Soil-Specific, Late-Season Nitrogen and Potassium Applications to Increase Corn Yields in the Mid-Atlantic Coastal Plain

by

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(Abstract)

Corn grain yields can be limited by nitrogen (N) and potassium (K) availability on sandy coastal plain soils when soil moisture is adequate for high yields. This study evaluated irrigated corn grain yield response to late-season (just prior to tassel) N and K fertilizer applications, and enabled the proposal of a method to predict potential for corn to utilize late-season N applications based on soil moisture. In an experiment to evaluate late-season fertilizer application rates, N and K were applied in a complete factorial of five N and K rates ranging from 0 to 112 kg ha^{-1}. Additionally, water use of high yielding corn was measured, and historical weather patterns evaluated in an effort to predict the need for late-season fertilizer applications based on soil moisture. Grain yield was increased significantly by late-season N applications in three of four experiments. Potassium applications did not affect yield, and there were no interactions between N and K. Significant drainage due to high rainfall levels in 2000 prohibited further refinement of corn water use data for Virginia climatic conditions. Historical weather patterns, potential evapotranspiration of corn, and soil water holding properties were evaluated. In order to provide corn with adequate moisture during a two-week moisture-sensitive critical period beginning at tassel, soils must be near field capacity at the start of the period and receive above-average (75^{th} percentile) rainfall during the period.

for Grandpa Polly

Collins Alexander "Polly" Lewis
Feb. 17, 1911 – Jul. 15, 1981

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Table of Contents

List of Tables

List of Figures

Chapter 1 – Introduction and Justification

Corn (*Zea mays L.*) is an economically important grain crop throughout the Mid-Atlantic Coastal Plain region. Growers in the region planted 1,436,235 ha (3,549,000 acres) and 1,371,485 ha (3,389,000 acres) in 1998 and 1999, respectively (National Agricultural Statistics Service, 2000b). Gross market value for corn in the region topped $601 million in 1998 (National Agricultural Statistics Service, 2000b). Virginia corn acreage totaled 202,343 ha (500,000 acres) in both 1998 and 1999 (National Agricultural Statistics Service, 2000b). Grain corn generally ranks second for acres harvested in Virginia (soybeans rank first), and third behind tobacco and soybeans for value of production (National Agricultural Statistics Service, 1997).

Though corn is clearly an economically important field crop throughout the Mid-Atlantic States, yields are significantly less than those of the Midwestern States (National Agricultural Statistics Service, 2000a). While the five primary corn-producing states of the Midwest (IL, IN, IA, MN, and NE) attained average yields of 8160 to 9100 kg/ha (130-145 bu/acre) for the years 1997-1999, yields for the Mid-Atlantic states of DE, MD, NC, PA, and VA ranged from 5024 to 6154 kg/ha (80-98 bu/a) for the same three-year period (National Agricultural Statistics Service, 2000a). Yield differences of this magnitude cause Mid-Atlantic States to be at a competitive disadvantage with the major U.S. corn-producing regions. However, the major competitive advantage for corn in the Mid-Atlantic is the excellent market provided by the poultry and swine industries.

Fertilizer inputs are a major expense required to produce high corn yields. Each metric ton of corn grain removed from the field contains approximately 16kg of N and 4kg of K (White and Collins, 1982). Consequently, 18,094 metric tons of N and 4,524 metric tons of K are removed from Virginia corn fields each year. Much of this is supplied by synthetic fertilizer applications. Additionally, recent price trends have reduced profitability, challenging the profitability of corn in the Mid-Atlantic region, even with the market advantage. More efficient production methods would improve the competitiveness of corn in the Mid-Atlantic.

The major yield-limiting factor to corn yields in the Mid-Atlantic Coastal Plain is available moisture during the silking and grain-fill periods (Wagger and Cassel, 1993). Specifically, a soil moisture deficit during a two-week critical period beginning at tasseling has been observed to reduce corn grain yields more than any other period (Shipley and Regier, 1976). Significant yield increases have been observed as available soil moisture was increased via irrigation during the critical silking and grain-fill period (Wagger and Cassel, 1993). Also, there is a high correlation between total July rainfall and average corn yield for the coastal plain counties of Virginia (Thornsbury et al., 1993). To achieve maximum yield, crop water requirements must be met by rainfall and soil water storage or supplemental irrigation.

