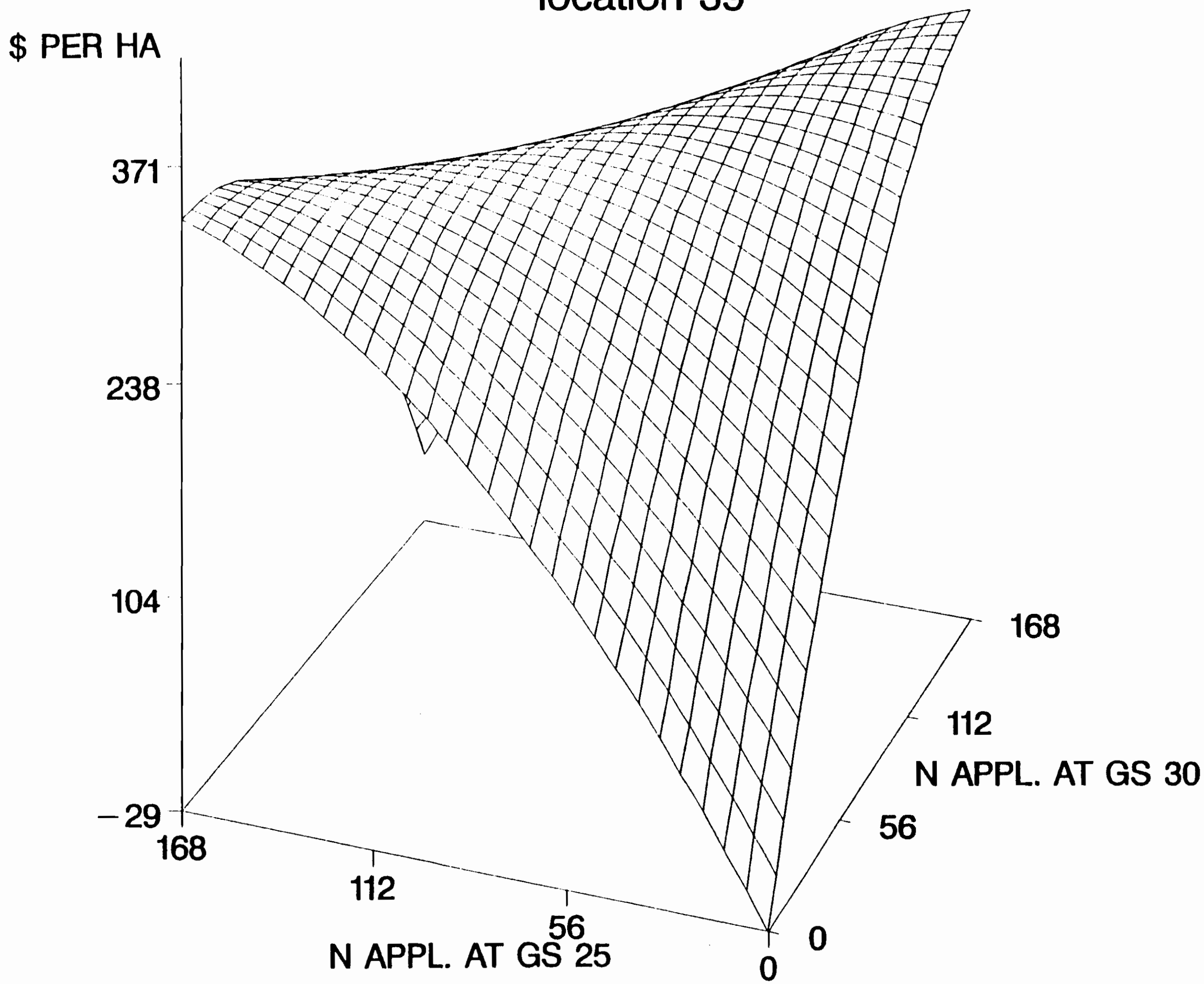
location 37



$ PER HA
476
343
210
76
168
112
56
N APPL. AT GS 25
0
0
56
N APPL. AT GS 30
112
168

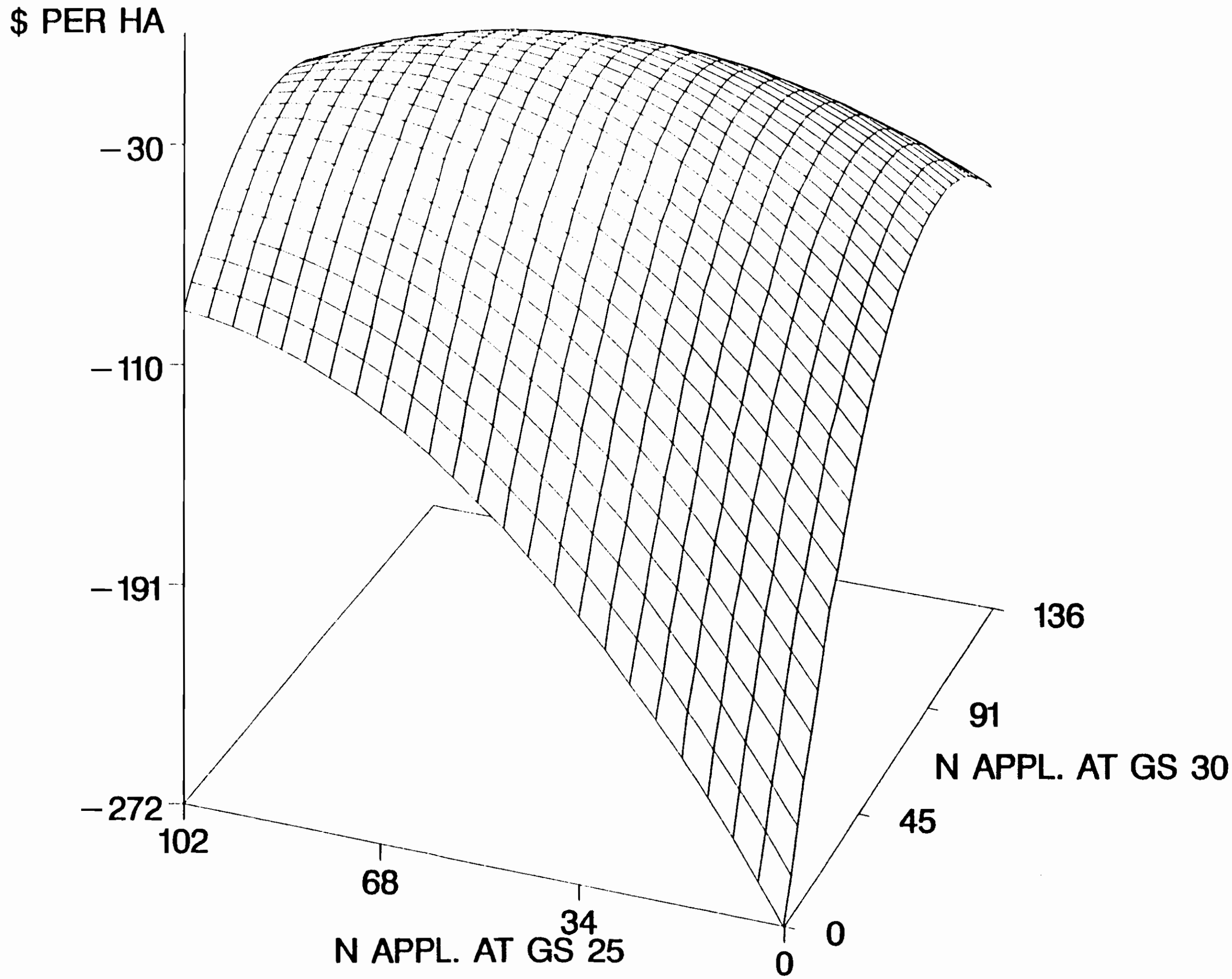

location 38
$ PER HA
379
279
179
79
168
112
56
N APPL. AT GS 25
0
0
56
112
168
N APPL. AT GS 30

