Nitrogen Management in No-till Winter Wheat Production Systems

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ABSTRACT

Determining optimum N fertilization rate and timing is critical to improve yields and economic sustainability for no-till winter wheat (*Triticum aestivum* L.) in the Virginia Coastal Plain. Little data are available evaluating N management strategies, optimum N rate prediction methods, or potential NO_3 leaching under no-till wheat in soils and climate similar to the mid-Atlantic region. The objectives of our research were: (1) to determine economic optimum N fertilization rates and timings; (2) evaluate selected methods for predicting optimum N rates at GS 25 and GS 30; and (3) measure NO_3 leaching loss under selected N management strategies. Eleven experiments over three years evaluated N rates at GS 25 and GS 30. Six experiments over two years evaluated pre-plant and December or GS 25 N rates under no-till winter wheat in farm fields of the Coastal Plain region of Virginia. Nitrate leaching was measured under selected pre-plant and December or GS 25 N application rates. All sites represented common Coastal Plain soil types and cultural practices for no-till wheat production. Yield data were used to calculate economic optimum N rates for a range of combinations of N management strategies. Optimum N rates were regressed against tiller density at GS 25, and wheat tissue N content and SPAD chlorophyll meter readings at GS 30, to determine their effectiveness as predictors of the optimum N rate at GS 25 or GS 30. Tiller density was an effective predictor of optimum GS 25 N rate in these split application management strategies. However, wheat tissue N contents and SPAD chlorophyll meter readings were not effective predictors of optimum N application at GS 30. Yields across all experimental designs were affected by planting date. Timely planted no-till wheat consistently produced higher yields compared to late planted. Sites under continuous no-till production for 8 years or more also produced higher yields than sites under continuous no-till production for less than 8 years. Including an additional December N application with the more traditional N management strategy of pre-plant, GS 25 and GS 30 N applications improved yields. Nitrate leaching loss at selected pre-plant and December or GS 25 N rates was not higher than background check plot levels under timely planted no-till wheat. Additionally, economic optimum N application rates and timings at these sites did not produce NO_3 leaching losses above background levels under timely or late planted wheat, except at one late planted site. These data indicate N application rates and timings in no-till wheat can be managed for improved economic sustainability and reduced environmental impact.

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Table of Contents

List of Tables

List of Figures

Chapter I

INTRODUCTION

OVERVIEW

Optimum nitrogen (N) rate and application time for conventionally tilled winter wheat grown in the mid-Atlantic region vary widely because of soil and climate conditions. Research over the past decade has established methods to more accurately predict optimum N application rates and timings on a field specific basis. However, conventionally tilled winter wheat in the mid-Atlantic is shifting toward no-tillage practices because of numerous economic and soil and water quality benefits associated with no-till production. Very little data exist that measures optimum Zadoks growth stage (GS) 25 or GS 30 N rates and timings (Zadoks et al., 1974), or the accuracy of optimum N rate prediction methods for no-till winter wheat in the mid-Atlantic coastal plain. Optimum GS 25 and GS 30 N rates and timings under no-till wheat might be different than those for conventional tillage due to differences in the soil environment and soil N dynamics under no-till. Furthermore, no-till may also impact N prediction methods that were successful in conventional tilled systems. The research presented in Chapter II of this dissertation was designed to evaluate optimum GS 25 and GS 30 N rate and timing of applications for no-till winter wheat and determine effectiveness of selected optimum N rate prediction methods.

The practice of adding an extra N application in December under no-tillage is becoming more common in conjunction with traditional pre-plant, application of N at GS 25 and

GS 30. This additional N application is an attempt to improve tiller development and prevent mid-winter N deficiency symptoms observed under no-till production. Surface residue potentially changes the amount and timing of N available to the crop over the growing season. Additionally, most soils in the Virginia Coastal Plain region commonly planted to winter wheat are sandy, have high hydraulic conductivities and relatively low water holding capacities. Combine these factors with the humid climate of the mid-Atlantic, where precipitation exceeds evapotranspiration in the winter and early spring, and the result is a higher risk of NO_3 leaching loss in this region of the Chesapeake Bay watershed. The research presented in Chapter III of this dissertation investigates optimum pre-plant and December or GS 25 N rates, and the nitrate (NO_3) leaching loss under selected treatments in these experiments with no-till winter wheat.

CONTEXT OF PRESENT RESEARCH

The Coastal Plain region of Virginia dominates the southern Chesapeake Bay watershed. The Columbia and Yorktown aquifers drain the region into the Bay and its lower tributaries. Physiographically, the region is underlain by unconsolidated sediments, with agronomic soils predominated by sandy loams or loamy sands. Unconfined groundwater in this region is transient, and emerges in seeps and springs as it travels toward the Bay. The water table can commonly be less than 10 meters from the soil surface (Reay and Simmons, 1992). These factors increase the vulnerability of ground and surface water contamination from excess NO_3 leaching. Ator and Ferrari (1997) found 10% of the groundwater samples tested in the mid-Atlantic exceeded the EPA drinking water standard of 10 mg l^{-1}. The majority of the higher NO_3 level samples were taken from agricultural areas.

Over 57 % of the N entering the Bay originates from non-point source pollution, mainly agriculture (Chesapeake Bay Program, 1999). Excess N leads to large algae blooms that block sunlight to submerged aquatic vegetation. This vegetation provides a habitat and oxygen source for marine life. Eventually these large quantities of algae biomass die. Microbial oxidation of algae tissue leads to oxygen depletion, which can further stress, and potentially kill fish and other marine life. The Chesapeake Bay Program is a regional partnership designed to lead and direct the restoration of the Bay. One of the goals was to reduce N entering the Bay by 40% by the year 2000. Although reductions have occurred, the region has not met N reduction goals, and efforts are being renewed to improve reduction of N entering the Bay (Boesch et al., 2001).

Managing N for no-till wheat is also challenging in the humid climate of the Coastal Plain. During the winter wheat growing season, precipitation exceeds evapotranspiration for extended periods of time. The soil becomes saturated and NO_3 can be transported below the wheat root zone in sandy soils. Studies on similar soil types have shown the highest flux of soil NO_3-N occurs during winter and early spring (Chichester, 1977).

No-tillage methods can also affect the soils' physical structure. Surface residue greatly reduces erosion and evaporative water loss, increasing water retention in the field. However, long-term continuous no-till soil profiles also have a greater number of macropores and wormholes, increasing water infiltration rates compared to conventional tillage (Edwards et al, 1988; Eck and Jones, 1992). These factors contribute to the potential for significant NO_3 leaching loss under no-till wheat during the winter and early spring in the Coastal Plain region of Virginia.

No-till also affects soil N dynamics, potentially altering optimum fertilizer N inputs compared to conventionally tilled soils. Producers have traditionally used more fertilizer N on no-till fields because of increased N immobilization. Microbial immobilization of inorganic N during the decomposition of previous crop residues is dependent on the C:N ratio. Residues with high organic C:N ratios such as corn stover (60:1), will result in higher immobilization of inorganic N by the microorganisms over the short term. However, long-term continuous no-till has potentially higher rates of mineralization and more stable overall N dynamics due to a build up of previous crop residues in progressive stages of decomposition. Carter and Rennie (1982) reported wheat under 12 to 16 year continuous no-till had 20 to 30 % greater potentially mineralizable N compared to similar conventionally tilled soils. However, immobilization is the primary process responsible for the need for additional early season N fertilization of no-till wheat compared to conventional tillage methods.

Fall, winter and early spring N fertilization in no-till is important for tiller development and yield potential. Scharf and Alley (1993) reported wheat with less than 1000 tillers m^{-2} at GS 25 produced the highest yields from a split spring N application at GS 25 to promote additional tiller development, and GS 30 to meet reproductive growth needs. Therefore, early spring plant available N is frequently crucial to producing economic yield levels. The addition of a December N application may improve tiller development, but is also at an increased risk of NO_3 leaching loss.

There is limited prior research concerning N fertilization management and prediction in no-till wheat for a humid climate such as the Virginia Coastal Plain. There is even less research that incorporates agronomic and environmental concerns into one comprehensive study. However, increasing concerns involving agricultural impacts on surface and ground water dictate that N rate and timing studies, such as proposed here, must incorporate measures of environmental impacts, such as NO_3 leaching. The goal is to have economic optimum N management in no-till wheat that minimizes potentially detrimental environmental impacts.

REFERENCES

Ator, S.W. and M.J. Ferrari. 1997. Nitrate and selected pesticides in ground water of the Mid-Atlantic region [Online]. Water Resources Investigations Report 97-4139. USGS and EPA. Available at http://dg33dmdtws.er.usgs.gov/maia/97-4139/ (verified 15 April 2001).

Boesch, D.F., R.B. Brinsfield, and R.E. Magnien. 2001. Chesapeake bay eutrophication: Scientific understanding, ecosystem restoration, and challenges for agriculture. J. Environ. Qual. 30:303-320.

Carter, M.R. and D.A. Rennie. 1982. Changes in soil quality under zero tillage farming systems: Distribution of microbial biomass and mineralizable C and N potentials. Can. J. Soil Sci. 62:587-597.

Chesapeake Bay Program. 1999. Stressors on the system. p. 24-37. *In* The State of the Chesapeake Bay: A report to the citizens of the bay region. Chesapeake Bay Program, Annapolis, MD. EPA 903-R99-013.

Chichester, F.W., 1977. Effects of increased fertilization rates on nitrogen content of runoff and percolate from monolith lysismeters. J. Environ. Qual. 6:211-217.

Eck, H.V. and O.R. Jones. 1992. Soil nitrogen status as affected by tillage, crops, and crop sequences. Agron. J. 84:660-668.

Edwards, W.M., L.D. Norton, and C.E. Redmond. 1988. Characterizating macropores that affect infiltration into nontilled soil. Soil. Sci. Soc. Am. J. 52:483-487.

Reay, W.G. and G.M. Simmons, Jr. 1992. Groundwater discharge in coastal systems: implications for Chesapeake Bay. p. 17-44. *In* Perspectives on Chesapeake Bay, 1992: Advances in estuarine sciences. Chesapeake Research Consortium, Solomona, MD.

Scharf, P.C. and M.M. Alley. 1993. Spring nitrogen on winter wheat II: A flexible multi-component rate recommendation system. Agron. J. 85:1186-1192.

Zadoks, J.C., T.T. Chang, and C.F. Konzak. 1974. A decimal code for the growth stages of cereals. Weed Res. 14:415-421.

Chapter II

No-till winter wheat in the Virginia Coastal Plain: Determining optimum spring N rate, time of application, and N rate prediction methods.

ABSTRACT

Determining optimum spring N fertilization rates is critical to optimizing yields and profits for winter wheat in the humid climate of the Virginia Coastal Plain. The increasing use of no-tillage practices in this region may influence optimum spring N fertilization rates and timings compared to conventional tillage. Eleven no-till wheat experiments were established during the 1997-98, 1998-99, and 1999-00 growing seasons in farm fields following either soybean or corn grain production. Experimental sites represented a range of soil types and wheat varieties commonly used in no-till winter wheat production in the region. Nitrogen fertilizer was applied at 4 levels at Zadoks growth stage (GS) 25 in combination with 5 levels at GS 30, in a randomized complete block design. Total N application rates ranged from 0 to 235 kg N ha^{-1}. Yields and economic optimum N rates and timings varied by sites within each season. Economic optimum yields ranged from 3.2 to 8.9 Mg ha^{-1}, while economic optimum N rates at GS 25 and 30 ranged from a total of 90 to 157 kg N ha^{-1}. The highest yields within each season occurred at timely planted sites, and sites that had been in longer term continuous no-till production. Tiller densities at GS 25 were a reasonable predictor of economic optimum GS 25 N rates. However, tissue N content and SPAD-502 chlorophyll meter measurements at GS 30 from all sites were not reasonable predictors of economic optimum GS 30 N rates over the three-year period.

INTRODUCTION

Spring N application rate and timing is a primary management factor affecting wheat yields in humid climates. However, wide spread progression from conventional tillage to no-till winter wheat production in the mid-Atlantic may alter field-specific evaluation and management of spring N applications. Surface residue reduces plant available N primarily through increasing N immobilization (Doran, 1980; Rice and Smith, 1984; Christensen et al., 1994; Schomberg et. al., 1994) and higher water retention and infiltration rates (Edwards et al., 1988; Eck and Jones, 1992). The potential for additional N loss through leaching is increased in the humid mid-Atlantic climate where precipitation often exceeds evapotranspiration during late winter and early spring (Smith and Cassel, 1991). These factors decrease plant available N and may account for the higher optimum N fertilization rates in no-till wheat production compared to conventional tillage reported by Jacobsen and Westerman (1988). However, if increased N fertilization rates are necessary for economic optimum no-till wheat production in the mid-Atlantic region, efficient N management through accurate field-specific evaluation of crop needs becomes increasingly important to prevent N leaching loss to ground and surface waters.

Spring plant N availability is critical for additional tiller development and winter wheat yield. Increasing N rates can overcome reduced tillering and yields associated with no-till (Rasmussen et al., 1997). More specifically, studies from Canada have shown superior grain yields from spring N applications compared to fall applications in no-till wheat (Olson and Swallow, 1984; Fowler and Brydon, 1989). In the mid-Atlantic region, Scharf and Alley (1993) reported that conventionally tilled wheat with less than 1000 tillers m^{-2} at GS 25 produced the highest yields from a split spring N application at GS 25 to stimulate further tiller development, and GS 30 to meet N requirements during reproductive growth.

Weisz and Bowman (1999) reported tiller development was slower in no-till wheat compared to conventional tillage. This suppression of tiller development in no-till wheat may be due to reduced early season soil temperatures (2 to 6^0C below conventionally tilled wheat) associated with surface residue (Hay et al., 1978). Determination of optimum GS 25 N application rate may be especially critical in no-till wheat to optimize yield and minimize N loss due to delayed tiller development.

Baethgen and Alley (1989a) and Zadoks et al. (1974) reported maximum N uptake in soft red winter wheat occurred after GS 30, and that N application at GS 30 was critical to optimize yields (Baethgen and Alley, 1989b). Baethgen and Alley (1989b) also reported N concentration for conventionally tilled winter wheat at Zadoks GS 30 was 39.5g N kg^{-1} tissue at 90% relative yield in Virginia. These results are similar to Roth et al. (1989) who reported critical tissue N levels at GS 30 of 35 g N kg^{-1} from conventionally tilled wheat in Pennsylvania. These studies show a strong correlation between wheat tissue N content at GS 30 and optimum N rate at GS 30 in conventionally tilled wheat, indicating plant tissue testing may be useful in determining no-till wheat N needs at this critical stage of growth.

Plant tissue testing may be a valuable tool for determining crop N requirements; however, this technique can be time consuming, delaying timely N application. The Minolta chlorophyll meter (model SPAD-502) was designed to evaluate the N status of a growing crop by measuring leaf chlorophyll content. The SPAD meter transmits two wavelengths of light through leaf tissue, measuring chlorophyll absorbance at 650 nm, and non-chlorophyll absorbance at 940 nm as an internal calibration (Inada, 1963). Several studies have shown that the SPAD readings are related to chlorophyll levels in plant tissue, which are highly correlated to leaf N content in grain crops, corn and rice (Takabe and Yoneyama, 1989; Pettygrove et al., 1991; Monje and Bugbee, 1992; Schepers et al., 1993; Shadchina and Dmitrieva, 1995). Utilizing leaf N content based on chlorophyll meter readings to predict N plant needs has been successful for some crops (Takabe and Yoneyama, 1990; Wood et al., 1992). However, other studies have found limitations of the SPAD meter due to variations in crop variety and environmental conditions such as water stress, cold stress, nutrient deficiencies other than N, and insect damage (Campbell et al., 1990; Schepers et al., 1992; Monje and Bugbee, 1992).

The objectives of this research were: (1) to determine economic and yield-based optimum spring N application rates and timings for no-till wheat; and (2) to evaluate selected methods for predicting optimum spring N rates including tiller densities at GS 25, and tissue N content and SPAD chlorophyll meter readings at GS 30.

MATERIALS AND METHODS

Eleven N fertilization rate and timing experiments were conducted during the 1997-98, 1998-99, and 1999-00 growing seasons in no-till winter wheat on the Coastal Plain region of Virginia. Sites were selected approximately 2 months after planting based on soil and stand uniformity. Soil types and production strategies were typical of Virginia Coastal Plain soils in row crop production (Table 1). Sites were planted into either wheat-double crop soybeans or corn stubble that had been in continuous no-till production for at least 2 years.

The experimental plan involved a complete factorial design with 4 levels of N applied at Zadoks growth stage (GS) 25 (Zadoks et. al., 1974), and 5 levels of N applied at GS 30 for all sites (Table 2). The twenty treatments were arranged in a randomized complete block design with four replications at each site. Total spring N applications ranged from 0 to 235 kg ha^{-1}. Individual plots measured 5 m by 5.5-m with 2.1-m alleyways between each replicate.

Urea-ammonium nitrate solution (30% N) was used as the N source for all treatment N applications. The N solution was applied with a carbon dioxide pressurized backpack sprayer. The sprayer boom was fitted with Teejet ‘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 calibrated and a stopwatch and metronome utilized to maintain proper walking speed during N application.

Table 1. Site, growing season, soil series, surface texture, soil subgroup, variety, planting date and residual soil N from 0 to 1.2-m for eleven experimental sites evaluating spring N fertilization of no-till winter wheat.

Site	Growing Season	Soil Series and Surface Texture	Soil Subgroup	Variety	Planting Date	Residual Soil N
						kg ha^{-1}
1	1997-98	Pamunkey fsl	Ultic Hapludalfs	Pioneer 2580	Nov 12	7
2	1997-98	Pamunkey fsl	Ultic Hapludults	SS 555	Oct 20	5
3	1997-98	Conetoe fsl	Arenic Hapludults	NK Coker 9704	Nov 12	11
4	1998-99	Eunola l	Aquic Hapludults	Pocahontas	Nov 6	26
5	1998-99	Kempsville sl	Typic Hapludults	Pioneer 2684	Oct 24	21
6	1998-99	Dogue l	Aquic Hapludults	Pioneer 2643	Nov 1	21
7	1998-99	Pamunkey fsl	Ultic Hapludults	Pioneer 2684	Oct 15	25
8	1999-00	Pamunkey fsl	Ultic Hapludults	Pioneer 2684	Oct 16	22
9	1999-00	Bojac ls	Typic Hapludults	SS 555	Nov 2	20
10	1999-00	Pamunkey fsl	Ultic Hapludults	Pioneer 2643	Nov 2	22
11	1999-00	Kempsville sl	Typic Hapludults	Roane	Oct 16	20

Table 2. Growth stage 25 and 30 N application rate and timing treatments for all experimental sites.

Treatment	GS 25 N application	GS 30 N application
	-----kg N† ha^{-1}-----	
1	0	0
2	0	34
3	0	67
4	0	101
5	0	134
6	34	0
7	34	34
8	34	67
9	34	101
10	34	134
11	67	0
12	67	34
13	67	67
14	67	101
15	67	134
16	101	0
17	101	34
18	101	67
19	101	101
20	101	134

† N supplied as 30% N urea-ammonium nitrate solution.