Coastal plain soils vary greatly in texture due to formation from alluvial deposits. Soil textural differences create major differences in water-holding capacities and corn yield potentials across fields. For example, available water-holding capacity ranges from .08 to .17 cm of water per cm of soil in the subsurface horizons of a Bojac and a Wickham soil, respectively (USDA-NRCS Soil Survey Division, 2000).

Modern corn hybrids are extremely responsive to N and K fertilizers (Polito and Voss, 1991; Dwyer et al. 1995; Sinclair and Muchow, 1995). Growers must estimate optimum N and K rates for each field that are adequate to utilize available soil moisture. However, excessive N and K fertilizer applications reduce profitability, and in the case of N, can produce adverse environmental impacts. Conversely, yield reductions due to lack of adequate N and K can result in major economic losses for growers. Phosphorus (P) was not considered in this research because most VA soil-test P levels are high, and P is relatively immobile in soil systems (Sharpley et al., 1994).

Yield potentials of modern corn hybrids are well in excess of 12,000 kg ha^{-1} under mid-Atlantic climatic conditions when available soil moisture is adequate during critical periods (Brann et al., 1999; Wagger and Cassel, 1993). Also, late season (immediately prior to tasseling) N applications have been observed to increase corn yields under irrigation (Elwali and Gascho, 1988). However, under rain-fed conditions, a side-dress N application when corn is 30 to 60 cm (12 to 24 inches) in height is usually the last N fertilizer application, and a preplant K application is generally the last K fertilizer application. Growers must estimate the yield potential based on historical field averages. Nitrogen rates are sometimes correct, but can be inadequate, or excessive, depending on rainfall four to six weeks after the side-dress N application. The situation may be similar for K applications, especially on sandy soils.

Technology is available to measure soil moisture levels rapidly and accurately. Variable rate fertilizer applicators are available to change rates quickly and accurately as the applicator moves across the field. Finally, high-clearance application equipment is available for making late-season fertilizer applications in corn.

This research sought to answer the following two questions: Can late-season additions of N and K improve corn grain yields and therefore profits when soil moisture conditions are favorable for high yields? Second, can the opportunity to increase yields by late-season N and K additions be reliably predicted? Measurements of available soil water and predictions of rainfall were used to assess yield potential and therefore additional fertilizer requirements.

Revision of yield expectation prior to tasseling, with the assistance of a decision-support model, will enable fertilizer applications to be tailored to current and predicted growing season conditions at a late growth stage. Benefits include optimizing yield in years of adequate precipitation, as well as maximizing profit margins and minimizing environmental impact. A late-season decision-support package provides producers with the ability to accurately customize N and K applications at a later point in the growing season, when yield potential is more predictable. The specific objectives of this research are to:

1. Measure the influence of late-season N and K fertilizer applications on corn yields under supplemental irrigation conditions on soils with low, moderate, and high water-holding capacities;

2. Develop a method to predict the potential for corn to utilize late-season N and K fertilizer applications, based on soil moisture supply and water use during the critical period.

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Chapter 2 – Irrigated Corn Yield Response to Late-Season Nitrogen and Potassium Applications

ABSTRACT:

Sub-optimum N and K fertilizer rates may limit corn (Zea mays L.) grain yields on sandy coastal plain soils when rainfall is optimum for corn growth, even when N and K fertilizers are applied at rates recommended for average yields. The objective of this experiment was to determine corn grain yield response to late-season (just prior to tassel, the VT growth stage) N and K applications when soil moisture is adequate for high yields. Four experiments over two years (1999 and 2000) were established to measure the response of corn to late-season N and K applications. Treatments were a factorial arrangement of five N rates and five K rates (0, 28, 56, 84, and 112 kg N ha^{-1} and 0, 28, 56, 84, and 112 kg K ha^{-1}) applied immediately prior to the VT growth stage. Average grain yield at the four locations ranged from 11290 kg ha^{-1} to 16495 kg ha^{-1}. Grain yields increased as a result of late-season N applications only. Potassium did not affect yields, and there was no interaction between N and K. Yield increase to late-season N was highly significant (1260 kg ha^{-1} yield increase) when corn received lower rates (rates normally used on very sandy soils) of starter and sidedress N fertilizer and residual soil N was low. The lack of response to K suggests that standard pre-plant K fertilization programs are adequate to produce high grain yields on Virginia's Coastal Plain soils.