location 39



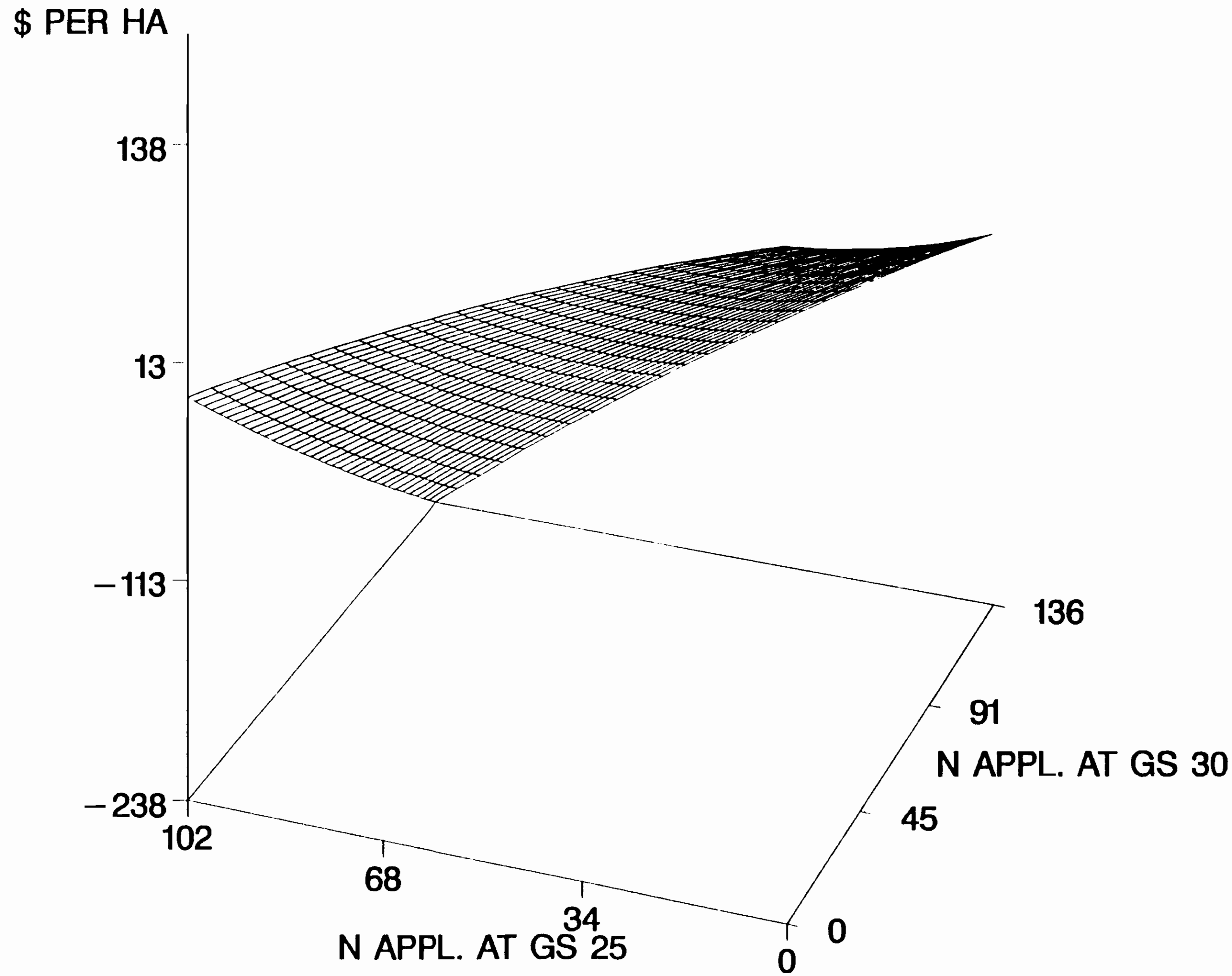
$ PER HA
371
238
104
– 29
168
112
56
0
N APPL. AT GS 25
0
56
112
168
N APPL. AT GS 30