Soil and Plant Sampling, Analysis and Tiller Counts

Soil samples were taken in mid-February to characterize soil texture and measure residual soil N (Table 1). Mass soil nitrate concentrations (mg kg^{-1}) were estimated from soil samples taken at depths of 0- to 0.15-, 0.15- to 0.30-, 0.30- to 0.61-, 0.61- to 0.91-, and 0.91- to 1.20-m. Soil samples were extracted in duplicate with 2 M KCl and filtered prior to analysis (Keeney and Nelson, 1982). Nitrate and ammonia concentrations were determined colorimetrically on a Lachat instruments Automated Analyzer using QuikChem Method 12-107-04-1-B and 12-107-06-2-A, respectively (Lachat Instruments, Milwaukee, WI).

Tillers per 0.91 meters of row were counted at GS 25 for each of the sites. Eight counts were conducted at each site with locations for each measurement selected randomly within the experimental area.

Plant tissue samples were collected at GS 30 from each GS 25 N rate treatment in each replication. The above ground plant tissue was clipped from two 1-m rows per plot. Samples were dried, ground to pass through a 40-mesh screen, and analyzed in duplicate for total Kjeldahl N content using QuikChem method no. 13-107-06-2-B (Lachat Instruments, Milwaukee, WI).

Minolta SPAD-502 chlorophyll meter readings were taken prior to tissue collection from the two 1-m rows per plot selected for plant tissue samples. Fifteen readings were taken and averaged from each row section. Sampling technique followed the procedures suggested by Murdock et al. (1997).

Grain Yields

Wheat grain was harvested in a 1.5 m wide area of each plot with a plot combine. Grain yields were adjusted to 135 g kg^{-1} moisture content. For each GS 25 N rate, GS 30 N rate was regressed against yield for each site. Profit was estimated for each plot as wheat value (yield x price) – N fertilizer cost (N rate x N price) – other fixed production costs for each season. For the 1997-98 season, N fertilizer cost estimates were \$0.44 kg^{-1}, wheat price was \$0.080 kg^{-1}, and fixed costs were estimated at \$247 ha^{-1} (Virginia Cooperative Extension, 1996). For the 1998-99 season, N fertilizer cost estimates were \$0.53 kg^{-1}, wheat grain was \$0.077 kg^{-1}, and fixed costs were estimated at \$313 ha^{-1} (Virginia Cooperative Extension, 1998). For the 1999-00 season, N fertilizer cost estimates were \$0.44 kg^{-1}, wheat grain was \$0.074 kg^{-1}, and fixed costs were estimated at \$313 ha^{-1} (Virginia Cooperative Extension, 1998). These costs and returns reflect actual conditions for each growing season. The least-squares response surface was calculated for estimated profit (loss) and yield as a function of N rate at GS 25 and 30 at each location (SAS Inst., 1999). The economic optimum GS 25 and GS 30 N rates corresponded to the highest point on the response surface curve.

RESULTS AND DISCUSSION

Economic Optimum Yield

Yield across all treatments and all sites averaged 5.3 Mg ha^{-1}. These levels indicate generally suitable fertility and cultural practices, and were higher than the average 1998 and 1999 Virginia wheat yields of 3.8 Mg ha^{-1} (Virginia Agricultural and Statistics Service, 1999). During the 1997-98 growing season, precipitation was above average in late spring, and some yield reductions occurred due to *Fusarium graminearum* infections (head scab) at sites 1 and 2. Site 3 was ready for harvest approximately 2 weeks earlier and was not as severely affected by scab during the 1997-98 season. During the 1999-00 growing season, climatic conditions were generally favorable; however, an early season drought may have contributed to lower yields on the Bojac loamy sand soil at site 9 (Table 3).

A comparison of no-till wheat response to N fertilization between the check plots and highest treatment yield shows that 9 out of the 11 sites had positive yield responses (2 Mg ha^{-1} or greater) to N treatments (Fig. 1a and c). Site 9 had no response to N applications while site 2 had a generally negative response to N fertilization. Regressing yield against GS 30 N treatments for each GS 25 N treatment was used to further describe grain yield response to N application rates and timings at each site (Appendix A).

Economic optimum GS 25 and GS 30 N application rates were determined from response surface curves (Appendix B). Total economic optimum N rates, excluding scab infested sites 1 and 2, ranged from 90 to 157 kg N ha^{-1} (Table 3).

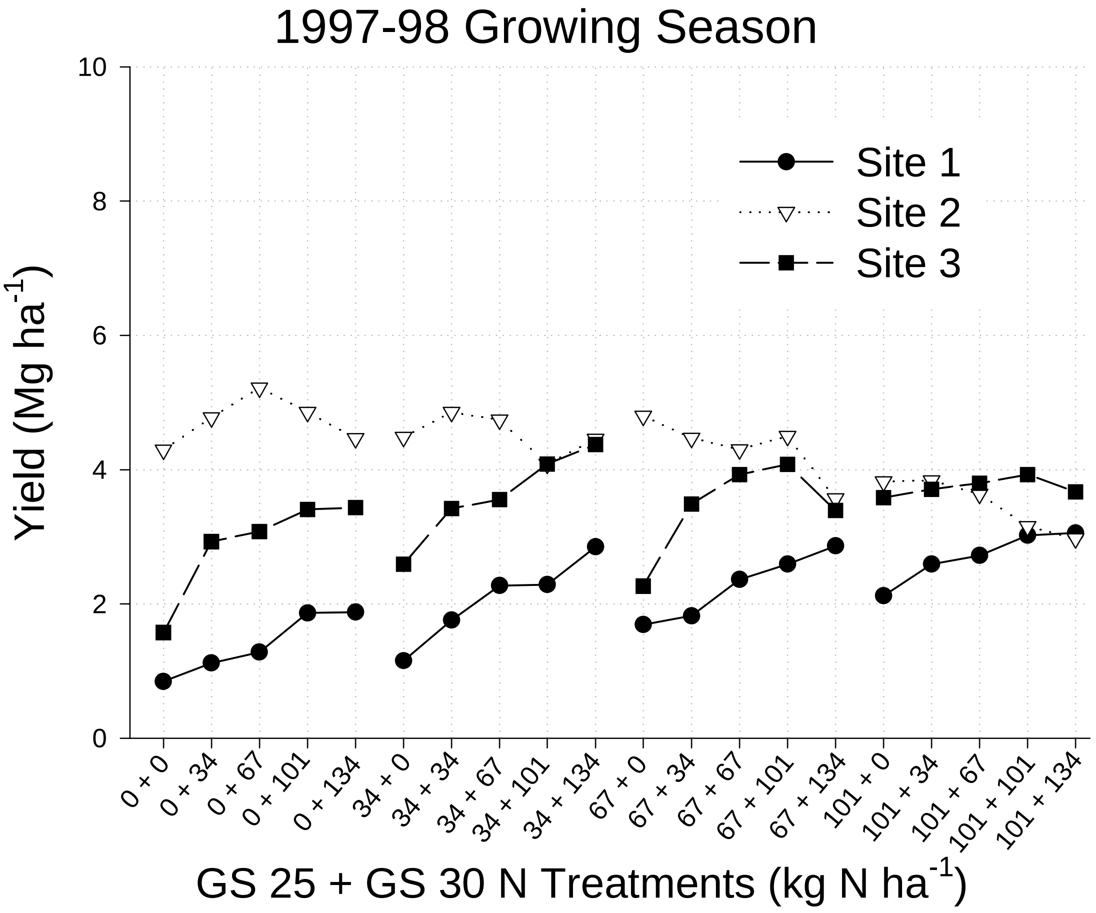


Figure 1a. Yields for each treatment during the 1997-98 growing season.

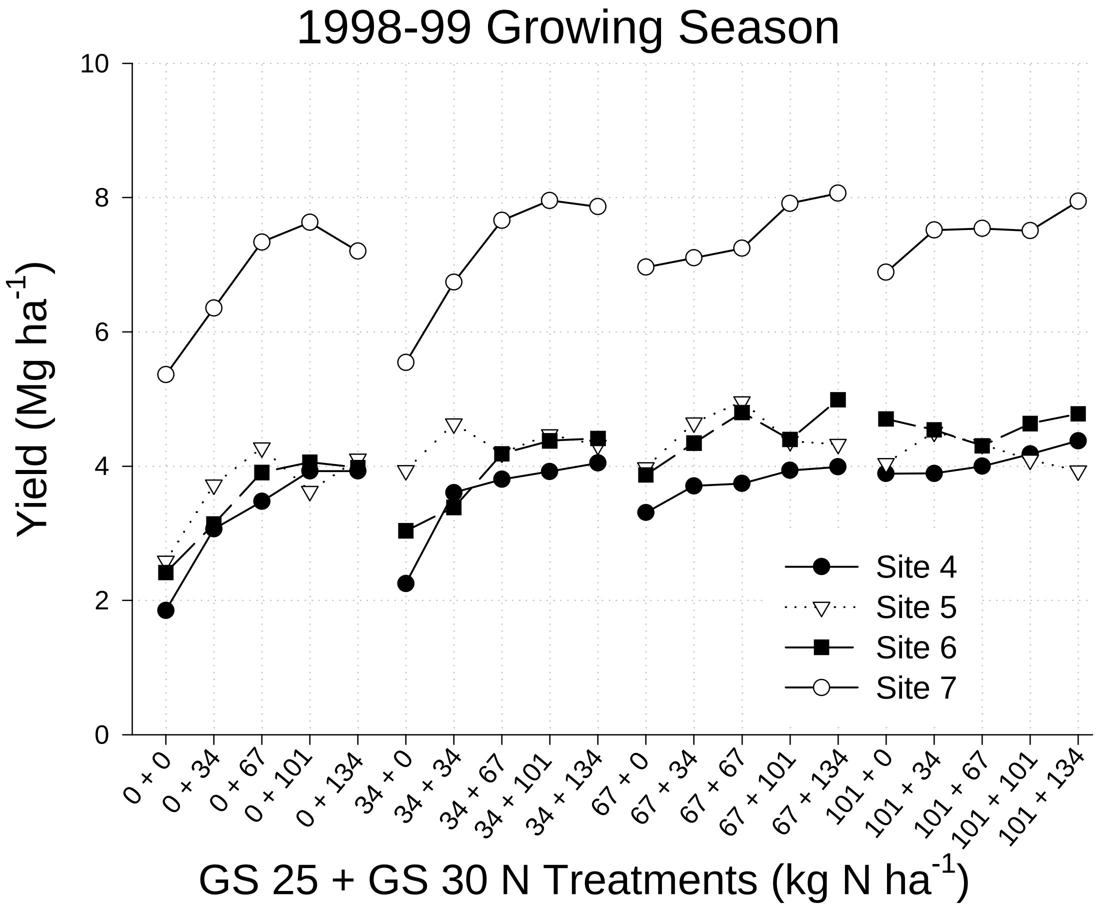


Figure 1b. Yields for each treatment for the 1998-99 growing season.

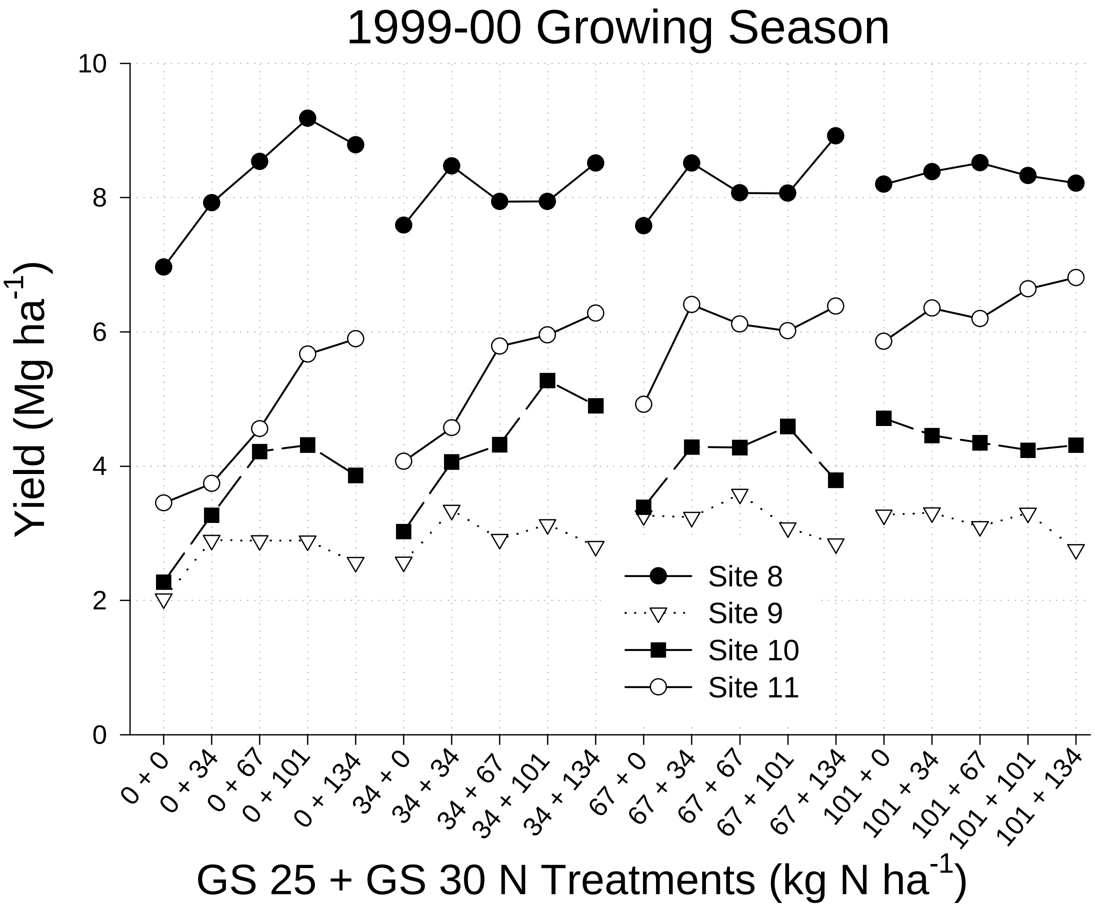


Figure 1c. Yields for each treatment for the 1999-00 growing season.

Table 3. Economic optimum GS 25 and GS 30 N application rates, yield, profit (loss), years in no-till production, and planting date for 11 sites over 3 years in no-till wheat planted in Virginia Coastal plain soils.

		Economic Optimum					
Site	Growing Season	GS 25	GS 30	Yield	Profit (loss)	Years in No-till	Planting Date
		---kg N ha^{-1}---		Mg ha^{-1}	\$ ha^{-1}		
1†	1997-98	101	123	2.9	(84)	< 4	Nov 12
2†	1997-98	11	17	4.3	128	> 8	Oct 20
3	1997-98	62	67	3.6	7	< 4	Nov 12
4	1998-99	101	56	4.2	(41)	< 4	Nov 6
5	1998-99	56	56	4.7	14	< 4	Oct 24
6	1998-99	101	39	4.6	0	< 4	Nov 1
7	1998-99	45	106	7.9	242	> 8	Oct 15
8	1999-00	0	123	8.9	289	> 8	Oct 16
9	1999-00	62	28	3.2	(109)	< 4	Nov 2
10	1999-00	56	67	4.6	(29)	< 4	Nov 2
11	1999-00	101	50	6.4	94	5	Oct 16

† Sites were excluded from further analysis due to scab infestation that masked accurate assessment of economic optimum N rates.

The discrepancies in economic optimum N rates relative to yields at sites 1 and 2 are the result of a *Fusarium graminearum* head scab infestation at both sites. Yield reductions due to scab probably masked accurate assessment of economic optimum N rates; therefore, sites 1 and 2 were excluded from analysis of economic optimum N rate prediction methods described later in this chapter.

Recommended planting date for conventionally tilled wheat in the Virginia Coastal Plain is one week before or after the first frost date, around October 20 (Alley et al., 1993). Planting between October 15 and 30 is preferable because soil temperatures are likely to be sufficiently high for crop emergence within 7 to 14 days. Also, wheat yield potential develops during the critical period between first frost and winter dormancy because of the importance of fall tillers to final yield (Alley et al., 1993). Planting prior to the recommended period may result in yield reductions due to Hessian fly infestation or freeze damage from excessive early growth. Sites 2, 7, 8, and 11 were higher yielding within their respective seasons (4.3, 7.9, 8.9, and 6.4 Mg ha^{-1}, respectively), and also the most profitable (128, 242, 289, 94 \$ ha^{-1}, respectively) sites at economic optimum N rates. These sites were also all planted between October 15 and October 20. Although the advantage of timely planting varied between seasons, earlier planted sites consistently achieved higher yields and consequently higher profits across all seasons (Table 3).

Studies in conventionally tilled wheat from New York and Nebraska have shown late planting can result in large yield reductions due to a poorly developed root system that increases wheat’s susceptibility to winter injury (Knapp and Knapp, 1978). Pittman and

Andrews (1961) and Winter and Musick (1993) have shown that timely planted wheat may better utilize plant available N due to a more expansive root system that more effectively intercepts available N. Rocheford et al. (1988) indicated similar planting date differences for winter wheat in the mid-Atlantic region.

Another factor that may have contributed to higher yields at sites 2, 7, 8, and 11 was the number of years the sites had been under continuous no-till. Sites 2, 7, and 8 had been in no-till production for 5 years or more, whereas the other sites had been in continuous no-till from 2 to 4 years prior to the experimental year.

A study by Bandel (1983) on coastal plain soils in Maryland showed 3 to 6 years were generally required for the yields of no-till corn to equal corn yield grown under conventional tillage on the same soil. After this time, yields under no-till consistently exceeded those under conventional tillage. The delay in achieving comparable yields under no-till compared to conventional tillage may be the development of differences in soil properties. Studies have shown soil under no-tillage management generally contains more organic C and N compared to conventional tillage, especially at the soil surface (Lal, 1976; Blevins et al., 1977; Eckert, 1985; Unger 1991). Dalal (1988) found higher total N in surface soil after 13 years of no-till compared to conventional tillage; however he found no difference in total N after 5 years. Carter and Rennie (1982) reported soil planted to wheat in Canada under no-till for 12 to 16 years had 20 to 30% greater potentially mineralizable N to a depth of 40 to 100 mm compared to conventional tillage. Furthermore, Franzluebbens and others (1995) reported soils under 10 year continuous no-till exhibited smaller seasonal changes in active soil C and N when compared to conventional tillage. These studies indicate continuous no-till can improve yields, in part, by conserving N in the surface residue and stabilizing overall changes in N dynamics over time.