Irrigated Corn Yield Response to Late-Season Nitrogen and Potassium Applications

INTRODUCTION

High corn grain yields may not be obtained on sandy coastal plain soils when rainfall is optimum for corn growth, and N and K fertilizers are applied at rates recommended for average yields. Corn grain demand for N and K fertilizers has been reported to be 20.1 kg N Mg^{-1} and 19.3 kg K Mg^{-1} under high-yield conditions (Flannery, 1986). Corn takes up approximately 40% of total N and 20% of total K after the initiation of tassel (growth stage = GS VT) (Flannery, 1986; Karlen et al., 1987; Ritchie et al., 1997). Several researchers have measured significant positive grain yield response to late-season fertilizer applications, especially with N (Russelle et al., 1983; Evanylo, 1991; Binder et al., 2000). Thus, late-season (prior to GS VT) fertilizer applications of N and K should correct yield-limiting N and K deficiencies in years when adequate soil moisture is available.

Effectiveness of sidedress (GS V6 to V10) N applications to increase corn grain yield and N use efficiency over preplant N applications has been substantiated in numerous studies (Welch et al., 1971; Jung et al., 1972; Olson et al., 1986; Reeves and Touchton, 1986; Killorn and Zourarakis, 1992; Alley et al., 1997; Sims et al., 1998). Fertilizer N is more directly channeled to grain when N application is delayed, due to higher rates of uptake and translocation during reproductive growth (Bigeriego et al., 1979).

Research with splitting N applications between sidedress and GS VT or R1 has shown that grain yield is highest when N deficiency does not occur prior to late-season applications (Rhoads and Stanley, 1981; Evanylo, 1991; Binder et al., 2000). Yield of irrigated corn grain increased by 1000 kg ha^{-1} with 90 kg N ha^{-1} at GS V13 on a Bonifay sand in Georgia (Elwali and Gascho, 1988). Corn grain yield was increased from 9,700 kg ha^{-1} to 11,100 kg ha^{-1} by delaying a 90 kg N ha^{-1} fertilizer application from planting to GS V16 on a Sharpsburg silty clay loam in Nebraska (Russelle et al., 1983). Corn grain yield in Virginia increased by 4641 kg ha^{-1} on a Bojac loamy sand with 112 kg N ha^{-1} applied at GS V16 when adequate N (81 kg N ha^{-1}) was applied at GS V5 (Evanylo, 1991). Significantly decreased yields associated with lower early sidedress N fertilization rates were thought to be a result of N deficiency prior to the GS V16 fertilizer application. Magnitude of yield response to late-season N applications diminished with early sidedress rates greater than 81 kg N ha^{-1}, and the author suggested that yield is more closely associated with total N rate when N deficiencies do not occur prior to late-season fertilization. Similarly, corn grain yields decreased 1694 kg ha^{-1} as a total N fertilizer application rate of 270 kg N ha^{-1} was split from 6 to 12 weekly applications on a Troup loamy sand in Florida (Rhoads and Stanley, 1981). This was probably due to N deficiency resulting from inadequate N fertilization early in the growing season.

Though corn grain yields are highest when N is adequate prior to late-season fertilization, additions of late-season N have been observed to increase yield when N deficiency occurs prior to GS VT (Miller et al., 1975; Evanylo, 1991). Grain yield response to late-season N applications on a Sharpsburg silty clay loam in Nebraska was most significant when N was applied on or before GS R1.5 to corn that would have become N deficient (Binder et al., 2000). Yield increases to late-season N applications were most significant when N deficiency developed early, and the authors suggested that N deficiency is adequate justification for late-season N fertilizer applications to corn. Similarly, researchers measured significant positive corn grain yield response to a late-season (GS VT) application of 270 kg N ha^{-1} on two silt loam soils in Kentucky when N deficiency was apparent at the time of application (Miller et al., 1975).