location 40

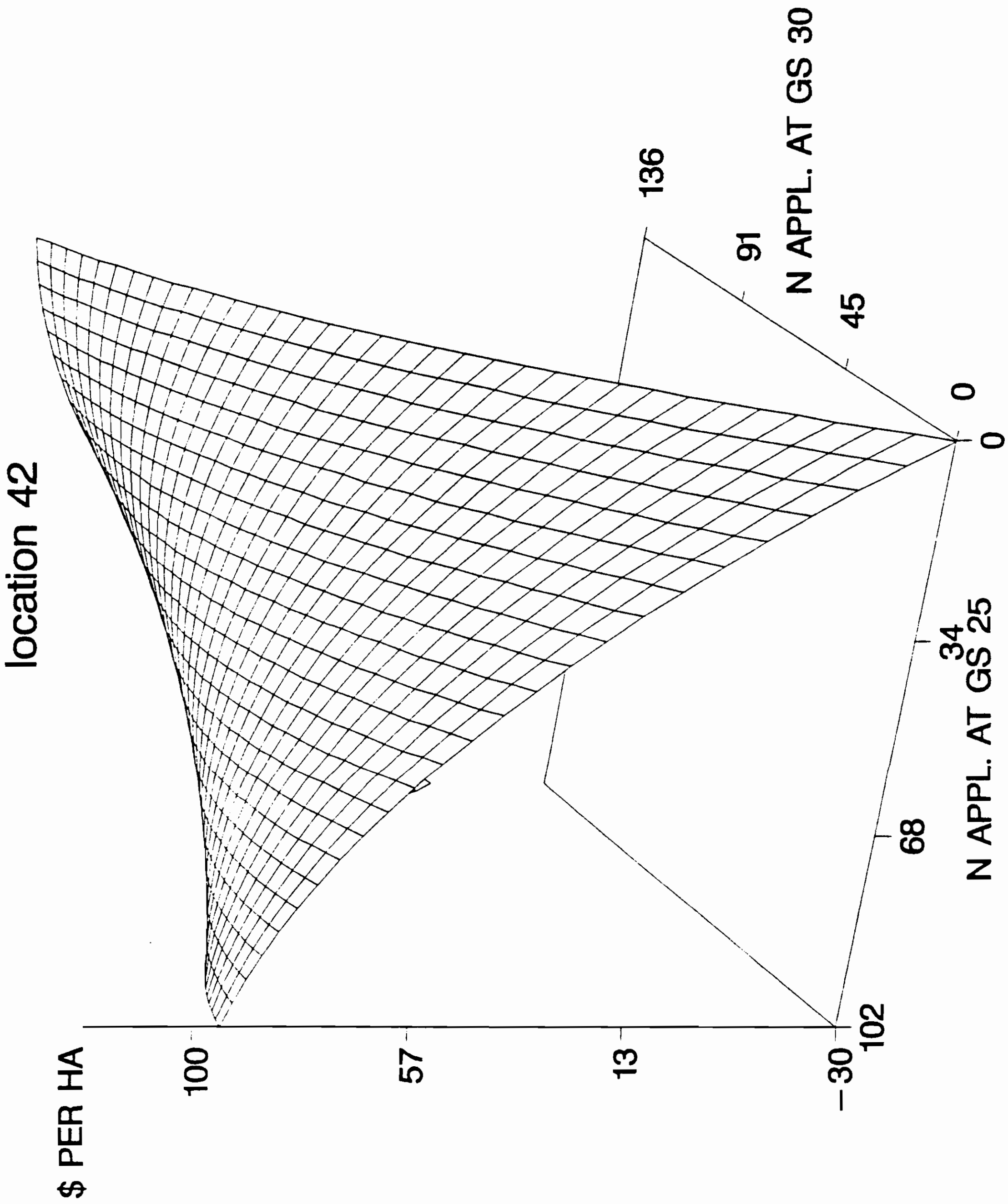


$ PER HA
-30
-110
-191
-272
102
68
34
0
N APPL. AT GS 25
136
91
45
0
N APPL. AT GS 30

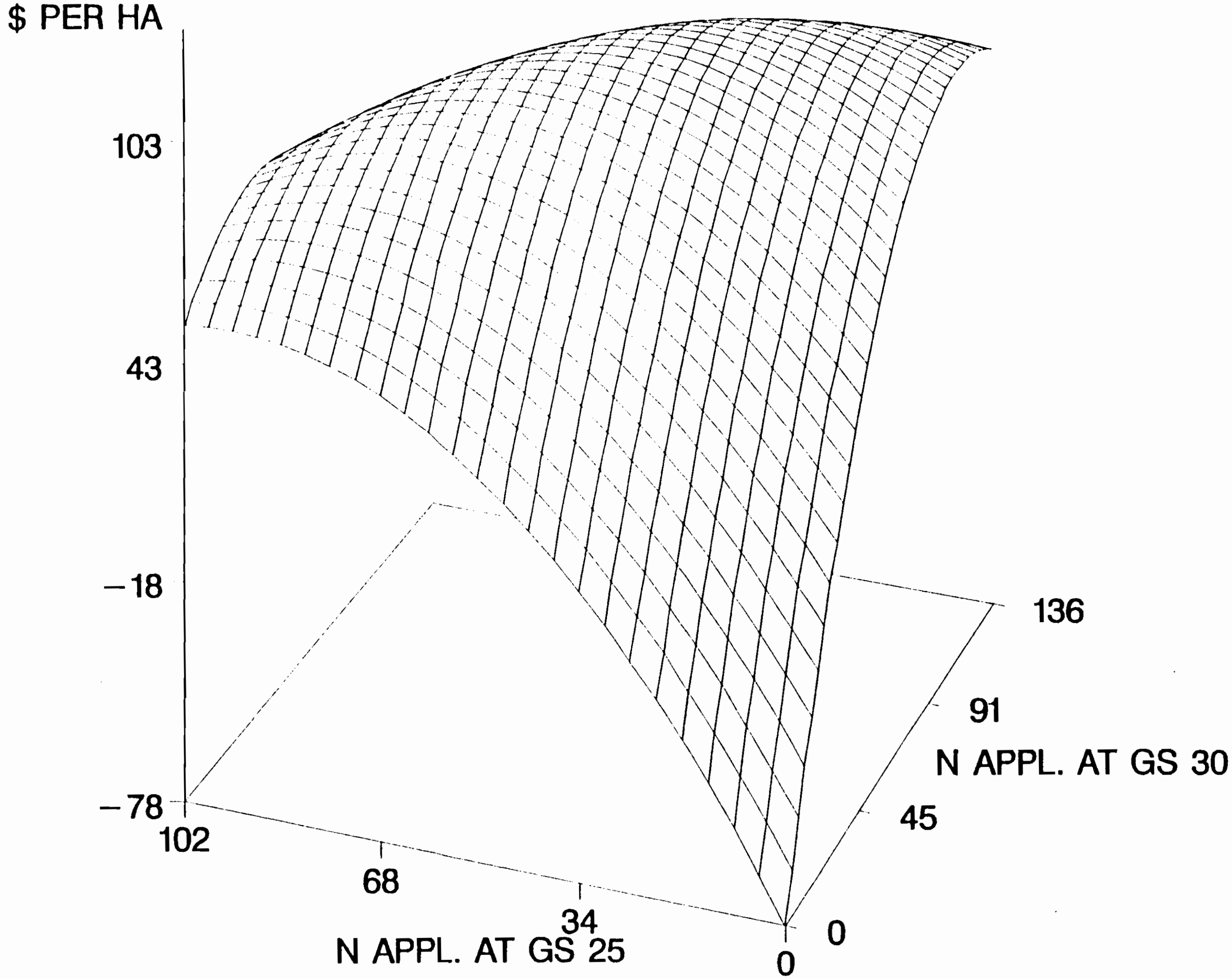
location 41



$ PER HA
138
13
−113
−238
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

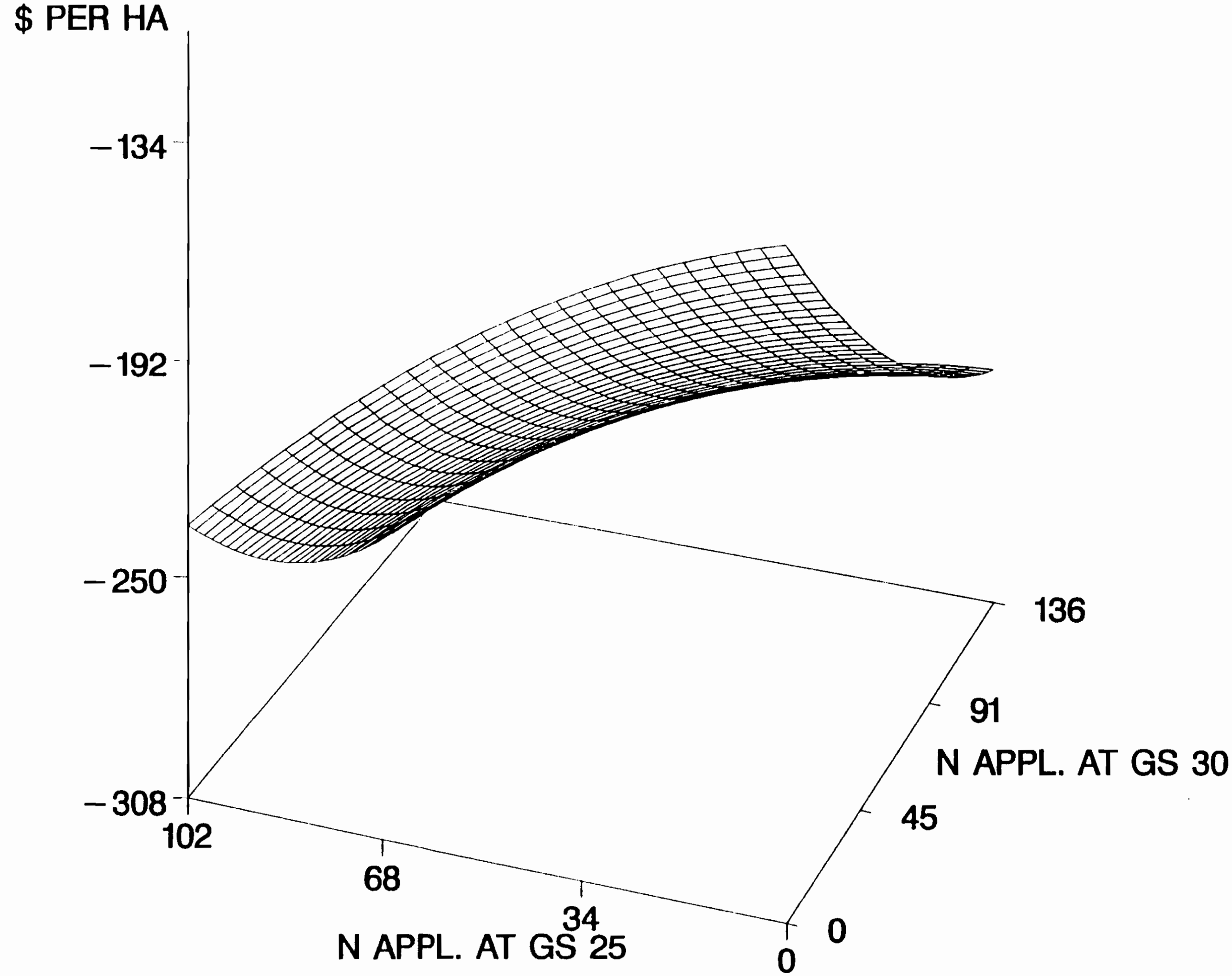

location 42
$ PER HA
100
57
13
−30
102
68
34
N APPL. AT GS 25
0
0
45
91
136
N APPL. AT GS 30

location 43

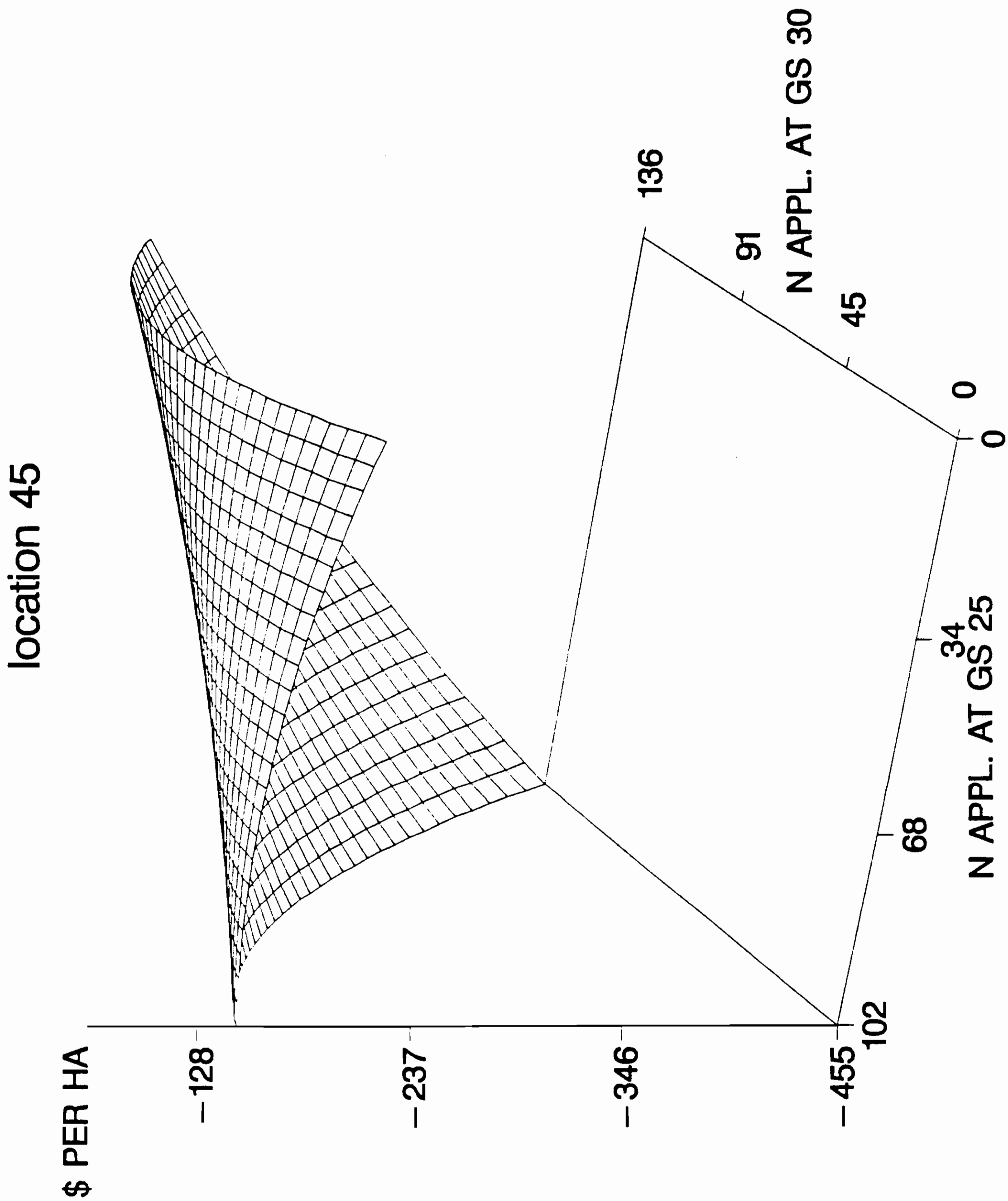


$ PER HA
103
43
−18
−78
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

location 44



$ PER HA
-134
-192
-250
-308
102
68
34
N APPL. AT GS 25
0
0
45
91
N APPL. AT GS 30
136



location 45
$ PER HA
-128
-237
-346
-455
102
68
34
0
N APPL. AT GS 25
0
45
91
136
N APPL. AT GS 30

APPENDIX H

SOIL PROFILE DESCRIPTIONS FOR EXPERIMENTAL LOCATIONS

Profile 1 - Pamunkey loam

Brandon Plantation, Prince George County

Ap-- 0 to 30 cm; dark brown (7.5YR 3/4) loam; moderate fine granular structure; friable, not sticky, plastic; many medium roots; clear smooth boundary.

Bt1-- 30 to 60 cm; strong brown (7.5YR 4/6) loam; weak medium subangular blocky structure; firm, sticky, very plastic; common fine roots; common faint clay films on the faces of peds; gradual smooth boundary.

Bt2-- 60 to 90 cm; strong brown (7.5YR 4/6) clay loam; weak medium subangular blocky structure; very firm, very sticky, very plastic; common fine roots; common faint clay films on faces of peds; gradual smooth boundary.