Tiller Densities, Tissue N, and SPAD meter

Tiller densities were measured at GS 25 and regressed against economic optimum GS 25 N application rates for all sites (Fig. 2). The relationship ($r^2 = 0.50$) indicates tiller densities can be a satisfactory measure for predicting GS 25 N application rates in no-till winter wheat. These findings are similar to Scharf and Alley (1993), who reported tiller densities could be the basis for making field-specific N rate recommendations at GS 25 in conventionally tilled wheat ($r^2 = 0.66$). Scharf and Alley (1993) also reported no economic response to GS 25 N applications at tiller densities above 1000 tillers m^{-2}. However, Weisz et al. (2001) reported an early or split N application is recommended when GS 25 tiller densities are <550 tillers m^{-2} in no-till wheat in the piedmont and coastal plain regions of North Carolina. Although data from the current study in no-till wheat did not indicate a similar critical point, the sample size is probably too small to accurately compare this aspect of these studies.

Wheat tissue N content (%) at GS 30 was regressed against economic optimum GS 30 N application rates for all sites (Fig. 3). This relationship ($r^2 = 0.40$) indicates wheat tissue N content is a poor predictor of optimum GS 30 N application rates in no-till wheat. These results are in contrast to studies by Baethgen and Alley (1989b) and Scharf and

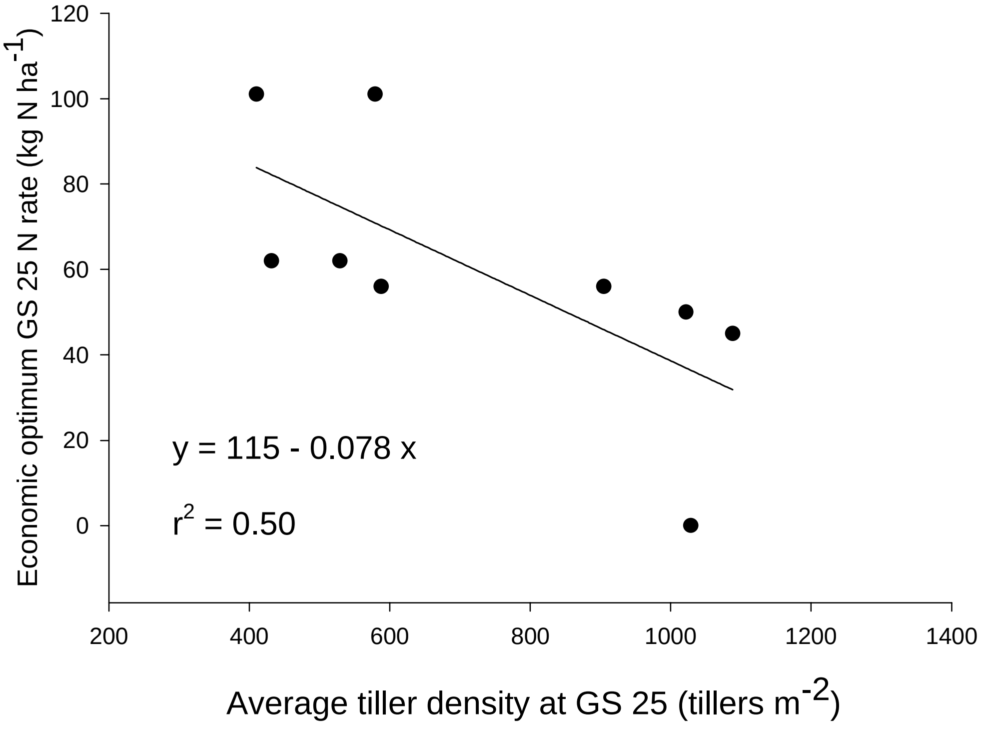


Figure 2. Average tiller densities at GS 25 regressed against economic optimum GS 25 N recommendation rate (excluding scab infested sites 1 and 2).

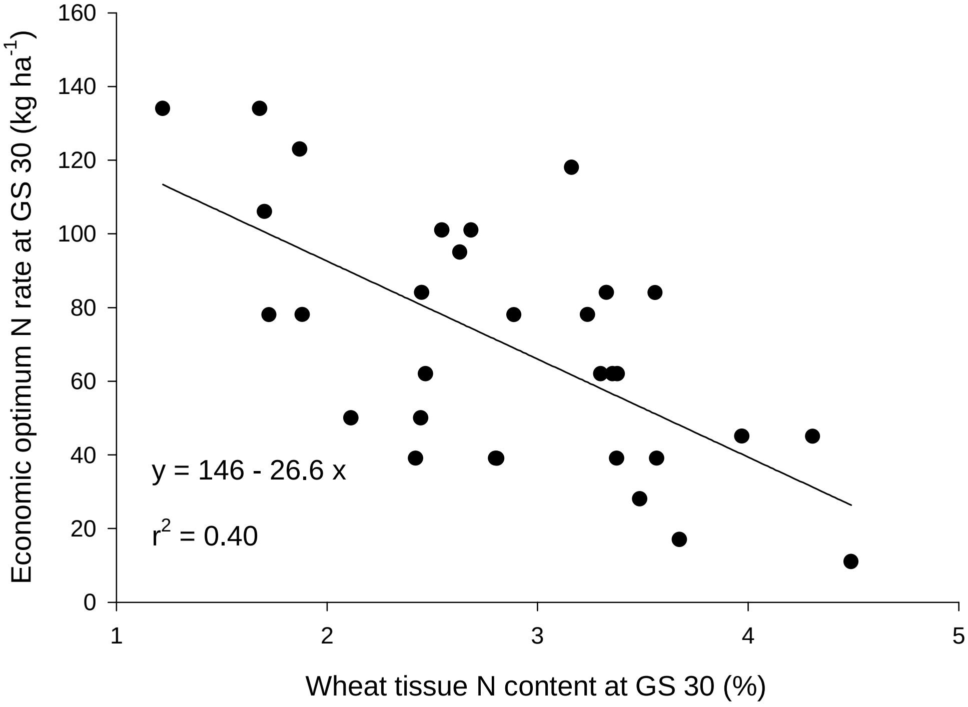


Figure 3. Wheat tissue N content at GS 30 regressed against economic optimum GS 30 N rate for each GS 25 N treatment (excluding scab infested sites 1 and 2).

Alley (1993) that indicated wheat tissue N content was a reasonable predictor ($r^2 = 0.59$ and 0.51, respectively) of optimum GS 30 N application rates in conventionally tilled wheat.

Hidema et al. (1992) and Kao and Forseth (1992) reported plant tissue N content is influenced by temperature, irradiation, soil water, and N source (organic versus inorganic N). Surface residue from no-till production lowers soil temperature, increases water retention and increases organic N compared to conventional tillage (Phillips and Phillips, 1984). These differences in no-till production may account for the poorer relationship between wheat tissue N content and economic optimum N rate compared to studies in conventionally tilled wheat.

The Minolta SPAD-502 chlorophyll meter readings taken at GS 30 were interpreted using the procedure of Murdock et al. (1997).

$$N = 6 + (7 \times D)$$

Where:

N = Pounds N acre^{-1} needed at Zadoks GS 30 for optimum growth

D = Difference between average chlorophyll readings from the field and the reference areas that received high N rates at Zadoks GS 25.

Nitrogen rate recommendations derived from SPAD meter readings at GS 30 were regressed against economic optimum GS 30 N recommendation rates (Fig. 4). The

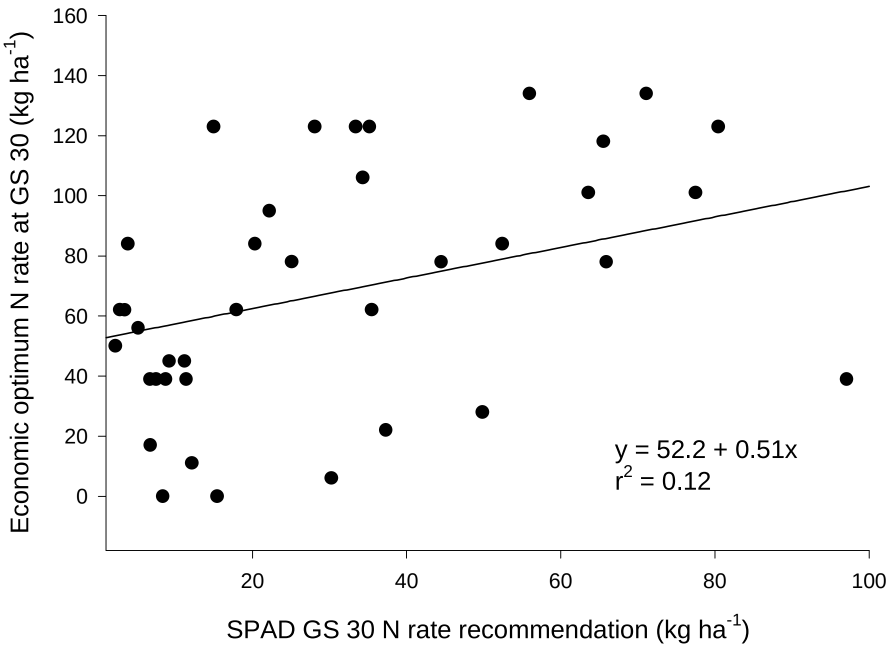


Figure 4. SPAD meter GS 30 N rate recommendation regressed against economic optimum GS 30 N rate (excluding scab infested sites 1 and 2).

SPAD meter was not a satisfactory predictor of economic optimum GS 30 N application rate ($r^2 = 0.12$). These results are in contrast to Reeves et al. (1993) who reported the SPAD leaf chlorophyll meter readings at GS 30, taken using the same method described previously, were a useful predictor of wheat grain yield ($r^2 = 0.58$) over various management practices in Alabama. However, the study by Reeves et al. (1993) did not relate GS 30 SPAD meter readings to optimum N recommendation rates at GS 30. Similar to the no-till wheat data, Pridgen (1995) reported the SPAD meter readings were not a useful predictor ($r^2 = 0.34$) of optimum GS 30 N rate in barley in the mid-Atlantic region.

Shadchina and Dmitrieva (1994) and Peikielek and Fox (1992) reported leaf chlorophyll content and SPAD chlorophyll meter readings were influenced by temperature, soil water, soil humidity, and irradiance. The variable conditions associated with no-till, mentioned previously, may again influence the usefulness of this method for predicting GS 30 economic N rate in a no-till environment.

In summary, economic optimum GS 25 and GS 30 N application rates were variable. Timely planted wheat produced higher yields, possibly due to more extensive root development that more effectively captured plant available N during the growing season. Selected methods for predicting GS 25 and GS 30 N rates in no-till wheat were not as reliable compared to results of similar studies in conventionally tilled wheat. Tiller densities at GS 25 were useful predictors of optimum GS 25 N application. Wheat tissue N content and SPAD chlorophyll meter readings at GS 30 were not useful predictors of optimum GS 30 N application. Surface residue from no-till production lowers soil temperatures, increases water retention, and increases organic N compared to conventional tillage. These factors may influence the relationship between the tested prediction methods and optimum N rates.

REFERENCES

Alley, M.M., D.E. Brann, E.L. Stromberg, E.S. Hagood, A.M. Herbert, E.C. Jones, and W.K. Griffith. 1993. Intensive soft red winter wheat production: A management guide. Ext. Pub. 424-803. Virginia Tech Coop. Ext., Virginia Tech, Blacksburg.

Baethgen, W.E. and M.M. Alley. 1989a. Optimizing soil and fertilizer nitrogen use by intensively managed winter wheat. I. Crop nitrogen uptake. Agron. J. 81:116-120.

Baethgen, W.E. and M.M. Alley. 1989b. Optimizing soil fertilizer nitrogen use by intensively managed winter wheat. II. Critical levels and optimum rates of nitrogen fertilizer. Agron. J. 81:120-125.

Bandel, V.A. 1983. No-tillage for corn: effects of fertilizer practices and time. Better Crops Plant Food 67:23-25.

Blevins, R.L., G.W. Thomas, and P.L. Cornelius. 1977. Influence of no-tillage and nitrogen fertilization on certain soil properties after five years of continuous corn. Agron. J. 69:383-386.

Bonde, T.A. and T. Rosswall. 1987. Seasonal variation of potentially mineralizable nitrogen in four cropping systems. Soil Sci. Soc. Am. J. 51:1508-1514.

Campbell, R.J., K.N. Mobley, R.P. Marini, and D.G. Pfeiffer. 1990. Growing conditions alter the relationship between SPAD-501 values and apple leaf chlorophyll. Hort. Science 25:330-331.

Carter, M.R. and D.A. Rennie. 1982. Changes in soil quality under zero tillage farming systems: Distribution of microbial biomass and mineralizable C and N potentials. Can. J. Soil Sci. 62:587-597.

Christensen, N.B., W.C. Lindemann, E. Salazar-Sosa, L.R. Gill. 1994. Nitrogen and carbon dynamics in no-till and stubble mulch tillage systems. Agron. J. 86:298-303.

Dalal, R.C. 1989. Long-term effects of no-tillage, crop residue, and nitrogen application on properties of Vertisol. Soil Sci. Soc. Am. J. 53:1511-1515.

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44:765-771.

Eck, H.V. and O.R. Jones. 1992. Soil nitrogen status as affected by tillage, crops, and crop sequences. Agron. J. 84:660-668.

Eckert, D.J. 1985. Effect of reduced tillage on the distribution of soil pH and nutrients in soil profiles. J. Fert. Issues 2:86-90.

Edwards, W.M., L.D. Norton, and C.E. Redmond. 1988. Characterizing macropores that affect infiltration into nontilled soil. Soil. Sci. Soc. Am. J. 52:483-487.

Fowler, D.B. and J. Brydon. 1989. No-till winter wheat production on the Canadian prairies: Timing of nitrogen fertilization. Agron. J. 81:817-825.

Franzluebbens, A.J., F.M. Hons, and D.A. Zuberer. 1995. Tillage and crop effects on seasonal soil carbon and nitrogen dynamics. Soil Sci. Soc. Am. J. 59:1618-1624.

Hay, R.M. K., J.C. Holmes, and E.A. Hunter. 1978. The effects of tillage, direct drilling, and nitrate fertilizer on soil temperatures under winter wheat and barley. J. Soil Sci. 29:174-183.

Hidema, J. A. Makino, Y. Kurita, T. Mae, and K. Ojima. 1992. Changes in the levels of chlorophyll and light-harvesting chlorophyll a/b protein of PS II in rice leaves aged at different irradiances from full expansion through senescence. Plant Cell Physiol. 53:1209-1214.

Inada, L. 1963. Studies on a method for determining the deepness of green chlorophyll content in intact crop leaves and its practical applications. I. Principles for estimating the deepness of green color and chlorophyll content of whole leaves. Proc. Crop Sci. Soc. (Jpn) 32:157-162.

Jacobsen, J.S. and R.L. Westerman, 1988. Nitrogen fertilization in winter wheat tillage systems. J. Prod. Agric. 1:235-239.

Kao, W.Y. and I.N. Forseth. 1992. Diurnal leaf movement, chlorophyll fluorescence and carbon assimilation in soybean grown under different nitrogen and water availabilities. Plant. Cell and Environ. 15:703-711.

Keeney, D.R. and D.W. Nelson. 1982. Nitrogen-inorganic forms. *In* A.L. Page, R.H. Miller, and D.R. Keeney (eds.) Methods of soil analysis, Part 2. Agron. Monogr. 9. 2nd ed. ASA and SSSA, Madison, WI.

Knapp, W.R., and J.S. Knapp. 1978. Response of winter wheat to date of planting and fall fertilization. Agron. J. 70:1048-1053.

Lal, R, 1976. No-tillage effects on soil properties under different crops in Nigeria. Soil. Sci. Soc. Am. J. 40:762-768.

Monje, O.A. and B. Bugbee. 1992. Inherent limitations of nondestructive chlorophyll meters: a comparison of two types of meters. HortScience. 27:69-71.

Murdock, L., S. Jones, C. Bowley, P. Needham, J. Jones and P. Howe. 1997. Using a chlorophyll meter to make nitrogen recommendations on wheat. Kentucky Cooperative Extension. University of Kentucky, Lexington, KY. Pub no. AGR-170.

Olson, R.V. and C.W. Swallow. 1984. Fate of labeled nitrogen fertilizer applied to winter wheat for five years. Soil Sci. Soc. Am. J. 48:583-586.

Pettygrove, G.S., R.O. Miller, J.Y. Deng, J.F. Williams, and C.M. Wick. 1991. Using a portable chlorophyll meter to determine leaf nitrogen content in grain crops. Soil and Water. 5.

Phillips, R.E. and S.H. Phillips. 1984. No-tillage Agriculture. Principles and Practices. VNR, New York, NY.

Piekielek, W.P. and R.H. Fox. 1992. Use of a chlorophyll meter to predict sidedress nitrogen requirements for maize. Agron. J. 84:59-65.

Pittman, U.J. and J.E. Andrews. 1961. Effects of date of seeding on winter survival, yield and bushel weight of winter wheat grown in Southern Alberta. Can. J. Plant Sci. 41:71-80.

Pridgon, T. 1995. Development of intensive N management strategies for winter barley in the mid-Atlantic region. M.S. thesis. Blacksburg.

Rasmussen, P.E., R.W. Rickman, and B.L. Klepper. 1997. Residue and fertility effects on yield of no-till wheat. Agron. J. 89:563-567.

Reeves, D.W., P.L. Mask, C.W. Wood, and D.P. Delaney. 1993. Determination of wheat nitrogen status with a hand-held chlorophyll meter: influence of management practices. J. Plant Nutri. 16(5):781-796.

Rice, C.W. and M.S. Smith. 1984. Short-term immobilization of fertilizer nitrogen at the surface of no-till and plowed soils. Soil Sci. Soc. Am. J. 48:295-297.

Rocheford, T.R., D.J. Sammons, and P.S. Baenziger. 1988. Planting date in relation to yield and yield components of wheat in the Middle Atlantic Region. Agron. J. 80:30-34.

Roth, G.W. R.H. Fox, and H.G. Marshall. 1989. Plant tissue tests for predicting nitrogen fertilizer requirements of winter wheat. Agron. J. 81:502-507.

SAS Institute. 1999. SAS/STAT User's Guide v. 7-1. SAS Inst., Cary, NC.

Scharf, P.C. and M.M. Alley. 1993. Spring nitrogen on winter wheat: II. A flexible multicomponent rate recommendation system. Agron. J. 85:1186-1192.

Schepers, J.S. 1993. Chlorophyll meter measures midseason nitrogen uptake. Solutions 37:44-45.

Schepers, J.S., D.D. Francis, M. Vigil, and F.E. Below. 1992. Comparison of corn leaf nitrogen concentration and chlorophyll meter readings. Commun. Soil. Sci. Plant Ana. 23:2173-2187.

Schomberg, H.H., J.L. Steiner, and P.W. Unger. 1994. Decomposition and nitrogen dynamics of crop residue: Residue quality and water effects. Soil Sci. Soc. Am. J. 58:372-381.

Shadchina, T.M. and V.V. Dmitrieva. 1995. Leaf chlorophyll content as a possible diagnostic mean for the evaluation of plant nitrogen uptake from the soil. J. Plant. Nutri. 18(7):1427-1437.

Smith, S.J. and D.K. Cassel. 1991. Estimating nitrate leaching in soil materials. p. 165-188. *In* R.F. Follet, D.R. Keeney, and R.M. Cruse (eds.) Managing nitrogen for groundwater quality and farm profitability. Soil Sci. Soc. Am., Madison, WI.