Soil residual N also affects corn grain yield response to applied N (Onken et al., 1985; Jokela and Randall, 1989; Oberle and Keeney, 1990; Evanylo and Alley, 1996; Karlen et al., 1998; Vyn et al., 1999). Soil residual N levels greater than 50 kg NO_3^- ha^{-1} in the 1.5-m profile were associated with lack of response to N applied at GS V8 on both a Mt. Carroll silt loam and a Webster clay loam in Minnesota, and yields in excess of 9,000 kg ha^{-1} were obtained (Jokela and Randall, 1989). Similarly, corn yielding 14,676 kg ha^{-1} did not respond to N fertilizer applications greater than 168kg N ha^{-1} on a Nicollet silty clay loam in

Iowa (Polito and Voss, 1991). The authors attributed the lack of response to residual soil N from a previous soybean crop.

Little research has been aimed at measuring corn grain yield response to late-season K applications. However, two studies on loamy sand soils have been reported in Florida. No significant yield response to K applications was measured when application time of 276 kg K ha^{-1} was delayed from preplant to 10 weeks after planting (Stanley and Rhoads, 1977). Grain yield decreased from 9,659 kg ha^{-1} to 7,965 kg ha^{-1} when K applications to irrigated corn were delayed from 6 to 12 weeks after planting (Rhoads and Stanley, 1981).

Potassium availability in soil is one of the most influential factors determining response of corn grain yield to K fertilizer applications. On two clay loam soils in Iowa with NH_4OAc extractable K (Knudsen et al., 1982) values above 100 mg kg^{-1}, K applications did not significantly influence corn or soybean grain yields over 14 years (Mallarino et al., 1991a). Eleven years of K fertilization in Iowa did not influence corn grain yield on a Kenyon loam with 170 mg kg^{-1} NH_4OAc extractable K (Mallarino et al., 1991b). Similarly, lack of corn grain yield response to K applications on a Kalmia sandy loam in Delaware was attributed to rapid replenishment of soil solution K by exchange sites (Liebhardt et al., 1976).

Experiments on soils with lower extractable K levels (<100 mg K kg^{-1}) generally produced significant grain yield response to K applications. Grain yield increased up to 900 kg ha^{-1} with 279 kg K ha^{-1} on several soils in Iowa that contained NH_4OAc extractable K levels of 67-91 mg K kg^{-1} (Polito and Voss, 1991). Grain yield increased by 4200 kg ha^{-1} to a preplant K application of 418 kg K ha^{-1} on an Orangeburg loamy sand in Florida with 51 mg kg^{-1} Mehlich 1 (Mehlich, 1953) extractable K in the plow layer (Obreza and Rhoads, 1988). Similarly, grain yield over three years was increased by an average of 840 kg ha^{-1} with a total K application of 215 kg K ha^{-1} on a Jefferson silt loam in Virginia that contained 2.7 mg kg^{-1} Mehlich 1 extractable K in the upper 7.5 cm of soil under no-till conditions (Moschler and Martens, 1975).

Research indicates that the uptake patterns for N and K by corn are different. Most K is taken rapidly up during vegetative growth, while a significant portion of N is accumulated after initiation of reproductive growth stages (Loué, 1980; Welch and Flannery, 1985; Ritchie et al., 1997). Measurements of nutrient flux into corn roots on a Chalmers silt loam in Indiana revealed much higher late-season uptake rates of N than K (Mengel and Barber, 1974).

Significantly more N than K is translocated to the grain (Sayre, 1948; Hanway, 1962a; Hanway, 1962b; Karlen et al., 1988). This partially explains the disparity in uptake patterns of N and K, since grain accounts for the majority of dry matter production after GS VT (Zhou et al., 1997).

Late-season applications of N and K fertilizers to corn can potentially increase grain yield when adequate moisture is available. Application rates and conditions necessary for corn grain yield response to late-season N and K applications have not been determined for the Mid-Atlantic Coastal Plain. The objective of this research was to determine grain yield response of conventionally managed corn to late-season N and K applications when soil moisture availability is adequate for high yields.

MATERIALS AND METHODS

Experiment Sites and Treatments

Yield goals for each soil were based on rain-fed, long-term average yields summarized in the Virginia Agronomic Land Use Evaluation System (VALUES) (Simpson et al., 1993). Plant population and fertilizer rates at each site were adjusted for soil water-holding capacity, due to its effects on yield when rainfall is limited. However, natural precipitation was supplemented with irrigation to provide optimal corn growing conditions, in order to simulate a season of above-average rainfall.