Bt3-- 90 to 124 cm; strong brown (7.5YR 4/6) sandy clay loam; weak medium subangular blocky structure; very firm, sticky, slightly plastic; few fine roots; common faint clay films; clear smooth boundary.

C1-- 124 to 152 cm; strong brown (7.5YR 4/6) loamy sand; massive; very friable, non-sticky, non-plastic; clear smooth boundary.

C2-- 152 to 180 cm; strong brown (7.5YR 5/8) sand; massive; very friable, non-sticky, non-plastic; twenty percent quartz pebbles.

Profile 2 - Bojac loamy sand

Camden Farms, Caroline County

Ap-- 0 to 20 cm; dark brown (7.5YR 3/4) loamy sand; weak fine granular structure; very friable, non-sticky, non-plastic; many medium and fine roots; clear smooth boundary.

AB-- 20 to 61 cm; strong brown (7.5YR 4/6) loamy sand; weak fine granular structure; very friable, non-sticky, non-plastic; common fine roots; diffuse smooth boundary.

Bt-- 61 to 99 cm; strong brown (7.5YR 4/8) sandy loam; weak medium subangular blocky structure; firm, non-sticky, non-plastic; common fine roots; few faint clay films on the faces of peds; diffuse smooth boundary.

C1-- 99 to 142 cm; strong brown (7.5YR 5/8) fine sand; single-grain; very friable, non-sticky, non-plastic; common fine roots to 120 cm; diffuse smooth boundary.

C2-- 142 to 180 cm; reddish yellow (7.5YR 6/6) sand; single-grain; very friable, non-sticky, non-plastic.

Profile 3 - Suffolk sandy loam

Chandler Farm, Westmoreland County

Ap-- 0 to 33 cm; dark yellowish brown (10YR 3/4) sandy loam; weak medium subangular blocky structure; firm, non-sticky, non-plastic; many medium and fine roots; gradual smooth boundary.

Bt-- 33 to 102 cm; strong brown (7.5YR 4/6) loam; moderate medium subangular blocky structure; very firm, slightly sticky, plastic; common fine roots; common distinct clay films on the faces of peds; diffuse smooth boundary.

C-- 102 to 180 cm; light yellowish brown (10YR 6/4) sand; single-grain; very friable, non-sticky, non-plastic; few fine roots to 120 cm.

Profile 4 - Emporia sandy loam

Corbin Hall, Middlesex County

Ap-- 0 to 28 cm; dark yellowish brown (10YR 3/4) sandy loam; weak fine granular structure; very friable, non-sticky, non-plastic; many medium and fine roots; clear smooth boundary.

E-- 28 to 50 cm; yellowish brown (10YR 5/4) sandy loam; weak fine granular structure; firm, slightly sticky, non-plastic; common fine roots; gradual smooth boundary.

Bt-- 50 to 90 cm; strong brown (7.5YR 5/6) sandy loam; few fine distinct light gray (N 7/) mottles; weak medium subangular blocky structure; firm, sticky, slightly plastic; common fine roots; common faint clay films on the faces of peds; gradual smooth boundary.

C1-- 90 to 175 cm; strong brown (7.5YR 5/8) sandy loam; common medium distinct light gray (N 7/) and yellow (10YR 7/6) mottles; massive; firm, slightly sticky, non-plastic; few fine roots to 107 cm; clear smooth boundary.

C2-- 175 to 180 cm; light yellowish brown (10YR 6/4) clay; many medium distinct light gray (N 7/) and common medium distinct strong brown (7.5YR 5/8) mottles; massive; very firm, sticky, very plastic.

Profile 5 - Cecil clay loam

Featherstone Farm, Amelia County

Ap-- 0 to 18 cm; dark reddish brown (5YR 3/4) clay loam; moderate medium granular structure; firm, slightly sticky, slightly plastic; many medium and fine roots; clear smooth boundary.

Bt1-- 18 to 50 cm; dark red (2.5YR 3/6) clay; strong coarse subangular blocky structure; very firm, very sticky, very plastic; many fine roots; common distinct clay films on the faces of peds; common fine flakes of mica; clear smooth boundary.

Bt2-- 50 to 142 cm; red (2.5YR 4/6) clay loam; common medium distinct red (2.5YR 5/8) mottles below 85 cm; many medium prominent light gray (2.5Y 7/2) mottles below 120 cm; medium coarse subangular blocky structure; firm, non-sticky, non-plastic; few fine roots to 66 cm; common prominent clay films on the faces of peds; many fine flakes of mica; clear smooth boundary.

C1-- 120 to 164 cm; red (2.5YR 4/6) loam; many medium prominent very pale brown (10YR 8/4) and yellowish red (5YR 5/8) mottles; weak fine granular structure; firm, non-sticky, non-plastic; few distinct clay flows; many fine flakes of mica; clear smooth boundary.

C2-- 164 to 180 cm; yellowish red (5YR 4/6) loam; few medium distinct very pale brown (10YR 8/4) mottles; massive; firm, non-sticky, non-plastic; many fine flakes of mica.

Profile 6 - State sandy loam

Liberty Hall, Westmoreland County

Ap-- 0 to 20 cm; dark brown (10YR 3/3) sandy loam; weak fine granular structure; firm, slightly sticky, non-plastic; many medium and fine roots; clear smooth boundary.

Bt-- 20 to 60 cm; dark yellowish brown (10YR 3/6) sandy clay loam; moderate medium subangular blocky structure; very firm, very sticky, plastic; common fine roots; many distinct clay films on the faces of peds; clear smooth boundary.

C-- 60 to 180 cm; yellowish brown (10YR 5/8) coarse sand; single-grain; very friable, non-sticky, non-plastic; ten percent quartz pebbles below 120 cm.

Profile 7 - Kempsville sandy loam

Montague Farms, Middlesex County

Ap-- 0 to 28 cm; dark brown (10YR 4/3) sandy loam; weak fine granular structure; friable, slightly sticky, slightly plastic; many medium and fine roots; clear smooth boundary.

Bt1-- 28 to 66 cm; strong brown (7.5YR 4/6) sandy loam; moderate medium subangular blocky structure; firm, slightly sticky, plastic; common fine roots; many faint clay films on the faces of peds; gradual smooth boundary.

Bt2-- 66 to 180 cm; strong brown (7.5YR 5/6) sandy loam; common medium distinct light brownish gray (10YR 6/2) and few medium distinct very pale brown (10YR 7/4) mottles; weak medium subangular blocky structure; friable, slightly sticky, non-plastic; few fine roots to 107 cm; few faint clay films on the faces of peds.

Profile 8 - Suffolk loamy sand

Randolph Farm, Hanover County

Ap-- 0 to 25 cm; dark yellowish brown (10YR 4/4) loamy sand; weak fine granular structure; friable, non-sticky, non-plastic; many medium and fine roots; clear smooth boundary.

Bt1-- 25 to 58 cm; dark yellowish brown (10YR 4/4) sandy loam; weak medium subangular blocky structure; firm, slightly sticky, plastic; common medium and fine roots; few faint clay films on the faces of peds; gradual smooth boundary.

Bt2-- 58 to 86 cm; strong brown (7.5YR 4/6) sandy loam; weak medium subangular blocky structure; firm, slightly sticky, plastic; common fine roots; few faint clay films on the faces of peds; gradual smooth boundary.

C1-- 86 to 127 cm; strong brown (7.5YR 5/8) loamy sand; massive; firm, non-sticky, non-plastic; few fine roots; diffuse smooth boundary.

C2-- 127 to 180 cm; very pale brown (10YR 7/4) loamy sand; many medium prominent yellowish brown (10YR 5/6) mottles; massive; friable, non-sticky, non-plastic; few fine roots to 150 cm.

Profile 9 - Catpoint loamy sand

Trice Farm, King & Queen County

Ap-- 0 to 20 cm; dark yellowish brown (10YR 3/4) loamy sand; weak fine granular structure; very friable, slightly sticky, non-plastic; many medium and fine roots; clear smooth boundary.

E-- 20 to 48 cm; yellowish brown (10YR 5/6) loamy sand; weak fine granular structure; very friable, slightly sticky, non-plastic; common fine roots; gradual smooth boundary.

Bt-- 48 to 80 cm; yellowish brown (10YR 5/6) loamy sand; weak fine granular structure; very friable, non-sticky, non-plastic; few fine roots; gradual smooth boundary.

C1-- 80 to 107 cm; yellowish brown (10YR 5/8) sand; weak very fine granular structure; very friable, non-sticky, non-plastic; few fine roots; clear smooth boundary.

C2-- 107 to 180 cm; gray (N 6/) clay; many medium distinct strong brown (7.5YR 5/8) mottles; weak very coarse subangular blocky structure; very firm, sticky, plastic; few fine roots to 137 cm.

Profile 10 - Savannah sandy loam

Chandler Farm, Richmond County

Ap-- 0 to 18 cm; dark brown (7.5YR 4/4) sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many fine and medium roots; clear smooth boundary.

Bt-- 18 to 58 cm; strong brown (7.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; firm, sticky, plastic; common fine and medium roots; many faint clay films on faces of peds; gradual smooth boundary.

C1-- 58 to 84 cm; yellowish brown (10YR 5/6) loamy sand; weak very fine granular structure; very friable, nonsticky, nonplastic; few fine roots; gradual smooth boundary.

C2-- 84 to 109 cm; yellowish brown (10YR 5/4) sandy loam; massive; very firm, nonsticky, nonplastic; gradual smooth boundary.

Bt'-- 109 to 160 cm; yellowish red (5YR 4/6) sandy clay loam; weak coarse subangular blocky structure; firm, sticky, plastic; common faint caly films on faces of peds; gradual smooth boundary.