Takabe, M., T. Yoneyama, K. Inada, and T. Murakami. 1990. Spectral reflectance ratio of rice canopy for estimating crop nitrogen status. Plant and Soil. 122:295-297.

Takabe, M. and T. Yoneyama. 1989. Measurement of leaf color scores and its implication to nitrogen nutrition of rice plants. Japan Agric. Res. Q. 23:86-93.

Unger, P.W. 1991. Organic matter, nutrient, and pH distribution in no- and conventional-tillage semiarid soils. Agron. J. 83:186-189.

Virginia Agricultural and Statistics Service. 1999. Winter wheat county estimates [Online]. Available at http://www.nass.usda.gov/va/wheat/989.pdf (verified 15 April 2001).

Virginia Cooperative Extension. 1996. Small grain and straw budgets [Online]. Available at http://www.ext.vt.edu/departments/agecon/spreadsheets/crops/smgrn.html (verified 1 April 1998).

Virginia Cooperative Extension. 1998. Small grain and straw budgets [Online]. Available at http://www.ext.vt.edu/departments/agecon/spreadsheets/crops/smgrn.html (verified 1 April 2001).

Weisz, R. and D.T. Bowman. 1999. Influence of tillage system on soft red winter wheat cultivar selection. J. Prod. Ag. 12:415-418.

Weisz, R., C.R. Crozier, and R.W. Heiniger. 2001. Optimizing nitrogen application timing in no-till soft red winter wheat. Agron. J. 93:435-442.

Winter, S.R. and J.T. Musick. 1993. Wheat planting date effects on soil water extraction and grain yield. Agron. J. 85:912-916.

Wood, C.W., and D.W. Reeves, R.R. Duffield, and K.L. Edmisten. 1992. Field chlorophyll measurements for evaluation of corn nitrogen status. J. Plant. Nutr. 15:487-500.

Zadoks, J.C., T.T. Chang, and C.F. Konzak. 1974. A decimal code for the growth stages of cereals. Weed Res. 14:415-421

Chapter III

Nitrogen management in no-till winter wheat: Yield and nitrate leaching at various early season fertilizer nitrogen application rates.

ABSTRACT

Early season fertilizer N is often applied in an effort to promote fall tiller development and increase yields in no-till wheat (*Triticum aestivum*) in Virginia's Coastal Plain. However, the impacts of these elevated early season N applications on yields and potential nitrate leaching losses have not been determined. Six no-till wheat experimental sites were established during the 1998-99 and 1999-00 growing season in fields following corn grain production. Nitrogen fertilizer was applied at selected pre-plant rates in combination with December or Zadoks growth stage (GS) 25 N application rates in a randomized complete block design. Total N application rates ranged from 0 to 224 kg N ha^{-1}. Planting date affected tillering, yield and the NO_3 leached over the growing season. Timely planted wheat had greater tiller densities and higher yields, however NO_3 leaching rates were similar to check plots where no nitrogen was applied. Economic optimum N application rates and timings were obtained from least-squares response surfaces, which estimated profit as a function of pre-plant and December or GS 25 N applications. Nitrate leaching loss was not different than check plots for most N treatments under timely planted no-till wheat, but NO_3 leaching loss was higher than check plot levels for most N treatments under late planted no-till wheat. However, the economic optimum N rates and timings did not produce NO_3 leaching losses beyond levels measured under check plots at any site during either growing season, with one

exception. Additionally, economic optimum N application that included a December N application had higher yields and profits compared to economic optimums for treatments without a December N application. These data indicate that the inclusion of December N applications is profitable, and when combined with timely planting, can be managed to prevent additional NO_3 leaching losses in Virginia Coastal plain soils.

INTRODUCTION

Improving no-till wheat yields through increasing N applications at pre-plant, in December and at Zadoks growth stage (GS) 25 (Zadoks et al., 1974) to promote additional tiller development, is becoming an increasingly common practice in the Coastal Plain region of Virginia. Increased immobilization of N under no-till is the primary process responsible for decreased plant available N compared to conventional tillage (Doran, 1980; Follett and Schimel, 1989; Groffman, 1984). Periods of warmer mid-winter temperatures and higher rainfall in the mid-Atlantic region can stimulate both immobilization and mineralization processes, and may also increase denitrification and NO_3 leaching losses. The milder climate also stimulates mid-winter crop growth. These combined factors may contribute to N deficiency symptoms, such as yellowing of the leaves, and reduced growth and tillering, which have been observed in no-till wheat during mid-winter in the Coastal Plain region of Virginia.

Research in various studies supports the concept that higher grain yields can be obtained using spring N applications compared to fall applications (Harper et al., 1987; Fowler and Brydon, 1989; Boman et al., 1995). However, these studies were performed in the cooler, drier climates of the mid-West and Canada, where mid-season N losses would be generally lower than in the sandy soils of the warmer, wetter Eastern Coastal Plain. In the mid-Atlantic region, Scharf and Alley (1993) found that N applications at Zadoks GS 25 improved tiller development at GS 30 and grain yield if tiller densities at GS 25 were less than 1000 tillers m^{-2}. In a study from Oklahoma, Bowman et al. (1995) found that timing of N fertilization had minimal influence on grain yield, however, apparent fertilizer N recovery in winter wheat forage was highest when N was applied at or before mid-January. Johnston and Fowler (1991), working in Canada, found that delaying spring fertilizer N by 3 weeks severely limited grain yield in winter wheat because it failed to correct early season N deficiencies until after yield potential was established. These studies indicate that N availability and uptake at, or prior to, GS 25 may be a key factor in establishing yield potential. In the warmer, more humid regions of the mid-Atlantic, where mid-winter N availability may be low, winter wheat may utilize fertilizer N applied at, or prior to, GS 25 to improve tillering and yield compared to drier climates.

Another consideration in the timing of N fertilization of winter wheat in Virginia is the potential for NO_3 leaching below the wheat root zone. The rooting depth of a mature winter wheat crop in coastal plain soils is generally considered to be 1.2 meters or less (Agus and Cassel, 1992; McCracken et. al., 1994). Sandy textured soils of the Coastal Plain region are often near field capacity during the winter because precipitation exceeds evapotranspiration for extended periods. Unconsolidated sediments, shallow groundwater, and a predominance of sand with little organic matter or clay, characterize the soils in the Virginia Coastal plain used for row crop production. These combined factors increase the vulnerability of ground and surface waters to contamination from NO_3 leaching.

Leaching of NO_3 to ground water has become an increasing environmental concern related to the use of agricultural fertilizers and application of animal wastes. Nitrogen inputs to the mid-Atlantic region in the early 1990's were estimated at 500 million kg per year from manure (Puckett, 1995) and 422 million kg per year from fertilizers (Battaglin and Goolsby, 1994). A major beneficiary of the use of inorganic N fertilizers in the mid-Atlantic region is grain crop production, including increasing no-till winter wheat production. Bachman and Phillips (1996) and Staver et al. (1996) sampled shallow groundwater, less than 31-m, in watersheds of the Chesapeake Bay. Watersheds primarily under cash grain production contained ground water NO_3 concentrations in excess of the EPA drinking water standard of 10 mg l^{-1}, compared to NO_3 concentrations of forested watersheds, which did not exceed the EPA standard. Ator and Ferrari (1997), reported median N concentrations in ground water under row crop production in the mid-Atlantic of 4.8 mg l^{-1}. However, 10% of their samples exceeded the EPA drinking water standard. In the same study, Ator and Ferrari (1997) reported the median N concentrations in ground water under forested areas was less than 0.10 mg l^{-1}.

The potential for NO_3 to reach ground or surface waters is a function of soil type, weather conditions, and crop N management (Alva and Wang, 1996; Wu et al., 1996). Chichester (1977) found that the highest levels of NO_3-N flux in soil percolate occurs in winter months when evapotranspiration has reached a minimum due to cessation of crop growth and percolation rates are at a maximum. Higher water infiltration rates associated with no-till compared to conventional tillage have also been widely reported (Edwards et al., 1988; Eck and Jones, 1992, Kanwar et al., 1988). These studies indicate that fall N management for no-till wheat in the wetter climate of the Coastal Plain of Virginia can significantly impact NO_3 leaching. Increasing N fertilizer use efficiencies through various application rates and timings can reduce NO_3 leaching (Francis, 1992; Ottman et al., 2000).

Effective fall and mid-winter N management strategies must collectively optimize economic yields while minimizing NO_3 leaching. The objectives of this research were to determine economic optimum pre-plant, December and GS 25 N application rates and timings, and measure NO_3 leaching losses in no-till winter wheat for the Virginia Coastal Plain.

MATERIALS AND METHODS

Experimental design

Six N fertilization rate and timing experiments were conducted during the 1998-99 and 1999-00 growing seasons in no-till winter wheat on the Coastal Plain region of Virginia. Soil types and production strategies were typical of Eastern Coastal Plain soils in grain crop production (Table 4). All experimental sites were planted into corn stubble and had been in continuous no-till production for 2 to 5 years.

The experimental plan involved a complete factorial design with 4 levels of pre-plant N applications and 4 levels of Zadoks growth stage (GS) 25 N applications (Zadoks et. al., 1974) at sites I and II. Sites V and VI were complete factorial designs with 3 levels of pre-plant N applications and 4 levels of December N applications. Sites III and IV consisted of 4 combinations of equal pre-plant and GS 25 N applications (Table 5). Treatments were arranged in a randomized complete block design with four replications at each site. Individual plots measured 5 by 5.5-m with 2.1-m alleyways between each replication. Ceramic suction lysimeters were placed in selected treatments (Table 5) to sample soil solute NO_3-N concentrations during the growing season.

Urea ammonium nitrate (30% N) was used as the N source for all treatment N applications. The N solution was applied with a carbon dioxide pressurized backpack sprayer. The sprayer boom was fitted with Teejet ‘raindrop’ tips. Flow rates for each tip size were measured at each experimental location prior to N application. Proper walking

Table 4. Soil type, seeding rate, winter wheat variety and planting date for six experimental sites evaluating N fertilization of no-till winter wheat.

Site	Year	Soil Type	Seeding rate	Variety	Planting Date
			Seeds m^{-2}		
I	1998	Eunola sandy loam, Fine-loamy, siliceous, thermic Aquic Hapludults	553	Pocahontas	November 6
II	1998	Bojac, loamy sand, Fine-loamy, siliceous, thermic Typic Hapludults	516	Pioneer 2684	October 14
III	1999	Suffolk, sandy loam Fine-loamy, siliceous, thermic Typic Hapludults	553	Roane	November 1
IV	1999	Kempsville, sandy loam Fine-loamy, siliceous, thermic Typic Hapludults	553	Roane	October 16
V	1999	Suffolk, sandy loam Fine-loamy, siliceous, thermic Typic Hapludults	553	Roane	November 1
VI	1999	Kempsville, sandy loam Fine-loamy, siliceous, thermic Typic Hapludults	553	Roane	October 16

Table 5. Nitrogen rate and timing treatments by site.

Sites I and II†			Sites III and IV†			Sites V and VI‡		
Trt.	**Pre-Plant**	**GS 25**	**Trt.**	**Pre-Plant**	**GS 25**	**Trt.**	**Pre-Plant**	**December**
	-----kg N ha^{-1}-----			-----kg N ha^{-1}-----			-----kg N ha^{-1}-----	
1¶	0	0	1¶	0	0	1¶	0	0
2	0	22	2¶	22	22	2	0	22
3	0	45	3¶	45	45	3¶	0	45
4	0	67	4¶	67	67	4¶	0	67
5	22	0	5§¶	0	0	5¶	34	0
6¶	22	22				6	34	22
7	22	45				7¶	34	45
8	22	67				8¶	34	67
9	45	0				9¶	67	0
10	45	22				10	67	22
11¶	45	45				11¶	67	45
12	45	67				12¶	67	67
13	67	0						
14	67	22						
15	67	45						
16¶	67	67						
17§¶	0	0						

† Uniform application of 34 kg N ha^{-1} applied at GS 30 to all treatments

‡ Uniform application of 45 kg N ha^{-1} applied at GS 25 and GS 30 to all treatments

§ Check plot, no N applications

¶ Ceramic suction lysimeters installed at 1.2-m

speed to obtain the desired application rate was calculated, and a stopwatch and metronome were used to calibrate and maintain the proper walking speed during N application.

Soil Sampling, Analysis and Tiller Counts

Soil samples were taken in early October to characterize soil texture and measure residual soil mineral N (Table 6). Mass soil mineral N (NH_4^+ and NO_3^-) concentrations (kg ha^{-1}) were estimated from soil samples taken at depths of 0- to 0.15-, 0.15- to 0.30-, 0.30- to 0.61-, 0.61- to 0.91-, and 0.91- to 1.20-m. Soil samples were immediately frozen using dry ice, then thawed and extracted in duplicate with 2 M KCl and filtered prior to analysis (Keeney and Nelson, 1982). Nitrate and NH_4^+ were determined colorimetrically on a Lachat Instruments Automated Analyzer using QuikChem Methods 12-107-04-1-B and 12-107-06-2-A, respectively (Lachat Instruments, Milwaukee, WI).

Tillers per 0.91 meters of row were counted at GS 25 for each of the treatments to determine tiller response to fall N application rates. Eight counts were conducted at each site with locations for each measurement selected randomly within the site boundaries.

Soil Water Monitoring

Soil water was monitored using time domain reflectometry (TDR) moisture probes (ESI, Vancouver, B.C.), installed at each site in early November. The probes were installed into plots receiving 45 kg N ha^{-1} at pre-plant and at GS 25, with the uniform application

Table 6. Soil texture and residual soil mineral N (NH_4^+ and NO_3^-) for each soil type for samples collected at wheat planting.

	Eunola		Bojac		Suffolk		Kempsville	
Depth	**Soil texture†**	**Residual N**	**Soil texture**	**Residual N**	**Soil texture**	**Residual N**	**Soil texture**	**Residual N**
meters		**kg ha^{-1}**		**kg ha^{-1}**		**kg ha^{-1}**		**kg ha^{-1}**
0.0 – 0.15	**sl**	**10.6**	**ls**	**8.4**	**sl**	**6.7**	**sl**	**8.6**
0.15 – 0.3	**l**	**4.6**	**ls**	**4.0**	**sl**	**7.2**	**l**	**4.5**
0.3 – 0.6	**cl**	**1.9**	**fsl**	**3.6**	**l**	**4.6**	**l**	**2.7**
0.6 – 0.9	**scl**	**4.1**	**fsl**	**4.8**	**sl**	**4.5**	**sl**	**3.6**
0.9 – 1.2	**sl**	**3.2**	**fsl**	**3.9**	**ls**	**4.2**	**sl**	**1.9**
Total		**26**		**25**		**27**		**21**

†Soil texture abbreviations: c = clay, l = loam, s=sand.

of 34 kg N ha^{-1} at GS 30 at sites I through IV. At sites V and VI, moisture probes were installed in plots receiving 34 kg N ha^{-1} at pre-plant and 45 kg N ha^{-1} in December with the uniform application of 45 kg N ha^{-1} at GS 25 and GS 30. Volumetric water content (%) was measured at 0- to 0.15-, 0.15- to 0.30-, 0.30- to 0.61-, 0.61- to 0.91-, and 0.91- to 1.20-m depths. Measurements were taken periodically after precipitation events and prior to each soil water sampling between November and May of each growing season.

Soil Water Sampling

Ceramic suction lysimeters were used to monitor NO_3-N concentrations (mg l^{-1}) in soil water because they caused minimal disturbance to the surrounding soil and wheat crop. One bar, high flow, ceramic suction lysimeters (Soil Moisture Equipment Corporation, Santa Barbara, CA) were installed at 1.2-m depths between wheat rows in November in selected treatments and check plots. Lysimeter installation and sampling followed the procedures outlined by Linden (1977) and Wu et al. (1995). Soil water sampling began when TDR moisture probe measurements indicated soil water had reached field capacity to a depth of 1.2-m. Field capacity was defined as the water content at which internal drainage ceased. Soil water was sampled 48 to 72 hours following precipitation events using a vacuum pump (12-volt, 1 Bar maximum) attached to a battery. Solid stoppers were removed from the tops of the 5-cm diameter lysimeters at the time of sampling. Lysimeters were evacuated of any residual moisture. Rubber stoppers fitted with tubing and a clamp were attached to the lysimeters and vacuum applied. The tubing was clamped and the lysimeters were allowed to remain with the applied vacuum for approximately 1.5 hours before the water sample was removed by siphon. Soil water samples were immediately placed in a cooler with ice. Nitrate and NH_4^+ were determined colorimetrically on a Lachat Instruments Automated Analyzer using QuikChem Methods 12-107-04-1-B and 12-107-06-2-A, respectively (Lachat Instruments, Milwaukee, WI).

Determination of Soil Water Balance and Nitrate Leaching

Daily soil water storage and drainage were determined using the water balance equation of Martin et al. (1991):

$\triangle S = P - Et + (R + D)$ where,

$\triangle S$ = Change in soil water storage (1.2m),

P = Precipitation,

Et = Evapotranspiration,

R = Surface Run-off,

D = Drainage.

No-till field sites were level, and precipitation events did not exceed soil infiltration rates, which ranged from 5 to 15 cm hr^{-1} (National Cooperative Soil Survey, 1982); therefore, surface run-off was assumed to be zero. Precipitation (mm) was measured by on-site weather stations (Spectrum Technology Weather Monitor II^{tm}). Evapotranspiration was calculated using potential pan evaporation measured in the Virginia Coastal plain, 161 kilometers south of the experimental sites. Potential pan evaporation field measurements were not taken from November through February of each growing season due to errors associated with freezing and thawing. Therefore, for this time period, potential pan evaporation was calculated using a modified Penman-Montieth equation (Allen et. al., 1998). Actual evapotranspiration (ET_a) was calculated using the method of Allen et al. (1998):

$ET_a = Et_o * K_c$ where;
ET_a = actual evapotranspiration,
ET_o = potential evapotranspiration,
K_c = crop coefficient.

Crop coefficient estimates were based on the FAO guideline (Allen et al., 1998). Values of K_c used for timely planted wheat over each season were: 0.8 from October through February, 1.0 for March through May, and 0.25 in June. Values of K_c used for late planted wheat over each season were: 0.7 from October through February, 0.8 in March, 1.0 in April and May, and 0.25 in June. Slightly higher crop coefficients were used for timely planted wheat due to the greater biomass observed in timely planted fields. Using the calculated ET_a, daily water balance was solved by adjusting available water content with inputs from rainfall and losses from ET_a.

Time series water content at each site was interpolated to a daily basis based on the procedures described by Schwab et al. (1993) and utilized by Sadler et al. (2000). Calculated daily soil water storage was verified using TDR moisture probe field measurements taken throughout the growing season. When predicted daily water content exceeded field capacity at the 1.2 m depth, the excess was considered drainage.