Pioneer brand corn cultivar 32K61 was planted no-till into barley mulch on May 2, 1999 at Camden Farm near Port Royal, VA. Site I was located on a Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludult) and Site II on a Wickham sandy loam (fine-loamy, mixed, semiactive, thermic Typic Hapludult). Starter-band P fertilizer was applied at the rate of 34 kg P_2O_5 ha^{-1}. Pioneer brand corn cultivar 3394 was planted minimum till (disc harrow and roller-packer) on May 1, 2000 on a State sandy loam (fine-loamy, mixed, semiactive, thermic Typic Hapludult) at Site III in Mt. Holly, VA. Pioneer brand corn cultivar 3245 was planted no-till into soybean mulch on April 4, 2000 on a State sandy loam at Site IV (fine-loamy, mixed, semiactive, thermic Typic Hapludult) near Mechanicsville, VA. Starter-band fertilizers were applied at the rates of 34kg P_2O_5 ha^{-1}, 6 kg S ha^{-1}, 1kg Zn ha^{-1}, and 0.6 kg B ha^{-1}. Preplant and starter N and K fertilizers were applied at all locations as outlined in Table 2.1. Soil samples were taken to a depth of 1.2 m prior to early side-dress N applications.

Early sidedress N was applied (Table 1) to bring the total N application rate (preplant + starter + early sidedress = total) to 17.9 kg N per Mg of expected yield, following Virginia Cooperative Extension recommendations (Alley et al., 1997). All sites were irrigated at regular intervals throughout the growing season to supplement rainfall and achieve high yields.

Experimental design was a randomized complete block with four replications. Treatments were a factorial arrangement of five N rates and five K rates applied immediately prior to GS VT, as outlined in Table 2. The factorial design was selected to produce response surfaces in order to determine optimum N and K fertilizer rate combinations. Plots were 6 rows (76-cm wide rows) by 7.6m long. Dribble applications of liquid fertilizer beside each row were made using a CO_2 backpack sprayer with a single nozzle wand and a short hose to place fertilizer on the soil surface below the canopy. Nozzle size and walking speed were adjusted to deliver the appropriate application rate. Nitrogen was applied in the form of 30% urea-ammonium nitrate (UAN) and K was applied in the form of a clear liquid (0-0-8.3 in 1999, 0-0-9.9 in 2000).

Ear leaf samples at silk (GS R1) were collected and analyzed for tissue N and K content. Basal stalk samples were collected after black layer formation (GS R6) from treatments 5, 10, 15, 20, and 25 and examined for nitrate content (Binford et al., 1992). The two center rows of each plot were hand-harvested September 20, 1999 from Site I and September 22, 1999 from site II. Similarly, corn was harvested with a small plot combine equipped with a scale, moisture tester, and data logger September 13 and 28, 2000 from sites IV and III, respectively. Yields were adjusted to 15% moisture for all plots. Statistical analysis was completed using the GLM procedures of SAS v. 7-1 (SAS Inst., 1999).

Laboratory Analysis

Selected chemical analyses were performed on the surface soil samples to a depth of 15cm (Table 2.3). Soil pH was measured in a 1:1 soil:water mixture after a 30-minute equilibration period. Mineral nutrients were extracted using the Mehlich 1 procedure (Donohue et al., 1996) and concentrations were measured by ICP-AES (Thermo Jarell Ash ICAP Model 61, Franklin, MA). Organic matter from the 2000 sites was determined with a modified Walkley-Black procedure (Nelson and Sommers, 1982; Donohue et al., 1996).

Residual soil nitrate (Table 4) was extracted with 2M KCl (Keeney and Nelson, 1982). Nitrate in the filtered extract was determined colorimetrically using QuikChem Method No. 12-107-04-B (Lachat Instruments, Milwaukee, WI) on a QuikChem model 8000 flow-injection ion analyzer.

Plant tissue samples were dried and ground to pass a 20-mesh screen, then placed in glass jars containing stainless steel rods of several diameters. The jars were placed on a conveyer belt and rolled for 12 hours, reducing particle size and thoroughly mixing the samples. Ear leaf tissue samples were subjected to Kjeldahl digestion (Jones and Case, 1990) and analyzed for total Kjeldahl N (TKN) by QuikChem Method No. 13-107-06-2 (Lachat Instruments, Milwaukee, WI), using a QuikChem model 8000 flow-injection ion analyzer. Ear leaf tissue samples from treatments 11 through 15 were digested with nitric acid (Jones and Case, 1990), and analyzed for K content by ICP-AES. Nitrate in basal stalk samples was extracted with 2M KCl (Binford et al., 1992). The filtered supernatant was analyzed for nitrate concentration by QuikChem Method No. 12-107-04-B (Lachat Instruments, Milwaukee, WI) on a QuikChem model 8000 flow-injection ion analyzer. Statistical analysis was completed using the GLM procedures of SAS v. 7-1 (SAS Inst., 1999).