C'-- 160 to 180 cm; strong brown (7.5YR 5/8) loamy sand; weak fine granular structure; very friable, nonsticky, nonplastic.

Profile 11 - State sandy loam

Liberty Hall, Westmoreland County

Ap-- 0 to 25 cm; dark brown (10YR 4/3) sandy loam; moderate fine granular structure; friable, slightly sticky, slightly plastic; many fine and medium roots; clear smooth boundary.

Bt-- 25 to 64 cm; yellowish red (5YR 4/6) sandy clay loam; weak medium subangular blocky structure; firm, sticky, plastic; common fine and medium roots; common faint clay films on faces of peds; gradual smooth boundary.

C1-- 64 to 104 cm; yellowish red (5YR 4/6) sand; single grain; loose, nonsticky, nonplastic; few fine roots; gradual smooth boundary.

C2-- 104 to 160 cm; yellowish red (5YR 5/8) gravelly sand; single grain; loose, nonsticky, nonplastic; 40 percent quartz fragments; diffuse smooth boundary.

C3-- 160 to 180 cm; reddish yellow (7.5YR 6/8) sand; single grain; loose, nonsticky, nonplastic.

Profile 12 - Munden sandy loam

Montague Farms, Essex County

Ap-- 0 to 25 cm; dark brown (10YR 4/3) sandy loam; moderate fine granular structure; friable, nonsticky, slightly plastic; many fine roots; clear smooth boundary.

E-- 25 to 51 cm; dark brown (10YR 4/3) sandy loam; massive; very firm, nonsticky, nonplastic; common fine roots; gradual smooth boundary.

Bt-- 51 to 86 cm; dark yellowish brown (10YR 4/4) sandy clay loam; weak medium subangular blocky structure; firm, slightly sticky, slightly plastic; common fine roots; common faint clay films on faces of peds; gradual smooth boundary.

C1-- 86 to 147 cm; brown (10YR 5/3) loamy sand; few yellowish brown (10YR 5/8) mottles; massive; firm, slightly sticky, nonplastic; few fine roots; gradual smooth boundary.

C2-- 147 to 180 cm; light yellowish brown (10YR 6/4) sand; single grain; loose, nonsticky, nonplastic.

Profile 13 - Pamunkey loam

Brandon Plantation, Prince George County

Ap-- 0 to 25 cm; dark yellowish brown (10YR 4/4) loam; weak fine granular structure; friable, slightly sticky, slightly plastic; many fine roots; clear smooth boundary.

Bt1-- 25 to 165 cm; dark yellowish brown (10YR 4/6) clay loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; many fine roots to 75 cm, few fine roots to 125 cm; many distinct clay films on faces of peds; diffuse smooth boundary.

Bt2-- 165 to 180 cm; dark brown (7.5YR 4/4) sandy clay loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many distinct clay films on faces of peds.

Profile 14 - Conetoe fine sand

Minor Farm, King & Queen County

Ap-- 0 to 25 cm; brown (7.5YR 5/4) fine sand; single grain; very friable, nonsticky, nonplastic; common fine roots; clear smooth boundary.

E-- 25 to 48 cm; reddish yellow (7.5YR 6/6) fine sand; single grain; loose, nonsticky, nonplastic; few fine roots; clear smooth boundary.

Bt-- 48 to 94 cm; yellowish red (5YR 5/8) loamy sand; weak fine granular structure; friable, slightly sticky, nonplastic; few fine roots; gradual smooth boundary.

C1-- 94 to 135 cm; reddish yellow (7.5YR 6/8) sand; weak very fine granular structure; loose, nonsticky, nonplastic; clear smooth boundary.

C2-- 135 to 152 cm; strong brown (7.5YR 5/6) clay; weak coarse subangular blocky structure; firm, sticky, plastic; clear smooth boundary.

Css-- 152 to 168 cm; strong brown (7.5YR 5/6) clay intertongued with strong brown (7.5YR 5/6) sand; many distinct gray (N 6/) clay mottles; weak coarse subangular blocky and single grain structure; clay is very firm, slightly sticky, plastic; sand is loose, nonsticky, nonplastic; few slickensides; clear smooth boundary.

Cssg-- 168 to 180 cm; pinkish gray (7.5YR 6/2) clay; few distinct strong brown (7.5YR 5/8) mottles; very firm, slightly sticky, plastic; few slickensides.

Profile 15 - Pamunkey loam

Brandon Plantation, Prince George County

Ap-- 0 to 23 cm; dark brown (10YR 4/3) silt loam; moderate medium granular structure; friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

Bt1-- 23 to 137 cm; yellowish brown (10YR 5/6) clay loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt2-- 137 to 180 cm; yellowish brown (10YR 5/6) sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; common faint clay films on faces of peds.

Profile 16 - Altavista fine sandy loam

Randolph Farm, New Kent County

Ap-- 0 to 30 cm; dark brown (10YR 3/3) fine sandy loam; weak fine granular structure; friable, slightly sticky, slightly plastic; common fine roots; abrupt smooth boundary.

E-- 30 to 66 cm; yellowish brown (10YR 5/4) loamy sand; single grain; friable, nonsticky, nonplastic; common fine roots; gradual smooth boundary.

Bt-- 66 to 127 cm; dark yellowish brown (10YR 4/4) sandy clay loam; few faint grayish brown (10YR 5/2) mottles; weak fine subangular blocky structure; friable, slightly sticky, slightly plastic; few fine roots; many distinct sand bridges and clay films on faces of peds; diffuse smooth boundary.

C-- yellowish brown (10YR 5/6) sand; single grain; loose, nonsticky, nonplastic.

Profile 17 - Kempsville sandy loam

Montague Farms, King & Queen County

Ap-- 0 to 23 cm; dark brown (10YR 3/3) sandy loam; weak fine granular structure;

friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

E-- 23 to 41 cm; pale brown (10YR 6/3) sandy clay loam; weak fine granular structure; friable, slightly sticky, slightly plastic; common fine roots; clear smooth boundary.

Bt1-- 41 to 74 cm; dark yellowish brown (10YR 4/6) sandy clay loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; few fine roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt2-- 74 to 107 cm; yellowish brown (10YR 5/6) sandy clay loam; common distinct pale brown (10YR 6/3) mottles; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many distinct clay films on faces of peds; gradual smooth boundary.

Bt3-- 107 to 157 cm; strong brown (7.5YR 4/6) sandy clay; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many distinct clay films on faces of peds; gradual smooth boundary.

Bt4-- 157 to 180 cm; yellowish brown (10YR 5/6) sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many distinct clay films on faces of peds.

Profile 18 - Suffolk fine sandy loam

Montague Farms, Middlesex County

Ap-- 0 to 25 cm; dark grayish brown (10YR 4/2) loamy sand; single grain; loose, nonsticky, nonplastic; many fine roots; abrupt smooth boundary.

E-- 25 to 50 cm; light yellowish brown (10YR 6/4) loamy sand; single grain; loose, nonsticky, nonplastic; common fine roots; clear smooth boundary.

Bt1-- 50 to 130 cm; dark yellowish brown (10YR 4/6) sandy clay loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; few fine roots; many distinct clay films on faces of peds; gradual smooth boundary.

C-- 130 to 180 cm; light gray (10YR 7/2) loamy sand; single grain; loose, nonsticky, nonplastic.

Profile 19 - State sandy loam

Liberty Hall, Westmoreland County

Ap-- 0 to 18 cm; dark brown (10YR 4/3) loamy sand; weak fine granular structure; loose, nonsticky, nonplastic; many fine roots; abrupt smooth boundary.

Bt1-- 18 to 66 cm; dark yellowish brown (10YR 4/6) sandy clay loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt2-- 66 to 102 cm; yellowish brown (10YR 5/6) loamy sand; single grain; loose, nonsticky, nonplastic; many distinct clay films; diffuse smooth boundary.

C1-- 102 to 135 cm; brownish yellow (10YR 6/6) sand; single grain; loose, nonsticky, nonplastic; diffuse smooth boundary.

C2-- 135 to 180 cm; dark yellowish brown (10YR 4/6) sand; single grain; loose, nonsticky, nonplastic.

Profile 20 - Emporia sandy loam

Roslyn Farm, Dinwiddie County

Ap-- 0 to 23 cm; brown (10YR 5/3) sandy loam; weak fine granular structure; friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

Bt1-- 23 to 53 cm; dark yellowish brown (10YR 4/6) sandy clay loam; weak fine subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; common faint clay films on faces of peds; gradual smooth boundary.

Bt2-- 53 to 107 cm; yellowish brown (10YR 5/8) sandy clay loam; common distinct grayish brown (10YR 5/2) mottles; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; few fine roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt3-- 107 to 132 cm; yellowish brown (10YR 5/8) sandy loam; many distinct gray (10YR 6/1) and yellowish red (5YR 5/8) mottles; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; common faint clay films on faces of peds; gradual smooth boundary.

Bt4-- 132 to 180 cm; brownish yellow (10YR 6/8) sandy loam; many distinct gray (10YR 6/1) and yellowish red (5YR 5/8) mottles; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; common faint clay films on faces of peds.

Profile 21 - Bojac sandy loam

Fitchett Farm, Accomack County

Ap-- 0 to 25 cm; dark brown (10YR 3/3) sandy loam; weak medium granular structure; very friable, nonsticky, nonplastic; many fine and medium roots; abrupt smooth boundary.

Bt1-- 25 to 79 cm; dark brown (7.5YR 4/4) sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine and medium roots; many medium distinct clay films on faces of peds; gradual smooth boundary.