Nitrate leaching estimates were determined according to the procedure of Hook and Kardos (1978) and Hook and Burton (1979), who utilized porous cup sampling along with water balance to estimate NO_3 leaching below 1.2 m on municipal sewage application sites. Soil water NO_3-N concentrations were interpolated to a daily basis through the growing season (Schwab et al., 1993). Nitrate N leached was calculated from the drainage volume and NO_3 concentration for each lysimeter and summed for the growing season. The resulting data were analyzed using SAS ANOVA procedure (SAS Institute, 1999). Treatment mean separation was determined using Duncans multiple range test.

Grain Yields

Wheat grain was harvested in a 1.5 m wide area of each plot with a plot combine. Grain yields were adjusted to 135 g kg^{-1} moisture content. Profit was estimated for each plot as wheat value (yield x price) – N fertilizer cost (N rate x N price) – other fixed production costs. For the 1998-99 season, N fertilizer cost estimates were \$0.53 kg^{-1}, wheat grain was \$0.077 kg^{-1}, and fixed costs were estimated at \$313 ha^{-1} (Virginia Cooperative Extension, 1998). For the 1999-00 season, N fertilizer cost estimates were \$0.44 kg^{-1}, wheat grain was \$0.074 kg^{-1}, and fixed costs were estimated at \$313 ha^{-1} (Virginia Cooperative Extension, 1998). These costs and returns reflect actual conditions for each growing season. The least-squares quadratic response surface was calculated for estimated profit and yield as a function of N rate for sites V and VI (SAS Inst., 1999).

RESULTS AND DISCUSSION

Planting Date, Tillering and Grain Yield

Planting date affected tiller densities at GS 25 and grain yield. Recommended planting date for the Virginia Coastal Plain is one week before to one week after the first frost date, around October 20 (Alley et al., 1993). Therefore, in the Coastal Plain of Virginia, winter wheat should be planted between October 15 and 30 to optimize conditions for emergence and fall tiller development.

Yields for no-till wheat planted timely (Sites II, IV and VI) were higher for almost all treatments except check plots, when compared to late planted wheat (Fig. 5). Knapp and Knapp (1978) reported late planting increases wheat's susceptibility to winter injury due to poorly developed root systems and may result in yield reduction. Although their study was undertaken in New York, where winter conditions are more severe than in the Coastal Plain of Virginia, the basic principle of yield reduction due to a poorly developed root system in late planted wheat is supported by other studies (Pittman and Andrews, 1961; Winter and Musick, 1993) including a study located in the mid-Atlantic Coastal Plain (Rocheford et al., 1988). These cited studies indicate timely planted wheat may more effectively utilize N applied in December, or at GS 25, due to an improved root system, ultimately producing higher yields.

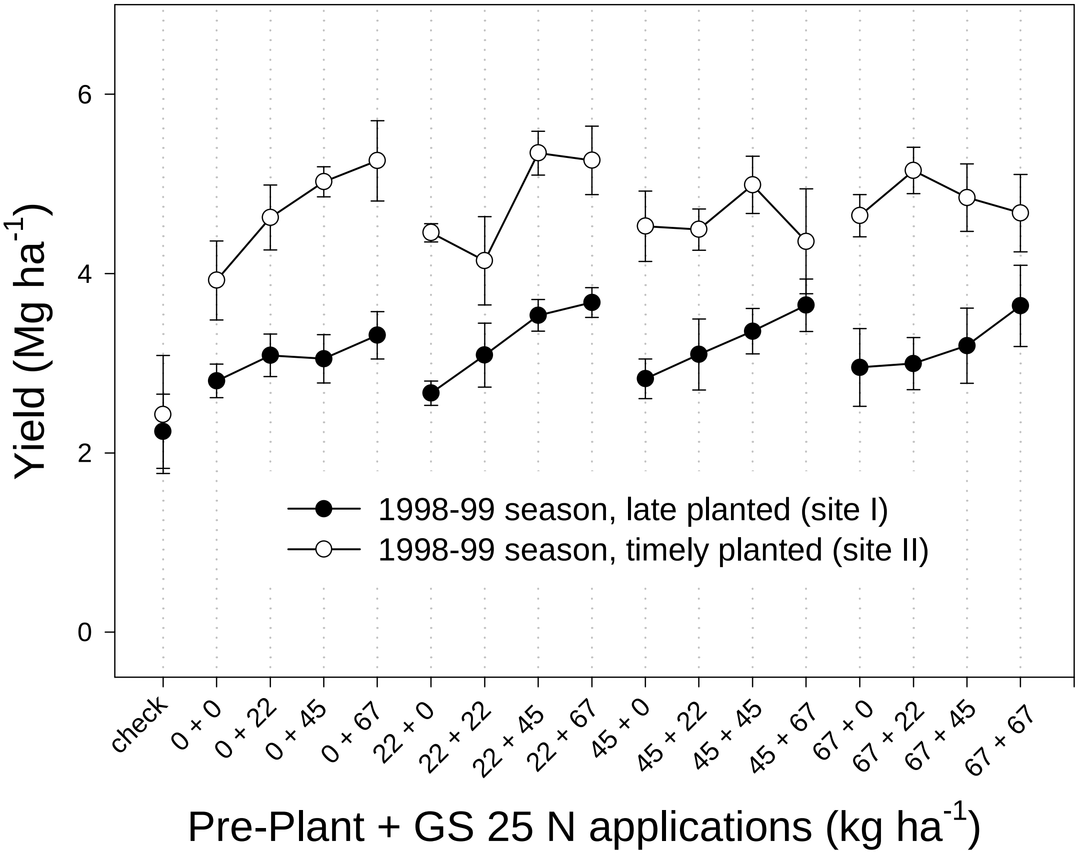


Figure 5a. Pre-plant plus GS 25 N rate and timing effect on yield with standard deviations for timely and late-planted no-till wheat in the Virginia Coastal Plain during the 1998-99 growing season.

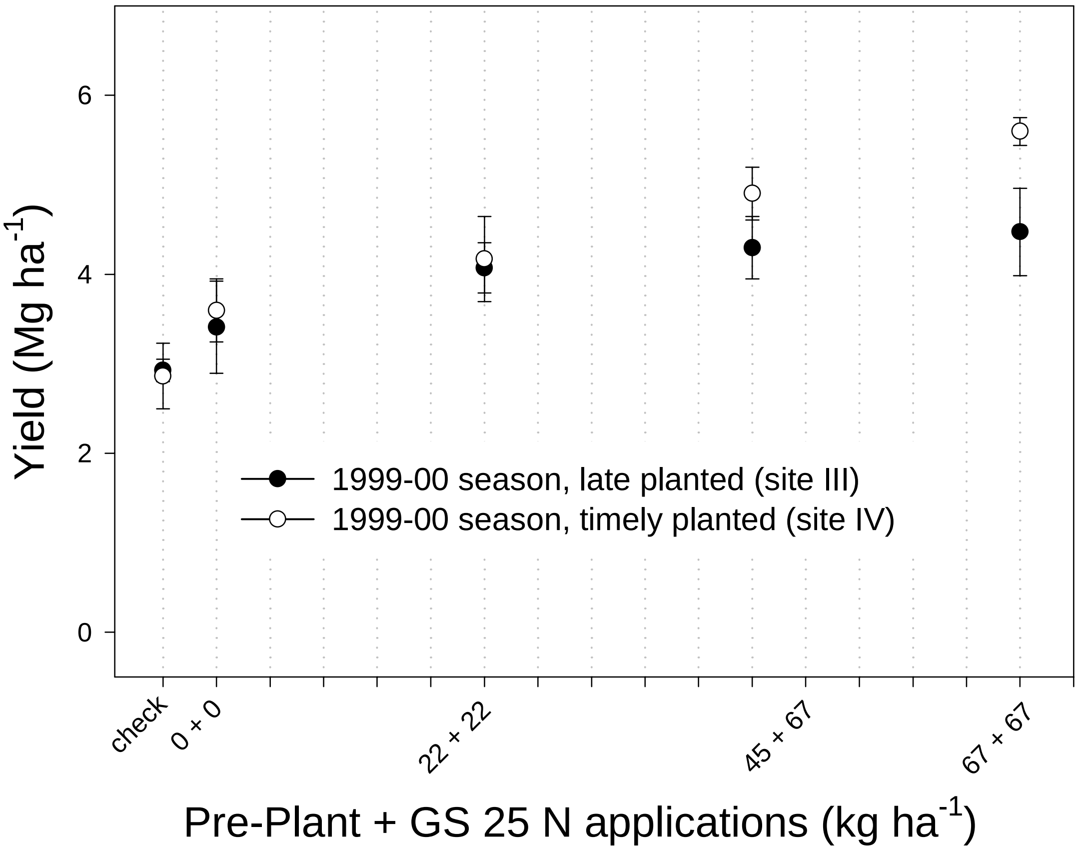


Figure 5b. Pre-plant plus GS 25 N rate and timing effect on yield with standard deviations for timely and late-planted no-till wheat in the Virginia Coastal Plain during the 1999-00 growing season.

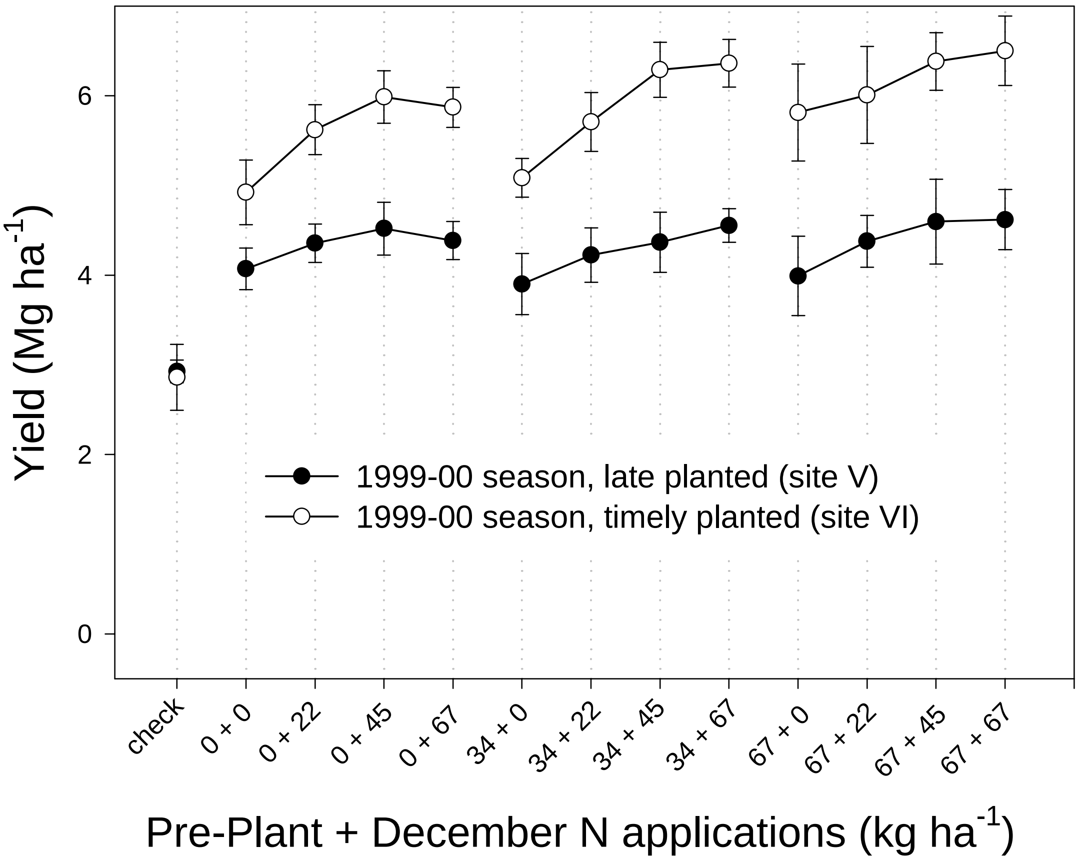


Figure 5c. Pre-plant plus December N rate and timing effect on yield with standard deviations for timely and late-planted no-till wheat in the Virginia Coastal Plain during the 1999-00 growing season.

Yields of treatments receiving no pre-plant N increased with increasing N rates at GS 25 or December N (Figs. 5a and 5c). The response to these N applications was greater for timely planted wheat. These data agree with results from Louisiana by Shah et al. (1994), who reported that additional spring N increased grain yield of early-planted wheat, but was not beneficial for late-planted wheat. This response difference supports the argument that timely planted wheat more effectively utilizes early spring applied N compared to late planted wheat.

Yield was also affected by N application rates and timings (Fig. 5). Pre-plant only N applications of 0, 22, 34, 45 and 67 kg N ha^{-1} did not affect yield for either timely or late planted wheat (Figs. 5a and 5c). The exception is for the timely planted wheat during the 1999-00 season (site VI), where nitrogen applications of 67 kg N ha^{-1} at pre-plant produced higher yields than other pre-plant only N application rates (Fig. 5c).

Planting date also affected tiller densities at GS 25. Sites II, IV, and VI were planted within the recommended planting period and had an average 695 tillers m^{-2}, compared to sites I, III and V, which were planted after the recommended planting period and had an average 444 tillers m^{-2} at GS 25 (Figs. 6 and 7). Tiller densities across treatments were variable, resulting in inconsistent trends in the data (Figs. 6 and 7). Variability in tiller densities may have been due to heavy residue that caused inconsistencies in planting, stand development, and difficulty counting tillers.

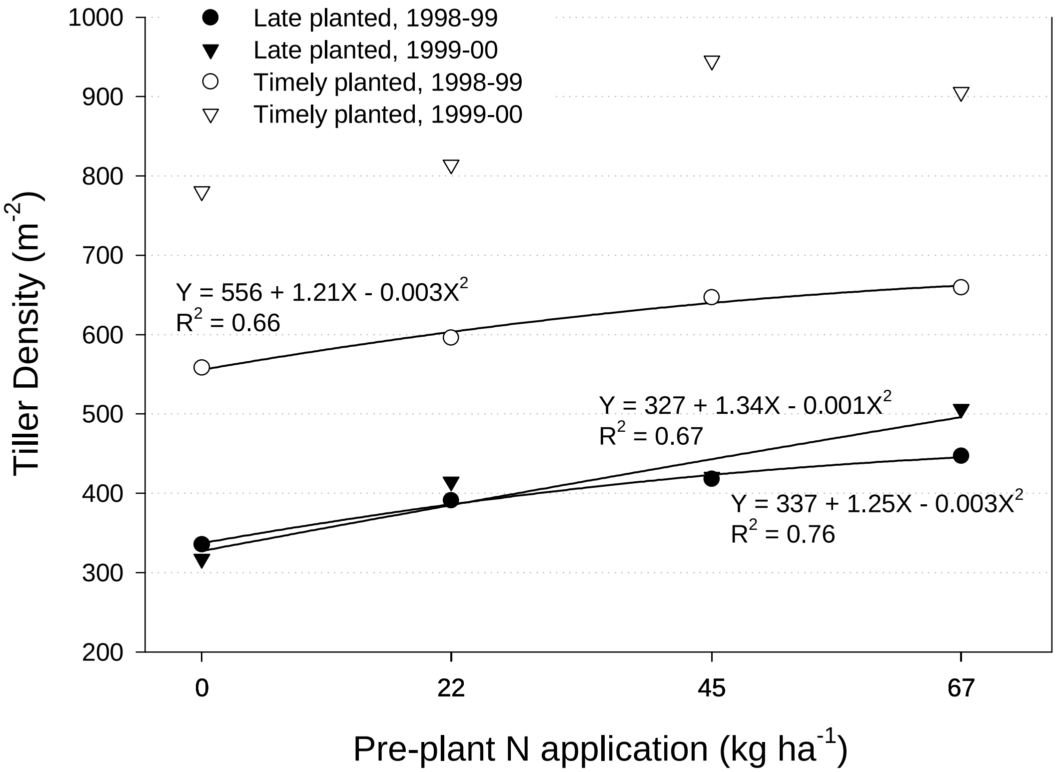


Figure 6. Tiller densities at GS 25 for various pre-plant N application rates in timely and late planted no-till winter wheat over 1998-99 and 1999-00 growing seasons. Regression analysis performed using all treatment replications. Points shown are treatment averages. Treatments with no regression line are not significantly different.

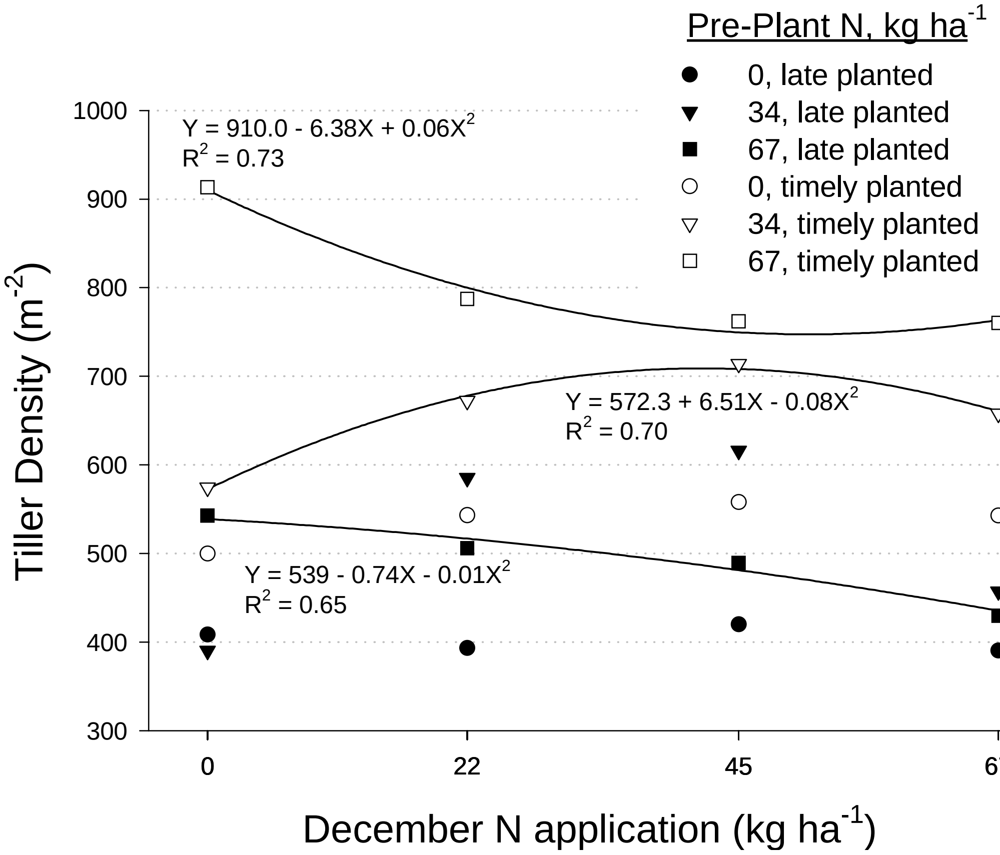


Figure 7. Tiller densities at GS 25 for various pre-plant and December N application rates in timely and late planted no-till winter wheat for the 1999-00 growing season. Regression analysis performed using all treatment replications. Points shown are treatment averages. Treatments with no regression line are not significantly different.