RESULTS AND DISCUSSION

Grain Yields

Relatively high grain yields were obtained in all four experiments with average grain yields ranging from 11,290 to 16,495 kg ha^{-1} (Table 2.2). Furthermore, average yields suggest that irrigation management at the four experimental locations was adequate to produce high-yielding environments that were desired for the purposes of this research.

A known source of variance in average yields was plant population; the Bojac soil at site I had the lowest population and average yield, while the State soil at site IV had a higher plant population and highest average yield (Tables 2.1 and 2.2). Variation in yield was also related to standard preplant and early sidedress fertilization programs. For example, site I received a total standard N fertilizer rate of 174 kg N ha^{-1} that resulted in a grain yield of 10,349 kg ha^{-1} without late-season N fertilizer. Similarly, site II received a standard N fertilizer program of 219 kg N ha^{-1} that resulted in a grain yield of 12,983 kg ha^{-1} without late-season N.

Treatment effects on grain yields were statistically significant ($p<0.10$) at sites I, III, and IV. Grain yield response to treatments on the Wickham soil (site II) was insignificant. Site II was impacted by a severe thunderstorm on July 24, 1999 with winds up to 85 km h^{-1} that caused significant stalk lodging, thereby increasing variability in measured yields.

Potassium did not influence yield, and there were no interactions between N and K. Lack of response to K treatments was due to high soil-test K levels at all locations (Table 2.3), agreeing with the work of Liebhardt et al. (1976), and Mallarino et al. (1991a,b). Moreover, these results indicate that standard preplant K fertilization programs, based on soil test results, are adequate for producing high corn yields, even on sandy soils with significant leaching potential.

Yield response to N fertilization (Fig. 2.1) was most significant on the Bojac soil (site I), due to lower levels of N fertilization prior to late-season treatments

(174 kg N ha^{-1}), as well as somewhat lower soil residual N (11mg kg^{-1}) in the surface 15-cm soil layer (Table 2.4). Grain yield response to N applications was less at site III due to more soil residual N (29 mg kg^{-1}) in the surface 15-cm soil layer (Table 2.4), as this experiment received a pre-treatment N fertilization rate of 168 kg N ha^{-1}. Soil residual nitrate levels at site IV were similar to site III (Table 2.4), and this site received a higher pre-treatment fertilizer N rate (191 kg N ha^{-1}). A higher plant population at site IV (65,480 plants ha^{-1}) apparently utilized the available N and responded positively to the late-season fertilization treatments. These results agree with the findings of Miller et al. (1975), Russelle et al. (1983), Elwali and Gascho (1988), and Evanylo (1991). Moreover, higher yield response measured at sites with lower residual and pre-treatment fertilizer N agrees with the findings of Jokela and Randall (1989), Evanylo (1991), and Binder et al. (2000).

Plant Tissue N and K Content

Concentrations of N and K in ear leaves at silk were within sufficiency ranges reported by Jones et al. (1990) (Tables 2.5 and 2.6). Sufficiency ranges for N in ear leaves at silk are reported to be between 21.0 and 40.0 g N kg^{-1}, while K is reported to be between 17.0 and 30.0 g K kg^{-1} (Jones et al., 1990). Concentration of N in ear leaves ranged from 23.5 to 30.8 g N kg^{-1}(Table 2.5), while K concentration ranged from 20.6 to 25.1 g K kg^{-1} (Table 2.6). Ear leaf N concentrations varied with late-season N fertilizer treatments at sites I, II, and III (Table 2.5). However, only the highest N rate was different from the check at sites I and III (Table 2.5), while 56 and 84 kg N ha^{-1}, respectively, were required to maximize yield at these sites. Response of ear leaf K concentration to late-season K fertilizer treatments was insignificant at all sites (Table 2.6) due to high soil test K, as well as the rapid early uptake of K by corn (Ritchie et al., 1997). These data indicate that standard K fertilization practices are sufficient to produce high yields.