Bt2-- 79 to 94 cm; dark brown (7.5YR 4/4) loamy sand; single grain; loose, nonsticky, nonplastic; few fine roots; common medium distinct clay films on faces of peds; gradual smooth boundary.

C1-- 94 to 150 cm; strong brown (7.5YR 5/6) sand; single grain; loose, nonsticky, nonplastic; few fine roots; diffuse smooth boundary.

C2-- 150 to 180 cm; yellowish brown (10YR 5/6) sand; dark yellowish brown (10YR 3/4) mottles; single grain; loose, nonsticky, nonplastic.

Profile 22 - Bojac sandy loam

Byrnes Farm, Northampton County

Ap-- 0 to 23 cm; dark brown (10YR 4/3) sandy loam; weak fine and medium granular structure; very friable, nonsticky, nonplastic; many fine and medium roots; abrupt smooth boundary.

Bt1-- 23 to 48 cm; dark yellowish brown (10YR 4/4) sandy clay loam; weak fine and medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine and medium roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt2-- 48 to 79 cm; dark brown (7.5YR 4/4) sandy loam; massive; very friable, nonsticky, nonplastic; common fine and medium roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt3-- 79 to 130 cm; dark yellowish brown (10YR 4/4) sandy clay loam; weak fine and medium subangular blocky structure; friable, slightly sticky, slightly plastic; few fine and medium roots; many distinct clay films on faces of peds; abrupt smooth boundary.

C-- 130 to 180 cm; pale brown (10YR 6/3) and brown (10YR 5/3) coarse sand; single grain; loose, nonsticky, nonplastic; 5 percent quartz pebbles.

Profile 23 - Emporia fine sandy loam

Roslyn Farms, Dinwiddie County

Ap-- 0 to 23 cm; dark brown (10YR 4/3) fine sandy loam; weak fine and medium granular structure; very friable, slightly sticky, slightly plastic; many fine and medium roots; abrupt smooth boundary.

Bt1-- 23 to 74 cm; yellowish brown (10YR 5/4) sandy clay loam; weak medium subangular blocky structure; friable, sticky, plastic; common fine and medium roots; many distinct clay films on faces of peds; diffuse smooth boundary.

Bt2-- 74 to 97 cm; yellowish brown (10YR 5/4) sandy clay loam; many pale brown (10YR 6/3) mottles; weak mediumsubangular blocky structure; friable, sticky, plastic; few fine and medium roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt3-- 97 to 140 cm; strong brown (7.5YR 5/6) sandy clay loam; many red (2.5YR 4/6) and light brownish gray (2.5Y 6/2) mottles; moderate medium subangular blocky structure; firm, sticky, plastic; many distinct clay films on faces of peds; gradual smooth boundary.

Bt4-- 140 to 180 cm; yellowish brown (10YR 5/6) sandy loam; many light brownish gray (2.5Y 6/2) and very pale brown (10YR 7/4) mottles; massive; firm, slightly sticky, slightly plastic.

Profile 24 - Pamunkey loam

Brandon Plantation, Prince George County

Ap-- 0 to 25 cm; dark brown (10YR 4/3) loam; moderate medium granular structure; friable, slightly sticky, slightly plastic; many fine and medium roots; abrupt smooth boundary.

Bt1-- 25 to 76 cm; dark yellowish brown (10YR 4/4) clay loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine and medium roots; many distinct clay films on faces of peds; few fine flakes of mica; diffuse smooth boundary.

Bt2-- 76 to 127 cm; dark yellowish brown (10YR 4/4) clay loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; few fine roots; many distinct clay films on faces of peds; few fine flakes of mica; gradual smooth boundary.

Bt3-- 127 to 180 cm; strong brown (7.5YR 4/6) fine sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many distinct clay films on faces of peds; common fine flakes of mica; gradual smooth boundary.

Profile 25 - State sandy loam

Randolph Farm, New Kent County

Ap-- 0 to 15 cm; dark grayish brown (10YR 4/2) loamy sand; weak fine granular structure; very friable, nonsticky, nonplastic; many fine and medium roots; abrupt smooth boundary.

E/B-- 15 to 30 cm; yellowish brown (10YR 5/4) sandy loam; weak fine granular structure; very friable, nonsticky, nonplastic; few fine roots; gradual smooth boundary.

Bt-- 30 to 76 cm; dary yellowish brown (10YR 4/4) sandy clay loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many distinct clay films on faces of peds; 2 percent coarse fragments; gradual smooth boundary.

C1-- 76 to 114 cm; yellowish brown (10YR 5/4) very gravelly loamy coarse sand; few medium distinct dark reddish brown (5YR 3/2) mottles; single grain; loose, nonsticky, nonplastic; 35 percent coarse fragments; diffuse smooth boundary.

C2-- 114 to 150 cm; light yellowish brown (10YR 6/4) and very pale brown (10YR 7/4) very gravelly coarse sand; single grain; loose, nonsticky, nonplastic; 55 percent coarse fragments.

Profile 26 - Emporia loam

Montague Farms, Essex County

Ap-- 0 to 20 cm; dark brown (10YR 3/3) loam; moderate medium granular structure; friable, slightly sticky, slightly plastic; many fine and medium roots; abrupt smooth boundary.

E/B-- 20 to 33 cm; dark brown (10YR 4/3) loam; weak medium granular structure; friable, slightly sticky, slightly plastic; many fine and medium roots; gradual smooth boundary.

Bt1-- 33 to 107 cm; dark yellowish brown (10YR 4/6) sandy clay loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine and medium roots; many distinct clay films on faces of peds; diffuse smooth boundary.

Bt2-- 107 to 150 cm; dark yellowish brown (10YR 4/6) sandy clay loam; many medium distinct light brownish gray (10YR 6/2) mottles; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many distinct clay films on faces of peds; diffuse smooth boundary.

C-- 150 to 180 cm; light yellowish brown (10YR 6/4) sandy loam with pockets of sandy clay loam; many medium distinct light brownish gray (10YR 6/2) mottles; massive; friable, slightly sticky, slightly plastic.

Profile 27 - Altavista sandy loam

Liberty Hall, Westmoreland County

Ap-- 0 to 23 cm; dark grayish brown (10YR 4/2) sandy loam; moderate medium granular structure; very friable, slightly sticky, slightly plastic; many fine and medium roots; abrupt smooth boundary.

Bt-- 23 to 69 cm; light olive brown (2.5Y 5/4) loam; moderate medium subangular blocky structure; friable, sticky, plastic; common fine and medium roots; many distinct clay films on faces of peds; gradual smooth boundary.

C1-- 69 to 99 cm; light yellowish brown (2.5Y 6/4) loamy sand; single grain; loose, nonsticky, nonplastic; diffuse smooth boudndary.

C2-- 99 to 155 cm; light gray (2.5Y 7/2) sand; common fine light yellowish brown (2.5Y 6/4) mottles; single grain; loose, nonsticky, nonplastic; diffuse smooth boundary.

C3-- 155 to 180 cm; light brownish gray (2.5Y 6/2) coarse sand; single grain; loose, nonsticky, nonplastic.

Profile 28 - Bojac sandy loam

Fitchett Farm, Accomack County

Ap-- 0 to 25 cm; dark grayish brown (10YR 4/2) sandy loam; weak fine granular structure; friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

Bt1-- 25 to 97 cm; dark brown (7.5YR 4/4) sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; many distinct clay films on faces of peds; diffuse smooth boundary.

Bt2-- 97 to 122 cm; yellowish brown (10YR 5/4) loamy sand; weak medium subangular blocky structure; loose, sticky, plastic; common distinct clay films on faces of peds; diffuse smooth boundary.

C-- 122 to 180 cm; light yellowish brown (10YR 6/4) sand; single grain; loose, nonsticky, nonplastic.

Profile 29 - Bojac sandy loam

Dodd Farm, Northampton County

Ap-- 0 to 25 cm; dark brown (10YR 4/3) sandy loam; weak fine granular structure; friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

Bt1-- 25 to 107 cm; dark yellowish brown (10YR 4/4) sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; many distinct clay films on faces ofpeds; diffuse smooth boundary.

Bt3-- 107 to 137 cm; yellowish brown (10YR 5/4) loamy sand; weak medium subangular blocky structure; very friable, nonsticky, nonplastic; 2 percent rock fragments; common distinct clay films on faces of peds; diffuse smooth boundary.

C-- 137 to 180 cm; light yellowish brown (10YR 6/4) sand; single grain; loose, nonsticky, nonplastic.

Profile 30 - Emporia fine sandy loam

Roslyn Farm, Dinwiddie County

Ap-- 0 to 25 cm; brown (10YR 5/3) fine sandy loam; weak fine granular structure; friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

Bt1-- 25 to 76 cm; yellowish brown (10YR 5/8) clay loam; common medium distinct reddish brown (2.5YR 4/4) mottles; moderate medium subangular blocky structure; friable, sticky, plastic; common fine roots; many distinct clay films on faces of peds; diffuse smooth boundary.

Bt2-- 76 to 114 cm; yellowish brown (10YR 5/6) clay; common medium distinct pale brown (10YR 6/3) mottles; moderate medium subangular blocky structure; friable, sticky, plastic; common fine roots; many distinct clay films on faces of peds; diffuse smooth boundary.

Bt3-- 114 to 150 cm; mottled yellowish brown (10YR 5/6), reddish brown (2.5YR 4/4), and gray (10YR 6/1) clay loam; moderate medium subangular blocky structure; friable, sticky, plastic; many distinct clay films on faces of peds; diffuse smooth boundary.