Timely planted check plots (no N applications), had higher tiller densities (665 tillers m^{-2}) compared to late planted wheat check plots (399 tillers m^{-2}) (Figs. 6 and 7). However, yield for check plots was not different between timely (2718 kg ha^{-1}) and late (2697 kg ha^{-1}) planted wheat (Fig. 5), indicating insufficient spring N was more influential to yield than planting date in check plots.

Yields quadratically regressed against tiller densities at GS 25 produced low regression coefficients ($0.10 < r^2 < 0.47$), possibly due to a combination of variability in tiller density and compensatory growth after GS 25. Scharf et al. (1993) reported that GS 25 N applications did stimulate formation of additional tillers and increased yield if GS 25 tiller densities were below 1000 m^{-2}. In Figures 5a and b, treatments receiving only 34 kg N ha^{-1} at GS 30, had higher yields than check plots that received no N applications. In Figure 5c, treatments receiving only 45 kg N ha^{-1} at GS 25 and 45 kg N ha^{-1} at GS 30 also had higher yields compared to check plots. This yield response to GS 25 and GS 30 applications alone indicates early spring N applications maintained tillers and contributed to grain production.

Soil Water Storage

The 30-year average precipitation between November and June for the region, where all sites were located, was 608 mm (National Weather Service, 2001). During the 1998-99 season, 559 mm precipitation occurred between November and June, while the same period of the 1999-00 season received 660 mm. The precipitation was well distributed throughout both growing seasons. However, soil profiles were dry during the beginning of the season due to late summer droughts, and gravimetric soil water content did not reach field capacity to a depth of 1.2 meters until late December (Fig. 8). Field capacity ranged from 298 to 377-mm from 0 to 1.2 m.

Soil water holding capacity was calculated to a depth of 1.2 meters and compared with the average TDR measurements for each soil type. The calculated soil water values followed TDR field measurements, indicating valid estimates of drainage at 1.2-m were obtained (Fig. 8). Actual soil water measurements were higher than calculated values during mid-March because field measurements were taken less than 24 hours after several large precipitation events when the soil was saturated and thus above field capacity.

Drainage, calculated using the equation of Martin et al. (1991), occurred between November and April at all sites over both seasons, and total drainage ranged from 196 to 275 mm. Lord and Mitchell (1998) reported over-winter drainage to 0.9 m from winter wheat on sandy loam and loamy sand soils between 242 and 296 mm during average seasons in England. Precipitation was not reported. Jaakkola (1984) reported seasonal drainage rates of 225 mm to a depth of 1.7-m from precipitation rates of 630 mm under winter wheat in a clay soil. Because clay soils have smaller pore sizes and higher surface areas, resulting in higher water holding capacities and more resistance to water flow, drainage is more restricted compared to sandy soils. Therefore, the lower drainage rates, even with higher precipitation, are reasonable in clay soils. These studies provide a guide

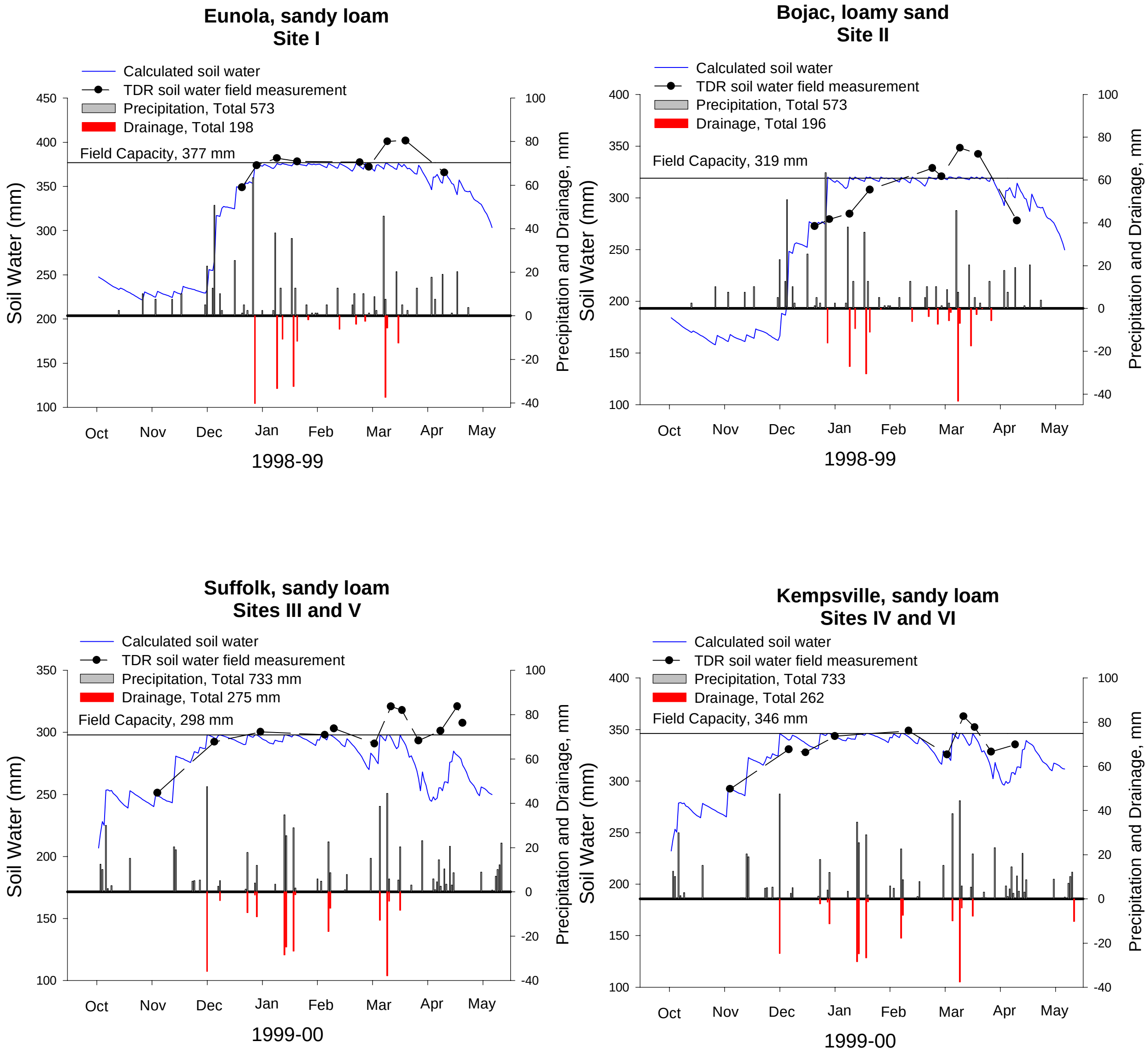


Figure 8. Actual and calculated soil moisture at 1.2-m, precipitation and drainage for each of 4 soil types during the 1998-99 and 1999-00 growing seasons.

for drainage rates, and show field drainage calculations for winter wheat in sandy loam Coastal Plain soils from the current study appear to be reasonable estimates.

Nitrate Leaching

Nitrate leached at 1.2 meters was lower under timely planted wheat at all sites over both the 1998-99 and 1999-00 growing seasons (Fig. 9). Nitrate leached under the true check plots was similar between timely and late planted wheat at sites III through VI, during the 1999-00 growing season. This is reasonable because the residual soil N, and precipitation amount and distribution, were similar between the sites. There was a difference between nitrate leached from check plots at sites I and II despite similar total residual soil N to 1.2-m (Fig 9a). This difference may relate to higher yields from the previous corn crop (8040 kg ha^{-1} compared to 5375 kg ha^{-1}) leading to greater surface residue subjected to mineralization during the growing season. However, NO_3 leached under late planted treatments at site I are still higher than the check plot, while NO_3 leached under timely planted wheat treatments at site II are not different than check plots (Figure 9a).

There were no effects of fertilization rate or timing on NO_3 leaching compared to background levels in check plots for the timely planted sites II and VI, with NO_3 leaching amounts ranging from 20 to 37 kg ha^{-1} over a growing season (Figure 9a and 9b). There was a difference in N rate and timing treatments at timely planted site IV. Pre-plant and GS 25 N applications of 22 and 22 kg ha^{-1} resulted in NO_3 leaching rates of 13 kg N ha^{-1},

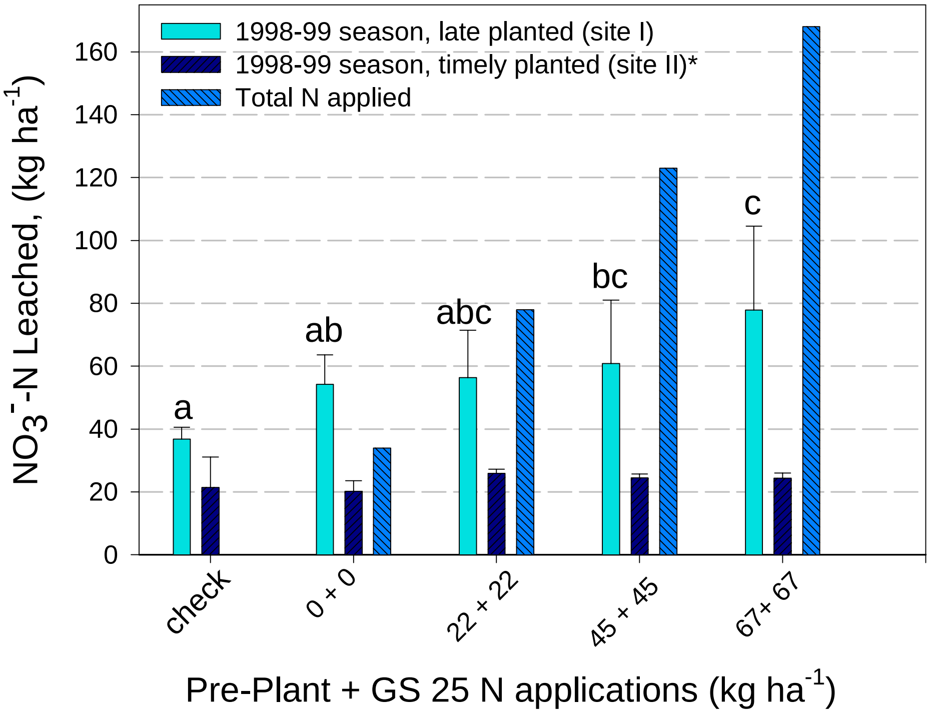


Figure 9a. Nitrate leached between December and May at 1.2-m under various pre-plant and GS 25 N applications rates in no-till wheat during the 1998-99 growing season. Treatments within the same site, marked by different letters, differ significantly at P = 0.05 by Duncan's multiple range test.

***NS = not significantly different at P= 0.05.**

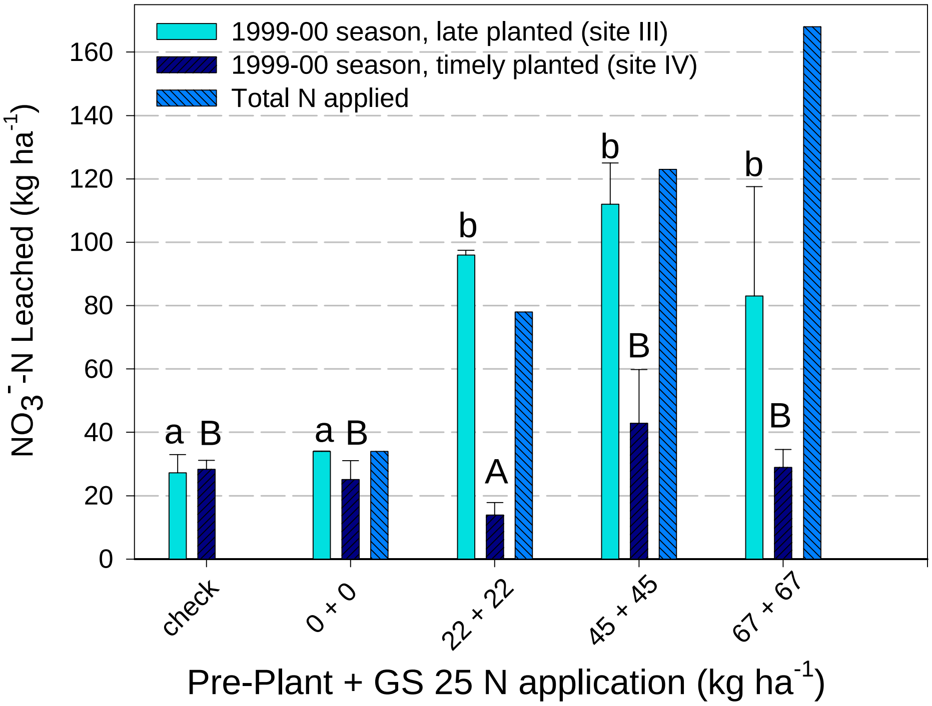


Figure 9b. Nitrate leached between December and May at 1.2-m under various pre-plant and GS 25 N applications rates in no-till wheat during the 1999-00 growing season. Treatments within the same site, marked by different letters, differ significantly at P = 0.05 by Duncan's multiple range test.

***NS = not significantly different at P= 0.05.**

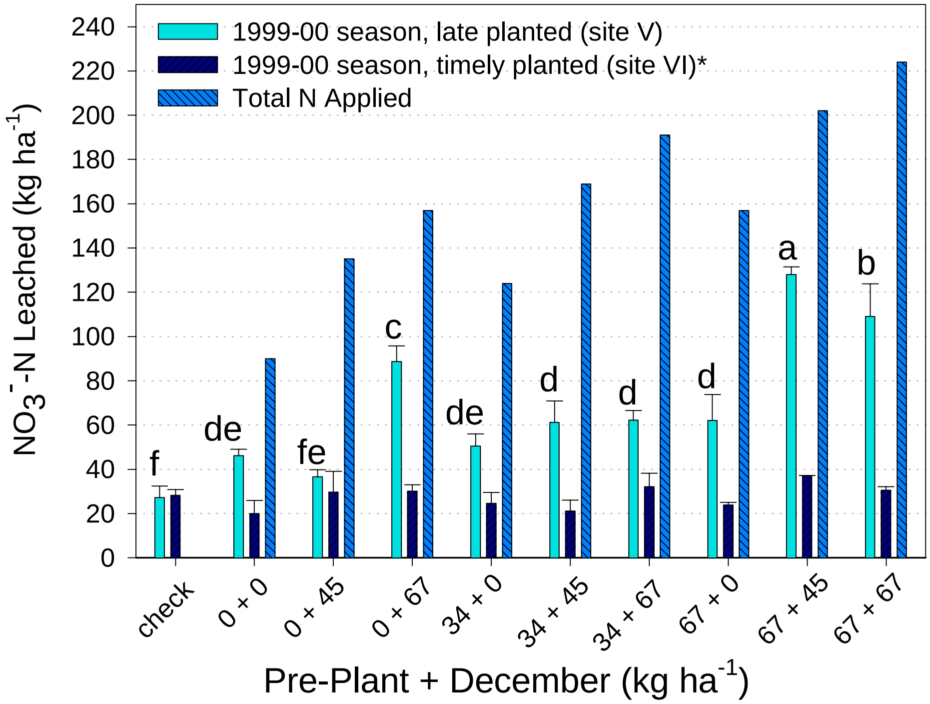


Figure 9c. Nitrate leached between December and May at 1.2-m under various pre-plant and December N applications rates in no-till wheat during the 1999-00 growing season. Treatments within the same site, marked by different letters, differ significantly at P = 0.05 by Duncan's multiple range test.

***NS = not significantly different at P= 0.05.**

while pre-plant and GS 25 N applications of 45 and 45 kg N ha^{-1} resulted in NO_3 leaching amounts of 43 kg N ha^{-1} during the 1999-00 growing season (Figure 9b).

Nitrogen fertilization rate and timing did affect NO_3 leached at all late planted sites when compared to background levels in check plots. However, N leaching under pre-plant and GS 25 treatments of 0 and 0, and 22 and 22 kg N ha^{-1} were not different than check plot levels at site I for the 1998-99 growing season (Fig. 9a). During the 1999-00 growing season, a treatment of 0 and 0 kg N ha^{-1} at pre-plant and GS 25 (GS 30 uniform N application of 34 kg N ha^{-1} only) was not different than check plot levels. Pre-plant and GS 25 N application rates of 67 and 67 kg N ha^{-1} at site I produced NO_3 leaching amounts of 78 kg N ha^{-1} over the 1998-99 growing season. The same treatment at site III produced similar NO_3 leaching amounts of 83 kg ha^{-1} over the 1999-00 growing season. Comparatively, the NO_3 leached for the same treatment under timely planted wheat was 24 and 29 kg ha^{-1}, respectively, for the 1998-99 and 1999-00 seasons (sites II and IV).

Lord and Mitchell (1998) reported average NO_3 leaching losses from cereal grain crops planted in sandy soil of 51 kg N ha^{-1} over winter for N fertilizer inputs of 154 kg N ha^{-1} applied in 6 steps. The use of 6 applications might lead to improved plant use efficiency and decreased NO_3 leaching loss. However, NO_3 leaching losses in Lord and Mitchell's experiment were comparable to data from the current study where N was applied in 3 or 4 steps. Jaakkola (1984) reported NO_3 leaching losses of 30 and 43 kg ha^{-1} for winter wheat on clay soil with 100 kg ha^{-1} total N fertilizer applied in 3 steps. Clay soils have higher water holding capacities and therefore may leach less NO_3 compared to sandier soils. With these considerations, Jaakkola's results also compare reasonably with the range of NO_3 leaching losses measured in the current study.

The absence of NO_3 leaching differences between check plots and most treatments in timely planted wheat indicates timely planted wheat is more efficient at capturing available N and preventing NO_3 leaching loss compared to late planted wheat. Therefore, N management strategies for timely planted wheat should focus on economic optimum N application rates and timings, which will be addressed later in this paper. However, grain crop production in the Virginia Coastal plain often involves planting hundreds of hectares of wheat with few people. The result is no-till wheat planted after optimum planting dates, requiring more intensive N management strategies to prevent excess NO_3 leaching.

An N management strategy for late planted wheat with pre-plant, GS 25 and GS 30 N applications of 22, 22 and 34 kg N ha^{-1}, respectively, was most effective at preventing NO_3 losses exceeding background levels during the 1998-99 growing season (Fig 9a). During the 1999-00 growing season, an N management strategy of 0 and 0 kg N ha^{-1} at pre-plant and GS 25, and 34 kg N ha^{-1} at GS 30 only, prevented NO_3 leaching losses from exceeding background levels (Fig. 9b). For a pre-plant and December N management strategy, N applications of 0 and 45 kg N ha^{-1}, respectively, were most efficient at preventing NO_3 leaching loss above check plot levels during the 1999-00 growing season (Fig. 9c). However, these management strategies for late planted wheat during 1999-00 growing season may not be suitable for adequate tiller development and optimum yield.

The highest NO_3 leaching rates in late planted no-till wheat occurred under pre-plant and GS 25 N management strategies of 22 and 22, 45 and 45 or 67 and 67 kg N ha^{-1} respectively, during both the 1998-99 and 1999-00 growing seasons. Pre-plant and December N management produced the highest NO_3 leaching at the higher N application rates of 67 and 45 kg N ha^{-1}, and 67 and 67 kg N ha^{-1}, respectively. Applying 0 and 67 kg N ha^{-1} at pre-plant and December, respectively, also produced higher NO_3 leaching rates. This result is probably a product of the timing of the N application. In the mid-Atlantic region, the highest risk of leaching NO_3 below the wheat root zone occurs between December and March, when mean monthly precipitation exceeds potential evapotranspiration (Smith and Cassel, 1991; Staver and Brinsfield, 1998). Therefore, December N applications are more vulnerable to leaching loss, especially in late planted wheat.

Plotting daily NO_3 leaching loss at 1.2-m over time reveals the differences in leaching patterns between timely and late planted wheat at various N application rates and timings. Daily NO_3 leaching losses for all treatments are located in Appendices F. Figure 10 represents a comparison of daily soil water NO_3 concentrations and daily cumulative NO_3 leaching for timely and late planted wheat in 4 selected pre-plant and GS 25 treatments at Sites I and II during the 1998-99 growing season. Nitrogen applications at pre-plant, GS 25 and GS 30 of 0, 0 and 34 kg N ha^{-1}, respectively, (Fig. 10) shows higher NO_3 concentrations under the late planted site from mid-February to early-March in comparison to the same treatment at the timely planted site. This difference in soil water NO_3 concentration creates a significant difference in cumulative leaching loss over the

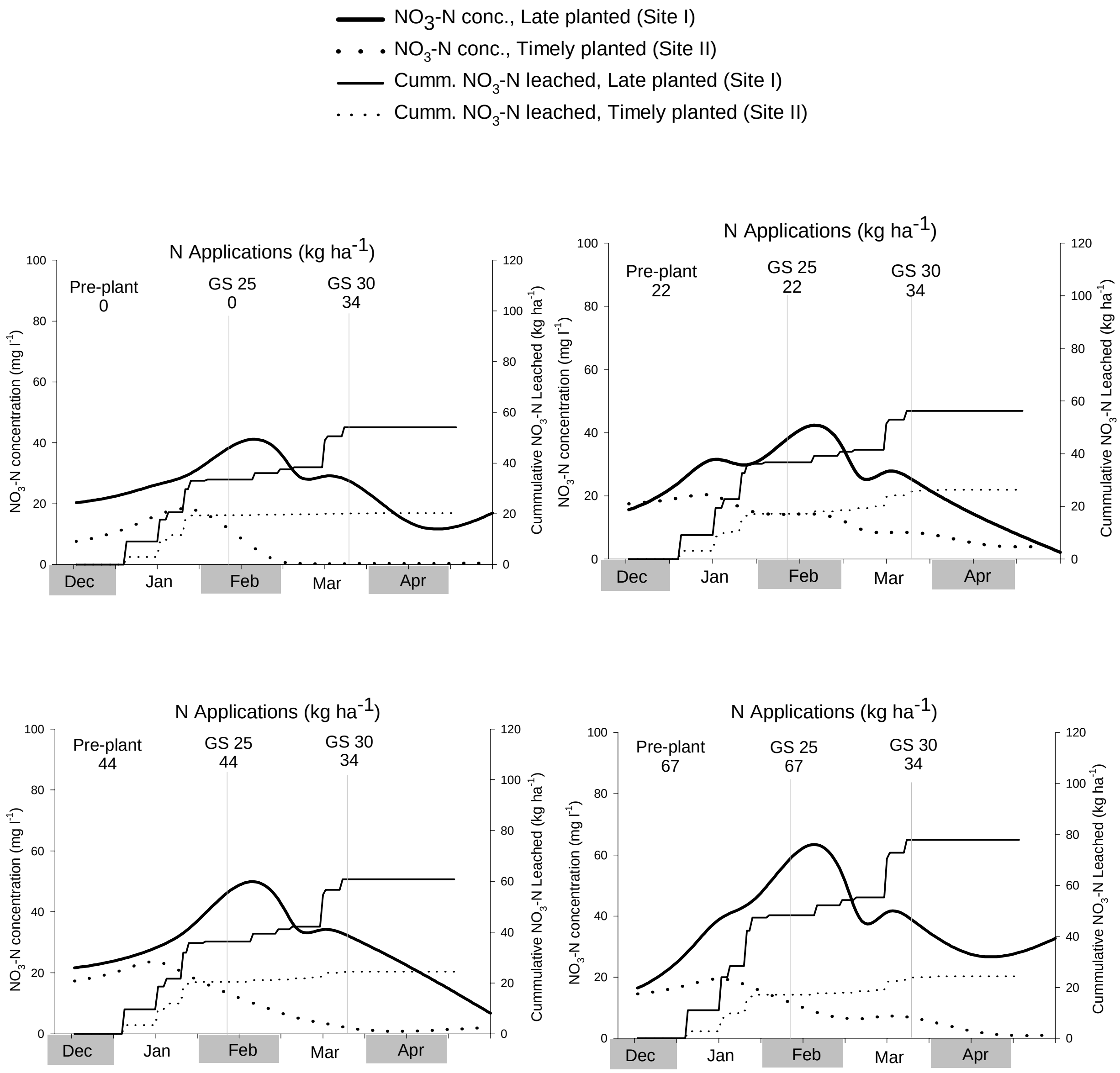


Figure 10. Nitrate nitrogen concentrations and cumulative NO_3 leached over the 1998-99 growing season for 4 pre-plant and GS 25 N management strategies.

growing season in late versus timely planted no-till wheat. As the pre-plant and GS 25 N applications increase in the proceeding treatments (Fig. 10), the cumulative leaching losses over a growing season under the late planted site become more pronounced due to higher soil water NO_3 concentrations.

Figure 11 represents the same comparisons of treatments for late and timely planted sites discussed previously, except measured during the 1999-00 growing season. In each of the 4 selected treatments, soil water NO_3 concentrations are again lower under timely planted wheat, leading to lower cumulative NO_3 leaching. However, peak soil water NO_3 concentrations occur later than in the previous season, from mid-March to early April.

Figure 12 shows a comparison of daily soil water NO_3 concentrations and daily cumulative NO_3 leaching for timely and late planted wheat in 5 selected pre-plant and December treatments at Sites V and VI during the 1999-00 growing season. Again, the difference in cumulative NO_3 leached over the season between the timely and late planted wheat is directly related to the higher soil water NO_3 concentrations. Soil water NO_3 concentrations under late planted wheat also peaked between mid-March and early April, and NO_3 leaching was progressively higher with increased N applications (Fig. 12). This is a similar pattern seen at Sites III and IV (Fig. 11), which received N applications at different times (pre-plant and GS 25), but within the same season.

Cumulative NO_3 leaching data shows the divergence of timely and late planted wheat with regard to NO_3 leaching loss under all treatments. From mid-January to mid-

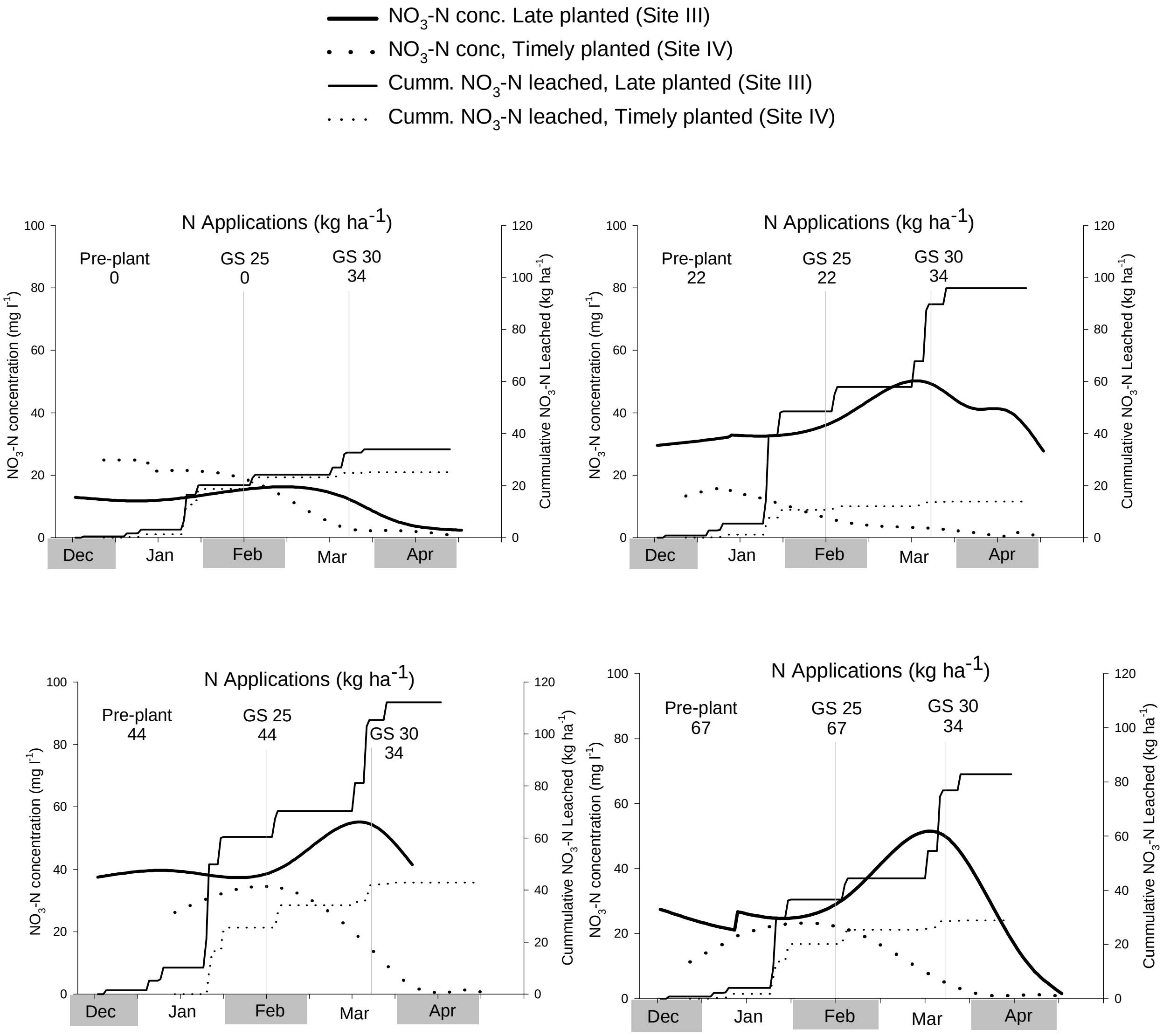


Figure 11. Nitrate nitrogen concentrations and cumulative NO_3 leached over the 1999-00 growing season for 4 pre-plant and GS 25 N management strategies.

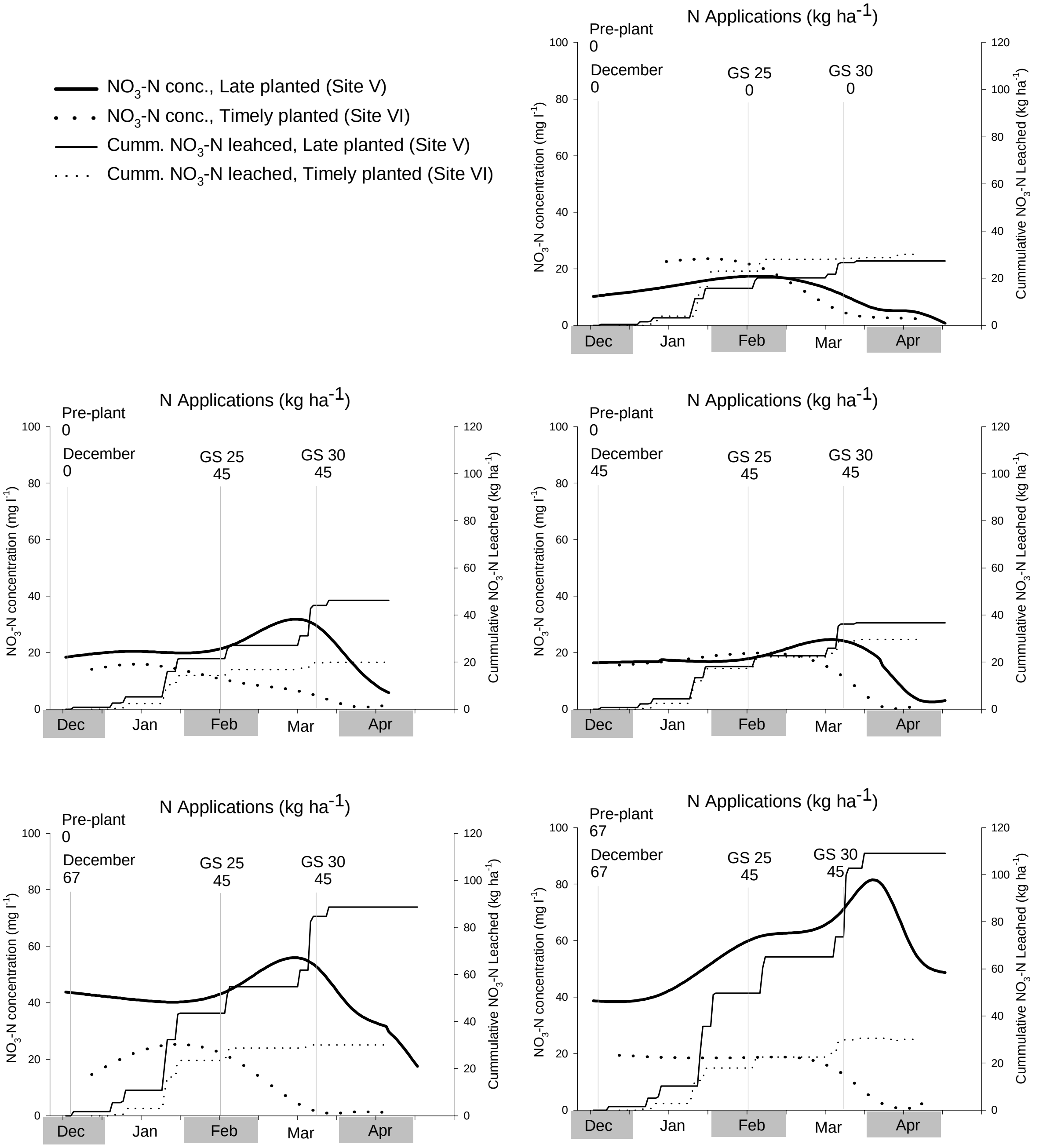


Figure 12. Nitrate nitrogen concentrations and cumulative NO_3 leached over the 1999-00 growing season for 5 pre-plant and December N management strategies.

February, NO_3 concentrations in soil water are generally declining under timely planted wheat during both the 1998-99 and 1999-00 growing seasons. However, over this same time period, NO_3 concentrations under late planted wheat are generally increasing, and in fact peak between mid-February and early-March during the 1998-99 growing season, and between mid-March and early-April during the 1999-00 growing seasons.

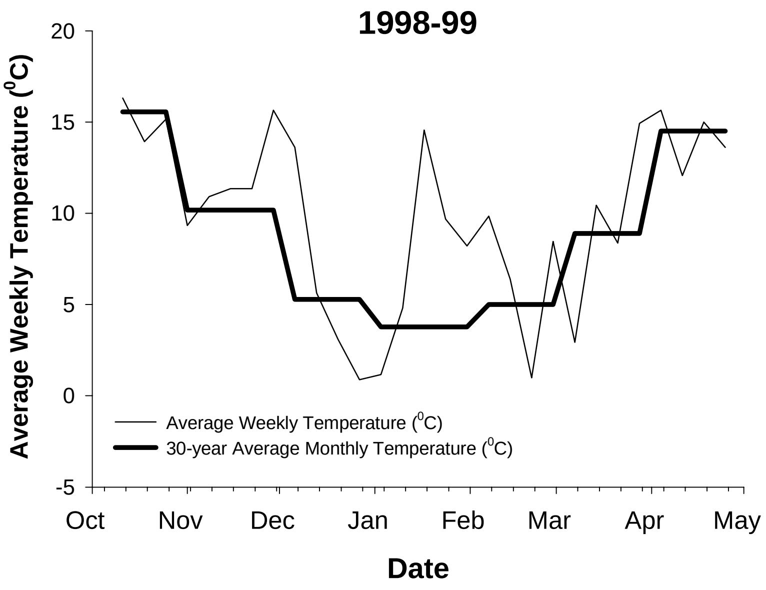
Nitrate transport in soil water is variable and dependent on factors such as soil porosity and hydraulic conductivity, and influx (precipitation). In saturated sandy loam soil, solute can be transported in soil water to a depth of 1.2-m within 24 to 72 hours (Brady, 1990; Hillel, 1998). However, under field conditions in the current experiment, the soil profile to 1.2-m may not have been completely saturated prior to each precipitation event. Combined with soil heterogeneity, the transport of N in the soil profile under field conditions is variable, and likely slower than the transport of N under controlled and continuously saturated conditions.

Nitrate concentrations in soil water at 1.2-m under late planted wheat began rising in January, peaking in mid-February during the 1998-99 growing season (Fig. 10). During the 1999-00 growing season, the NO_3 rise under late planted wheat began in early-March, and peaked near mid-March (Fig. 11). These NO_3 concentrations peaks coincided with periods of above average temperatures during both seasons. Havlin and others (1999) reported that microbial activity associated with N cycling processes such as mineralization, is most active at temperatures above 10^0 C. Average daily air temperatures were above 10^0C for 1 week or more between January and February of the

1998-99 growing season, and between February and March of the 1999-00 growing season (Fig. 13). A study by Hansen and Djurhuus (1996) concluded that increased leaching associated with increased fertilization in Denmark was not caused by soil inorganic N, but by greater mineralization, mainly in autumn in Denmark under spring barley. The timing of the soil water NO_3 peak concentrations under late planted no-till wheat in the current study indicates NO_3 leached may be a combination of fertilizer N and mineralized N.