Bt4-- 150 to 180 cm; mottled dark yellowish brown (10YR 6/4), light gray (10YR 7/1), and yellowish brown (10YR 5/6) sandy clay; weak medium subangular blocky structure; firm, sticky, plastic; many distinct clay films on faces of peds.

Profile 31 - Pamunkey loam

Brandon Plantation, Prince George County

Ap-- 0 to 25 cm; dark yellowish brown (10YR 4/4) loam; weak fine granular structure; friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

Bt1-- 25 to 127 cm; dark yellowish brown (10YR 4/4) clay loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; many distinct clay films on faces of peds; diffuse smooth boundary.

Bt2-- 127 to 165 cm; dark yellowish brown (10YR 4/4) clay loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; many distinct clay films on faces of peds; diffuse smooth boundary.

Bt3-- 165 to 180 cm; dark brown (7.5YR 4/4) sandy clay loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many distinct clay films on faces of peds.

Profile 32 - Kempsville loamy sand

Randolph Farm, Hanover County

Ap-- 0 to 25 cm; dark brown (10YR 4/3) loamy sand; weak fine granular structure; friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

Bt1-- 25 to 76 cm; dark brown (7.5YR 4/4) sandy clay loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt2-- 76 to 109 cm; strong brown (7.5YR 4/6) sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt3-- 109 to 150 cm; yellowish red (5YR 4/6) sandy loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; few fine roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt4-- 150 to 180 cm; strong brown (7.5YR 4/6) sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many distinct clay films on faces of peds.

Profile 33 - Kempsville loam

Montague Farms, Middlesex County

Ap-- 0 to 25 cm; dark brown (10YR 4/3) loam; weak fine granular structure; friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

Bt1-- 25 to 76 cm; strong brown (7.5YR 4/6) loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt2-- 76 to 114 cm; yellowish red (5YR 4/6) sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; 2 percent rock fragments; many distinct clay films on faces of peds; gradual smooth boundary.

Bt3-- 114 to 147 cm; yellowish red (5YR 4/6) gravelly coarse sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; 5 percent rock fragments; many distinct clay films on faces of peds; gradual smooth boundary.

Bt4-- 147 to 180 cm; yellowish red (5YR 4/6) gravelly coarse sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; 30 percent rock fragments; many distinct clay films on faces of peds.

Profile 34 - Suffolk fine sandy loam

Montague Farms, Middlesex County

Ap-- 0 to 23 cm; grayish brown (10YR 5/2) fine sandy loam; weak fine granular structure; friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

Bt1-- 23 to 74 cm; yellowish brown (10YR 5/4) fine sandy loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; many fine roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt2-- 74 to 104 cm; yellowish brown (10YR 5/6) fine sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; many distinct clay films on faces of peds; gradual smooth boundary.

C1-- 104 to 142 cm; pale brown (10YR 6/3) and light brownish gray (10YR 6/2) fine loamy sand; single grain; loose, nonsticky, nonplastic; gradual smooth boundary.

C2-- 142 to 180 cm; pale brown (10YR 6/3) and light brownish gray (10YR 6/2) fine sand; single grain; loose, nonsticky, nonplastic.

Profile 35 - State coarse sandy loam

Liberty Hall, Westmoreland County

Ap-- 0 to 20 cm; dark grayish brown (10YR 4/2) coarse sandy loam; weak fine granular structure; friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

Bt1-- 20 to 71 cm; strong brown (7.5YR 4/6) coarse sandy loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; many fine roots; many distinct clay films on faces of peds; diffuse smooth boundary.

Bt2-- 71 to 107 cm; strong brown (7.5YR 4/6) coarse loamy sand; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many distinct clay films on faces of peds; diffuse smooth boundary.

C-- 107 to 180 cm; brownish yellow (10YR 6/6) coarse sand; single grain; loose, nonsticky, nonplastic.

Profile 36 - Pamunkey loam

Camden Farms, Caroline County

Ap-- 0 to 23 cm; dark brown (7.5YR 4/4) loam; weak fine granular structure; friable, slightly sticky, slightly plastic; common fine flakes of mica; many fine roots; abrupt smooth boundary.

Bt1-- 23 to 74 cm; yellowish red (5YR 4/6) clay loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; many fine flakes of mica; common fine roots; many distinct clay films on faces of peds; diffuse smooth boundary.

Bt2-- 74 to 119 cm; yellowish red (5YR 4/6) loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many fine flakes of mica; many distinct clay films on faces of peds; gradual smooth boundary.

Bt3-- 119 to 157 cm; dark brown (7.5YR 4/4) very fine sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; many fine flakes of mica; many distinct clay films on faces of peds; gradual smooth boundary.

C-- 157 to 180 cm; dark brown (7.5YR 4/4) fine sand; single grain; loose, nonsticky, nonplastic; many fine flakes of mica.

Profile 37 - Hayter loam

Whitethorn Farm, Montgomery County

Ap-- 0 to 25 cm; dark brown (10YR 4/3) loam; weak fine granular structure; friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

Bt1-- 25 to 117 cm; dark brown (7.5YR 4/4) loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; many distinct clay films on faces of peds; clear smooth boundary.

gravel and cobble bed at 117 cm

Profile 38 - Hayter loam

Whitethorn Farm, Montgomery County

Ap-- 0 to 25 cm; dark brown (10YR 4/3) loam; weak fine granular structure; friable, slightly sticky, slightly plastic; many fine roots; abrupt smooth boundary.

Bt1-- 25 to 117 cm; dark brown (7.5YR 4/4) loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; many distinct clay films on faces of peds; clear smooth boundary.

gravel and cobble bed at 117 cm

Profile 39 - Ross fine sandy loam

Agronomy Research Farm, Giles County

Ap-- 0 to 36 cm; very dark grayish brown (10YR 3/2) fine sandy loam; moderate fine granular structure; friable, slightly sticky, slightly plastic; common fine flakes of mica; many fine roots; abrupt smooth boundary.

Bt1-- 36 to 127 cm; dark brown (7.5YR 4/4) fine sandy loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; 10 percent coarse fragements below 85 cm; common fine flakes of mica; common fine roots; many distinct clay films on faces of peds; diffuse smooth boundary.

Bt2-- 127 to 180 cm; dark brown (7.5YR 4/4) and black (10YR 2/1) fine sandy loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; 1 percent coarse fragments; many fine flakes of mica; many distinct clay films on faces of peds.

Profile 40 - Conetoe sand

Camden Farms, Caroline County

Ap-- 0 to 28 cm; dark brown (7.5YR 4/4) sand; moderate very fine granular structure; very friable, nonsticky, nonplastic; many fine roots; clear smooth boundary.

AB-- 28 to 46 cm; brown (7.5YR 5/4) loamy sand; weak very fine granular structure; very friable, nonsticky, nonplastic; few fine roots; gradual smooth boundary.

Bt-- 46 to 89 cm; strong brown (7.5YR 4/6) sandy loam; weak coarse subangular blocky structure; friable, nonsticky, nonplastic; few fine roots; gradual smooth boundary.

C1-- 89 to 114 cm; strong brown (7.5YR 5/8) loamy sand; massive; very friable, nonsticky, nonplastic; gradual smooth boundary.

C2-- 114 to 180 cm; reddish yellow (7.5YR 6/8) sand; single grain; loose, nonsticky, nonplastic.

Profile 41 - State fine sandy loam

Randolph Farm, New Kent County

Ap-- 0 to 25 cm; dark brown (10YR 3/3) fine sandy loam; moderate fine granular structure; very friable, nonsticky, nonplastic; many fine and medium roots; clear smooth boundary.

E-- 25 to 50 cm; strong brown (7.5YR 5/6) fine sandy loam; moderate fine granular structure; very friable, nonsticky, nonplastic; common fine roots; 2 percent quartz pebbles; gradual smooth boundary.

Bt-- 50 to 94 cm; strong brown (7.5YR 4/6) sandy loam; moderate medium subangular blocky structure; firm, slightly sticky, plastic; common fine roots; many faint clay films on faces of peds; 4 percent quartz pebbles; gradual smooth boundary.

C1-- 94 to 127 cm; yellowish brown (10YR 5/4) loamy sand; single grain; very friable, nonsticky, nonplastic; 6 percent quartz pebbles; gradual smooth boundary.

C2-- 127 to 160 cm; yellowish brown 10YR 5/4) loamy sand; single grain; loose, nonsticky, nonplastic; 50 percent quartz pebbles.

auger stopped by stones at 160 cm

Profile 42 - Suffolk loamy fine sand

Randolph Farm, Hanover County

Ap-- 0 to 23 cm; dark brown (10YR 4/3) loamy fine sand; weak fine granular structure; very friable, nonsticky, nonplastic; common fine roots; clear smooth boundary.

E-- 23 to 38 cm; brown (7.5YR 5/4) loamy fine sand; weak fine granular structure; friable, nonsticky, nonplastic; common fine roots; clear smooth boundary.

Bt1-- 38 to 58 cm; strong brown (7.5YR 5/6) sandy loam; weak fine subangular blocky structure; firm, slightly sticky, nonplastic; common fine roots; few faint clay films on faces of peds; gradual smooth boundary.

Bt2-- 58 to 90 cm; strong brown (7.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; firm, sticky, plastic; few fine roots; common faint clay films on faces of peds; gradual smooth boundary.

C1-- 90 to 168 cm; strong brown (7.5YR 4/6) loamy sand; massive; very friable, nonsticky, nonplastic; few fine roots; gradual smooth boundary.

C2-- 168 to 180 cm; strong brown (7.5YR 4/6) sand; few distinct white (N 8/) mottles; single grain; loose, nonsticky, nonplastic.