Economic Optimum N Fertilization Rates and Timings and Nitrate Leaching

Timely planted wheat more efficiently utilizes applied N to produce higher yields, lower NO_3 leaching rates, and ultimately, higher profitability (Table 7). Variations in soil types can influence yield and NO_3 leaching, but sites selected for these studies had similar soils. Economic optimum N application rates produced an average of 1745 kg ha^{-1} higher yields under timely planted wheat and averaged 30$ ha^{-1} in profits compared to an average of 53 $ ha^{-1} loss under late planted wheat. Yield regression or yield and economic response surface curves for all sites are located in Appendices D and E. Economic optimum N application rates at all sites produced NO_3 leaching rates that were not significantly different than check plot NO_3 leaching rates in the same experiment, with the exception of site III. The higher NO_3 leaching rate at site III may be a product of higher soil water movement coinciding with high NO_3 concentrations in the soil water during March of the 1999-00 growing season (Fig. 11). However, with the exception of site III, economic optimization of N fertilizer application rates and timings in timely



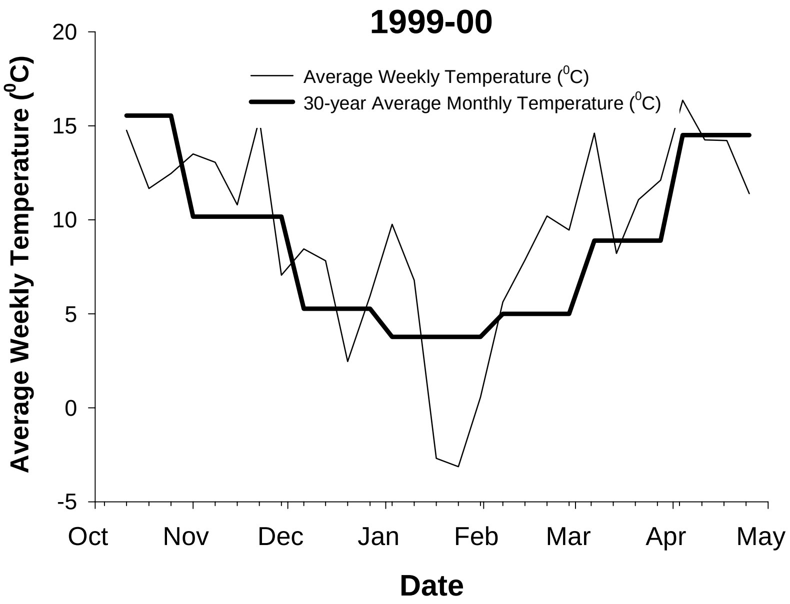


Figure 13. Average air temperature during 1998-99 and 1999-00 growing seasons compared to 30-year average temperatures.

planted no-till wheat also decreased the risk of NO_3 leaching loss, averaging 34 kg N ha^{-1} NO_3 leaching loss (Table 7). These results are supported by Lord (1992), who estimated average NO_3 leaching losses from winter cereals in England at around 35 kg N ha^{-1} with optimum N fertilization rates.

December N applications affected yield and profitability. Sites that received N applications in December, in addition to pre-plant and GS 25 and 30 N applications, produced 906 kg ha^{-1} higher yields and 55 \$ ha^{-1} more profit, on average, than sites that received pre-plant, GS 25 and 30 N applications only. These data indicate that the inclusion of December N applications is more profitable, and when combined with timely planting, can be managed to prevent excess NO_3 leaching losses in Virginia Coastal plain soils.

Table 7. Economic optimum† early season N rate and timings for treatments with NO_3 leaching data.

Site	Planting	Season	Pre-plant	Dec.	GS 25	Yield	Profit (loss)	Nitrate Leached
			-------kg N ha^{-1}------			kg ha^{-1}	\$ ha^{-1}	kg N ha^{-1}
I§	Late	98-99	22	--	22	3090	(110)	56
II§	Timely	98-99	45	--	45	4989	12	24
III§	Late	99-00	22	--	22	4072	(50)	96‡
IV§	Timely	99-00	67	--	67	5595	29	29
V¶	Late	99-00	0	45	45	4435	(0)	36
VI¶	Timely	99-00	0	67	45	6250	50	24

† Economic optimum N rates were calculated in the 1998-99 season using: UAN = 0.53\$ kg^{-1} N, grain = 0.077\$ kg^{-1}, variable cost = 313\$ ha^{-1}; and in the 1999-00 season: UAN = 0.44\$ kg^{-1} N, grain = 0.74\$ kg^{-1}, variable cost = 313\$ ha^{-1}.

‡ Significantly different from check plots ($P<0.05$).

§ 34 kg N ha^{-1} applied at GS 30.

¶ 45 kg N ha^{-1} applied at GS 30.

REFERENCES

Agus, F., and D.K. Cassel. 1992. Field-scale bromide transport as affected by tillage. Soil Sci. Soc. Am. J. 56:254-260.

Allen, R. G., L.S. Pereira, D. Raes, M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO irrigation and drainage paper. 56. FAO Publishers, Rome.

Alley, M.M., D.E. Brann, E.L. Stromberg, E.S. Hagood, A.M. Herbert, E.C. Jones, and W.K. Griffith. 1993. Intensive soft red winter wheat production: A management guide. Virginia Cooperative Extension, Virginia Tech. Pub no. 424-803.

Alva, A.K., and F.L. Wang. 1996. Leaching of nitrogen from slow-release urea sources in sandy soils. Soil Sci. Soc. Am. J. 60:1454-1458.

Ator, S.W. and M.J. Ferrari. 1997. Nitrate and selected pesticides in ground water of the Mid-Atlantic region [Online]. Water Resources Investigations Report 97-4139. USGS and EPA. Available at http://dg33dmdtws.er.usgs.gov/maia/97-4139/ (verified 15 April, 2001).

Bachman, I.J., and P.J. Phillips. 1996. Hydrologic landscapes on the Delmarva Peninsula Part 2: Estimates of base-flow nitrogen load to Chesapeake Bay. J. Amer. Water Resour. Assoc. 32: 779-791.

Battaglin, W.A., and Goolsby, D.A. 1994. Spatial data in a geographic information system format on agricultural chemical use, land use, and cropping system practices in the United States: U.S. Geological Survey Water-Resources Investigation Report 94-4176, 87 p.

Blake, G.R., and K.H. Hartge. 1986. Bulk density. p. 364-367. *In* A. Klute (ed.) Methods of soil analysis. Part 1. Agron. Monogr. 9. 2nd ed. ASA and SSSA, Madison, WI.

Bowan, R.K., R.L. Westerman, W.R. Raun, and M.E. Jojola. 1995. Time of nitrogen application: effects on winter wheat and residual soil nitrate. Soil Sci. Soc. Am. J. 59:1364-1369.

Brady, N.C. 1990. Soil Water: Characteristics and Behavior. p. 138. *In*: N.C. Brady (ed) The Nature and Properties of Soils. Macmillan Publishing Company, New York, NY.

Chichester, F.W., 1977. Effects of increased fertilization rates on nitrogen content of runoff and percolate from monolith lysismeters. J. Environ. Qual. 6:211-217.

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44:765-771.

Eck, H.V. and O.R. Jones. 1992. Soil nitrogen status as affected by tillage, crops, and crop sequences. Agron. J. 84:660-668.

Edwards, W.M., L.D. Norton, and C.E. Redmond. 1988. Characterizating macropores that affect infiltration into nontilled soil. Soil. Sci. Soc. Am. J. 52:483-487.

Follet, R.F., and D.S. Schimel. 1989. Effect of tillage practices on microbial biomas dynamics. Soil Sci. Soc. Am. J. 53:1091-1096.

Fowler, D.B. and J. Brydon. 1989. No-till winter wheat production on the Canadian prairies: Timing of nitrogen fertilization. Agron. J. 68:815-825.

Francis, D.D. 1992. Control mechanisms to reduce fertilizer nitrogen movement into groundwater. J. Soil Water Conserv. 47:444-448.

Glendining, M.J., D.S. Powlson, and P.R. Poulton. 1990. Some agricultural and environmental consequences of long-term application of inorganic nitrogen fertilization. pp. 189-196. *In*: R. Merckx, H. Vereecken, and K. Vlassak (eds.) Fertilization and the Environment, Leuven University Press.

Groffman, P.M. 1984. Nitrification and denitrification in conventional and no-tillage soils. Soil Sci. Soc. Am. J. 49:329-334.

Hansen, E.M. and J.Djurhuus. 1996. Nitrate leaching as affected by long-term N fertilization on a coarse sand. Soil Use and Management. 12:199-204.

Harper, I.A., R.R. Sharpe, G.W. Langdale, and J.E. Giddens. 1987. Nitrogen cycling in a wheat crop: Soil, plant and aerial nitrogen transport. Agron. J. 79:965-973.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 1999. Soil Fertility and Fertilizers. Macmillan, New York, NY.

Hay, R.M.K., J.C. Holmes, and E.A. Hunter. 1978. the effects of tillage, direct drilling, and nitrate fertilizer on soil temperature under winter wheat and barley. J. Soil Sci. 29:174-183.

Hillel, D. 1998. Movement of solutes and soil salinity. P.243-273. *In* Environmental Soil Physics. Academic Press. San Diego, CA.

Hook, J.E. and T.M. Burton. 1979. Nitrate leaching during sewage irrigated perennials as affected by cutting management. J. Environ. Qual. 8:496-502.

Hook, J.E. and L.T. Kardos. 1978. Nitrate leaching during long-term spray irrigation for treatment of secondary sewage effluent on woodland sites. J. Environ. Qual. 7:30-34.

Jaakkola, A. 1984. Leaching losses of nitrogen from a clay soil under grass and cereal crops in Finland. Plant and Soil 76:59-66.

Johnston, A.M. and D.B. Fowler. 1991. No-till winter wheat production: response to spring applied nitrogen fertilizer form and placement. Agron. J. 83:722-728.

Kanwar, R.S., J.L. Baker, and D.G. Baker. 1988. Tillage and split N-fertilization effects on subsurface drainage water quality and crop yields. Trans. Of ASAE. Vol. 31 (2):453-461.

Keeney, D.R. and D.W. Nelson. 1982. Nitrogen-inorganic forms. *In* A.L. Page, R.H. Miller, and D.R. Keeney (eds.) Methods of soil analysis, Part 2. Agron. Monogr. 9. 2nd ed. ASA and SSSA, Madison, WI.

Klute, A. 1986. Water retention: Laboratory methods. p. 635-662. *In* Klute. A. (ed.) Methods of soil analysis. Part 1. Physical and mineralogical Methods. Agron. Monogr. 9. 2nd ed. ASA and SSSA, Madison, WI.

Knapp, W.R., and J.S. Knapp. 1978. Response of winter wheat to date of planting and fall fertilization. Agron. J. 70:1048-1053.

Linden, D. 1977. Design, installation, and use of porous ceramic samplers for monitoring soil –water quality. Technical Bulliten No. 1562. USDA-ARS, Washington, D.C.

Lord, E.I. 1992. Modelling of nitrate leaching: nitrate sensitive areas. Aspects Appl. Biol. 30:19-28.

Lord E.I., and R.D.J. Mitchell. 1998. Effects of nitrogen inputs to cereals on nitrate leaching from sandy soils. Soil Use and Management 14: 78-83.

Martin, D.L., J.R. Gilley, and R.W. Skaggs. 1991. Soil water balance and management. p. 200-205. *In* Follet. R.F., D.R. Keeney, and R.M. Cruse (eds.) Managing Nitrogen for Groundwater Quality and Farm Profitability. SSSA, Madison, WI.

McCracken, D.V., M.S. Smith, J.H. Grove, C.T. MacKowen, and R.I. Blevins. 1994. Nitrate leaching as influenced by cover cropping and nitrogen source. Soil Sci. Soc. Am. J. 58:1476-1483.

National Cooperative Soil Survey. 1982. Soil Survey of Richmond County Virginia. USDA-SCS. U.S. Gov. Print. Office, Washington, DC.

National Weather Service. 2001. Thirty year average precipitation from Warsaw, Virginia [Online]. Available at http://water.dnr.state.sc.us/cirrus/owa/cirrus.login (verified 15 April, 2001).

Ottman, M. J., and N.V. Pope. 2000. Nitrogen fertilizer movement in the soil as influenced by nitrogen rate and timing in irrigated wheat. Soil Sci. Soc. Am. J. 64:1883-1892.

Pittman, U.J. and J.E. Andrews. 1961. Effects of date of seeding on winter survival, yield and bushel weight of winter wheat grown in Southern Alberta. Can. J. Plant Sci. 41:71-80.

Powlson, D.S., P.B.S. Hart, G. Pruden, and D.S. Jenkinson. 1986. Recovery of ^{15}N-labelled fertilizer applied in autumn to winter wheat at four sites in eastern England. J. Agric. Science, UK 107:611-620.

Puckett, L.J.1995. Identifying the major sources of nutrient water pollution: Environmental Science and Technology, v. 29, no. 9, p. 408-414.

Rocheford, T.R., D.J. Sammons, and P.S. Baenziger. 1988. Planting date in relation to yield and yield components of wheat in the Middle Atlantic Region. Agron. J. 80:30-34.

Sadler, E.J., P.J. Bauer, W.J. Busscher, and J.A. Millen. 2000. Site-specific analysis of a droughted corn crop: II. Water use and stress. Agron. J. 92:403-410.

SAS Institute. 1999. SAS/STAT. User's Guide v. 7-1. SAS Inst., Cary, NC.

Scharf, P.C. and M.M. Alley. 1993. Spring nitrogen on winter wheat II: A flexible multicomponenet rate recommendation system. Agron. J. 85:1186-1192.

Schwab, G.O., D.D. Fangmeier, W.J. Elliot, and R.K. Frevert. 1993. Soil and water conservation engineering. 4th ed. John Wiley & Sons, New York.

Shah, S.A., S.A. Harrison, D.J. Boquet, P.D. Colyer, and S.H. Moore. 1994. Management effects on yield and yield components of late-planted wheat. Crop Sci. 34:1298-1303.

Smith, S.J. and D.K. Cassel. 1991. Estimating nitrate leaching in soil materials. p. 165-188. *In* R.F. Follet, D.R. Keeney, and R.M. Cruse (eds.) Managing nitrogen for groundwater quality and farm profitability. Soil Sci. Soc. Am., Madison, WI.

Staver, K.W. and R.B. Brinsfield. 1998. Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. J. Soil and Water Cons. 53:230-240.

Staver, L., K.W. Staver, and J. Stevenson. 1996. Watershed discharge effects on water quality in the Choptank River estuary: Implication for water shed management. Estuaries. 19:342-358.

Vinther, F.P. 1994. Nitrogen fluxes in a cropped sandy and a loamy soil measured by sequential coring. European J. Agron. 3:311-316.

Virginia Agricultural and Statistics Service. 1999. Winter wheat county estimates [Online]. USDA and VDACS. Available at http://www.nass.usda.gov/va/wheat/989.pdf (verified 15 April, 2001).

Virginia Cooperative Extension. 1998. Small grain and straw budgets [Online]. Available at http://www.ext.vt.edu/departments/agecon/spreadsheets/crops/smgrn.html (verified 1 April 1999).

Welch, L.F., P.E. Johnson, J.W. Pendleton, and L.B. Miller. 1966. Efficiency of fall- versus spring-applied nitrogen for winter wheat. Agron. J. 58:271-274.

Wilkins, D.E., B.L. Klepper, and P.E. Rasmussen. 1988. Management of grain stubble for conservation-tillage system. Soil Tillage Res. 12:25-35.

Winter, S.R. and J.T. Musick. 1993. Wheat planting date effects on soil water extraction and grain yield. Agron. J. 85:912-916.

Wu, L., M. Baker, and R.R. Allmaras. 1995. Numerical and field evaluation of soil water sampled by suction lysimeters. J. Environ. Qual. 24:147-152.

Wu, Q.J., A.D. Ward, and S.R. Workman. 1996. Using GIS in simulation of nitrate leaching from heterogeneous unsaturated soils. J. Environ. Qual. 25:526-534.

Zadoks, J.C., T.T. Chang, and C.F. Konzak. 1974. A decimal code for the growth stages of cereals. Weed Res. 14:415-421.

Chapter IV

SUMMARY AND CONCLUSIONS

Our study showed timely planted no-till wheat consistently produced higher yields and greater profitability with minimal NO_3 leaching losses, under selected N rates and timings over three growing seasons. The optimum planting window for winter wheat in the Coastal Plain of Virginia (October 15 through October 20) maximizes ideal conditions for crop emergence. The planting period also minimizes potential damage from Hessian fly infestation, or freeze damage that can occur if wheat is planted too early or too late. However, some delayed planting is inevitable due to difficulties such as excessively wet or dry conditions, equipment problems, or simply a lack of manpower. Our data showed that increasing N fertilization rates at selected times will not overcome the negative effects of late planting, but instead, can increase NO_3 leaching loss under no-till wheat in the Virginia Coastal Plain.

Spring N management is important in the development and maintenance of tillers necessary for optimum yield production. Economic optimum GS 25 and GS 30 N rates and timings varied between sites and over seasons. However, timely planted wheat more effectively utilized applied fertilizer N to produce higher yields. Research has shown timely planting allows for greater root development, which more effectively captures plant available N throughout the growing season. Additionally, sites in continuous no-till production for 8 years or more produced higher yields. Studies report continuous no-till conserves N in the surface residue, and creates greater stability in overall N dynamics over time.

Predicting site-specific GS 25 and GS 30 wheat N requirements would improve fertilizer N efficiency. Our studies showed tiller densities at GS 25 were a reasonable predictor of optimum GS 25 N in no-till wheat in the Virginia Coastal Plain. However, wheat tissue N content and SPAD chlorophyll meter readings were not accurate predictors of economic optimum GS 30 N application rates. Studies have shown fluctuations in soil temperature, soil water, irradiation, and organic versus inorganic N source, affect plant tissue N content, and chlorophyll content. Surface residue from no-till production lowers soil temperature, increases water retention and increases organic N compared to conventional tillage. These factors, along with the limited number of sites, potentially reduced the effectiveness of the GS 30 N rate prediction methods in this study for no-till winter wheat in the Virginia Coastal Plain.

The increasingly common practice of including an N application in December, along with the more traditional pre-plant, GS 25 and GS 30 N applications, was effective in improving yield for no-till wheat in the Coastal Plain. Furthermore, timely planted wheat showed greater yield response to the December N applications. Pre-plant N applications alone did not affect yields for either timely or late planted wheat.

Precipitation exceeds evapotranspiration during the winter and early spring in the mid-Atlantic, creating an increased risk of NO_3 leaching loss with N inputs at December and GS 25. However, our study showed NO_3 leached at selected December and GS 25 N application rates was not different than check plot levels under timely planted wheat. Additionally, at both pre-plant and GS 25, and pre-plant and December, economic optimum N application rates and timings, NO_3 leaching was not different than check plot levels at any of the six timely or late planted sites, with the exception of late planted site III. These results indicate timely planted wheat more effectively used fertilizer N to produce higher yields without increasing NO_3 loss to leaching.

Seasonal patterns of NO_3 concentrations in soil water at 1.2 meters were different under timely and late planted wheat. Nitrate concentrations began declining in mid to late-January under timely planted wheat, but continued rising under late planted wheat. Soil water NO_3 concentrations under late planted wheat generally peaked in late February during the 1998-99 growing season, and in late March during the 1999-00 season. The peak NO_3 concentrations coincided with above average temperatures during each growing season. These data indicate NO_3 leached under late planted no-till winter wheat may be the result of a combination of inorganic fertilizer N applications and N mineralization. Timely planted no-till wheat was again able to more effectively capture the additional plant available N without producing NO_3 leaching losses beyond background levels.

Many factors affect N management strategies under no-till wheat production. Successful management of no-till wheat depends on optimizing yields for economic sustainability while minimizing environmental impact. However, further research is necessary to more completely understand the processes and impacts of various crop and N management strategies on no-till wheat in the Virginia Coastal Plain.