Profile 43 - Emporia sandy loam

Otto Farm, Essex County

Ap-- 0 to 23 cm; yellowish brown (10YR 5/4) sandy loam; weak fine granular structure; friable, nonsticky, nonplastic; many fine and medium roots; 10 percent sub-rounded stones; clear smooth boundary.

Bt1-- 23 to 56 cm; strong brown (7.5YR 5/6) sandy clay loam; weak medium subangular blocky structure; firm, sticky, plastic; common fine and medium roots; common distinct clay films on faces of peds; 10 percent sub-rounded stones; gradual smooth boundary.

Bt2-- 56 to 66 cm; strong brown (7.5YR 5/8) sandy clay loam; weak medium subangular blocky structure; firm, sticky, plastic; few fine roots; few faint clay films on faces of peds; 10 percent sub-rounded stones.

auger stopped by stones at 66 cm

Profile 44 - Wolfgap loam

Bluestone Farms, Botetourt County

Ap-- 0 to 28 cm; very dark grayish brown (10YR 3/2) loam; strong medium subangular blocky structure parting to strong fine granular structure; firm, sticky, very plastic; many fine roots; common fine clay films on faces of peds; gradual smooth boundary.

Bt1-- 28 to 60 cm; dark brown (10YR 3/3) clay loam; strong medium angular blocky structure; very firm, sticky, very plastic; common fine roots; many distinct clay films on faces of peds; gradual smooth boundary.

Bt2-- 60 to 180 cm; dark brown (10YR 3/3) clay loam; strong medium angular blocky structure; very firm, sticky, plastic; common fine roots to 100 cm, few fine roots to 180 cm; many distinct clay films on faces of peds.

Profile 45 - Groseclose loam

Neuhoff Farms, Pulaski County

Ap-- 0 to 15 cm; yellowish brown (10YR 5/4) loam; moderate medium subangular blocky structure; friable, slightly sticky, plastic; many fine roots; common faint clay films on faces of peds; clear smooth boundary.

Bt1-- 15 to 30 cm; light yellowish brown (10YR 6/4) clay loam; moderate medium subangular blocky structure; friable, sticky, plastic; common fine roots; many faint clay films on faces of peds; gradual smooth boundary.

Bt2-- 30 to 65 cm; light yellowish brown (10YR 6/4) sandy clay loam; few distinct yellowish red (5YR 5/8) mottles; moderate medium angular blocky structure; friable, very sticky, plastic; few fine roots; many faint clay films on faces of peds; gradual smooth boudary.

Css1-- 65 to 117 cm; yellowish red (5YR 5/8) clay; few distinct light yellowish brown (10YR 6/4) mottles; weak coarse subangular blocky structure; very firm, sticky, very plastic; common distinct clay flows; few prominent slickensides; gradual smooth boundary.

Css2-- 117 to 180 cm; yellowish red (5YR 5/8) clay; few distinct black (N 2/), pale yellow (2.5Y 7/4), and brownish yellow (10YR 6/8) mottles; weak coarse subangular blocky structure; very firm, sticky, plastic; few prominent clay flows; few prominent slickensides.

APPENDIX I

EXPERIMENTAL TREATMENTS FOR FALL N EXPERIMENTS IN CHAPTER V

Experimental treatments for fall N experiments in Chapter V

treatment number	treatment description
1	no fall N
2	34 kg N ha^{-1} as preplant incorporated urea
3	34 kg N ha^{-1} as preplant incorporated S-coated urea
4	34 kg N ha^{-1} as preplant incorporated polymer-coated urea
5	17 kg N ha^{-1} as preplant incorporated urea, 17 kg N ha^{-1} as preplant incorporated polymer-coated urea
6	34 kg N ha^{-1} as preplant incorporated IBDU
7	17 kg N ha^{-1} as preplant incorporated urea, 17 kg N ha^{-1} as UAN solution top-dressed 4 weeks after planting
8	34 kg N ha^{-1} as preplant incorporated urea, 22 kg N ha^{-1} as UAN solution top-dressed 4 weeks after planting
9	34 kg N ha^{-1} as preplant incorporated urea, 22 kg N ha^{-1} as UAN solution top-dressed in January
10	no preplant N, 34 kg N ha^{-1} as UAN solution top-dressed 4 weeks after planting

APPENDIX J

INDIVIDUAL PLOT YIELD DATA FOR EXPERIMENTS IN CHAPTER V

Individual plot yields are presented in this appendix because of their importance in the analyses in Chapter V. Plots were 5 m long by 5.5 m wide. Each experiment was 8 plots long by 5 plots wide. The 5 plots in a range were all immediately adjacent, so experiment width was 5 (5.5 m) = 27.5 m. Each range of 5 plots was separated from immediately adjacent ranges by a 2 m wide alleyway, so experiment length was 8 (5 m) + 7 (2 m) = 54 m. Two adjacent ranges of five plots each constituted a ten-plot replication.

Individual plot yields for location 1 (Chapter V)

plot number	treatment number	grain yield
		Mg ha^{-1}
101	10	5.98
102	8	5.86
103	6	5.72
104	1	4.38
105	3	5.18
106	2	5.21
107	7	5.74
108	5	5.42
109	9	4.92
110	4	5.33
201	5	missing
202	3	5.48
203	9	5.36
204	10	4.80
205	8	4.51
206	1	4.68
207	4	4.82
208	2	4.94
209	6	4.52
210	7	4.80
301	7	4.93
302	6	5.48
303	3	5.60
304	9	5.33
305	5	5.20
306	8	5.08
307	10	5.07
308	1	4.93
309	2	4.30
310	4	4.78
401	2	5.08
402	9	5.46
403	7	4.94
404	3	4.52
405	6	4.92
406	4	4.95
407	8	4.79
408	10	4.92
409	5	4.66
410	1	4.25

Individual plot yields for location 2 (Chapter V)

plot number	treatment number	grain yield
		Mg ha^{-1}
101	10	3.63
102	8	3.86
103	6	3.93
104	1	3.12
105	3	3.18
106	2	3.71
107	7	3.70
108	5	4.00
109	4	3.41
110	9	3.18
201	5	3.72
202	3	3.71
203	9	3.27
204	10	3.34
205	8	3.20
206	1	3.93
207	4	3.86
208	2	3.77
209	6	3.48
210	7	2.75
301	7	3.76
302	6	3.84
303	3	4.29
304	9	3.78
305	5	3.78
306	8	4.14
307	10	3.62
308	1	3.98
309	2	3.55
310	4	3.93
401	2	3.92
402	9	4.06
403	7	4.49
404	3	3.99
405	6	3.79
406	4	4.30
407	8	3.85
408	10	4.35
409	5	3.26
410	1	3.19

Individual plot yields for location 3 (Chapter V)

plot number	treatment number	grain yield
		Mg ha^{-1}
101	10	5.24
102	8	4.91
103	6	4.96
104	1	3.98
105	3	4.26
106	2	4.94
107	7	4.54
108	5	4.94
109	4	3.98
110	9	4.97
201	5	4.69
202	3	4.34
203	9	4.83
204	10	3.74
205	8	4.11
206	1	5.07
207	4	4.69
208	2	3.84
209	6	3.77
210	7	3.76
301	7	5.25
302	6	4.05
303	3	3.82
304	9	4.48
305	5	3.68
306	8	4.80
307	10	4.11
308	1	3.70
309	2	3.47
310	4	3.70
401	2	4.69
402	9	4.40
403	7	3.64
404	3	3.75
405	6	3.50
406	4	4.82
407	8	4.20
408	10	3.64
409	5	4.07
410	1	3.15

Individual plot yields for location 4 (Chapter V)

plot number	treatment number	grain yield
		Mg ha^{-1}
101	10	4.75
102	8	4.63
103	6	4.35
104	1	4.86
105	3	5.31
106	2	5.02
107	7	5.15
108	5	4.16
109	4	4.15
110	9	5.34
201	5	5.40
202	3	4.99
203	9	4.75
204	10	4.77
205	8	4.90
206	1	4.61
207	4	4.60
208	2	3.94
209	6	3.80
210	7	4.64
301	7	4.76
302	6	4.50
303	3	3.54
304	9	5.15
305	5	4.75
306	8	5.17
307	10	4.35
308	1	3.19
309	2	4.89
310	4	4.51
401	2	5.15
402	9	4.30
403	7	4.22
404	3	4.76
405	6	4.51
406	4	6.37
407	8	6.40
408	10	6.64
409	5	5.99
410	1	4.91

Vita

The author was born in Moscow, Idaho, in 1959. He grew up in a rural non-farm setting in southern Wisconsin and graduated from McFarland High School in 1977. He enrolled in the University of Wisconsin, studying biology and working in a number of biological research labs. In 1982 he was awarded the Bachelor of Science-Natural Science degree with majors in Biochemistry and Genetics.

After graduating, he spent several years living in Madison, Wisconsin working as a baker, a cook, and a lab specialist. In the fall of 1984 he bicycled to Blacksburg, Virginia. Early in 1985 he began working as a technician in the Agronomy Department at Virginia Polytechnic Institute and State University in Blacksburg, and in the fall of 1985 he enrolled for graduate study in the same department. In 1988 he was awarded the Master of Science degree in Agronomy under the direction of Dr. Mark Alley.

From 1988 to 1991 he worked in the same department (now renamed Crop and Soil Environmental Sciences) as a research associate. In the spring of 1990 he enrolled in the graduate school for study leading to the degree of Ph.D. in Crop and Soil Environmental Sciences, and in the fall of 1991 switched to full-time student status in pursuit of this degree.