Concentration of nitrate in cornstalks at maturity is a useful indicator of N status in corn. Optimal concentrations for maximum profits are reported to range from 0.7 to 2.0 mg NO_3^- kg-1 (Binford et al., 1992). Stalk nitrate concentrations at site II were in or above the optimum range for all N fertilization rates, partially explaining the lack of response to N fertilization (Fig. 2.2). Conversely, 112 kg N ha^{-1} was required to bring stalk nitrate concentrations within the reported optimum range at site I (Fig. 2.2). Leaching of N through the sandy Bojac profile may have limited N availability, resulting in lower stalk nitrate concentrations and yields. Late-season N fertilization rates below 28 and 84 kg N ha-1 at sites IV and III, respectively, resulted in stalk nitrate concentrations below the reported sufficiency range (Fig. 2.2). Lack of horizontal root proliferation at the time of fertilizer treatments was not suspected to have limited N availability, since the nodal root system is generally well distributed by growth stage V6 (Ritchie et al., 1997).

CONCLUSIONS

Four experiments over two years have shown that the potential exists for late season N fertilizer applications, in addition to standard preplant and sidedress N applications, to increase corn yields when adequate moisture is available. Yields increased by as much as 1130 kg ha^{-1} with 56 kg N ha^{-1}. Yield increases to late-season N fertilization will likely be significant when soil N status is limiting higher yields and plant populations are adequate to utilize the additional N. Moreover, the potential for corn to utilize late-season N has been substantiated in numerous irrigation experiments in other regions. More research is needed to determine the level of N deficiency at which late-season N fertilization will significantly improve corn grain yields. Potassium from standard pre-plant K fertilization programs was adequate to produce high yields in all cases.

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Table 2.1. Soil series and N and K fertilizer rates for the four experiments.

Site	Soil Series	Population	Preplant K	Preplant N	Starter N	Sidedress N	Total N†
		plants ha^{-1}			kg ha^{-1}		
I	Bojac‡	48 430	93	34	56	84	174
II	Wickham§	67 640	93	34	56	129	219
III	State§	52 390	--	56	--	112	168
IV	State§	65 480	280	45	34	112	191

† Total N = Preplant N + Starter N + Sidedress N

‡ Coarse-loamy, mixed, semiactive, thermic Typic Hapludults

§ Fine-loamy, mixed, semiactive, thermic Typic Hapludults

Table 2.2. Nitrogen and potassium fertilizer treatments and average measured corn grain yields at the four experiments.

			Average Corn Grain Yield†			
			1999		2000	
Trt.	N Rate	K Rate	Site I	Site II	Site III	Site IV
			kg ha^{-1}			
1	0	0	10 537	12 669	13 359	15 994
2	0	28	10 474	12 168	13 046	16 684
3	0	56	10 412	12 168	13 171	15 994
4	0	84	10 098	13 297	13 422	15 931
5	0	112	9 784	13 548	13 359	16 119
6	28	0	11 415	12 669	13 610	15 931
7	28	28	10 851	13 234	13 297	16 370
8	28	56	10 976	12 607	13 798	16 307
9	28	84	11 666	12 983	13 234	16 056
10	28	112	11 039	12 105	13 673	16 872
11	56	0	12 419	13 673	13 610	17 185
12	56	28	11 540	13 673	14 175	16 809
13	56	56	11 227	12 105	13 422	16 182
14	56	84	10 976	14 300	13 798	16 809
15	56	112	12 042	12 795	13 485	16 934
16	84	0	11 603	13 422	14 112	16 809
17	84	28	11 540	13 171	14 551	15 994
18	84	56	11 980	12 544	13 861	16 433
19	84	84	12 293	13 736	13 924	16 934
20	84	112	12 042	12 356	13 610	16 684
21	112	0	12 356	13 297	13 610	17 060
22	112	28	13 046	12 419	13 673	16 684
23	112	56	12 544	12 920	13 610	17 123
24	112	84	12 042	13 610	13 297	16 370
25	112	112	12 230	13 798	14 049	16 495
	Site Average:		11 290	13 108	13 610	16 495

† Means separations are indicated in Fig. 2.1, due to lack of response to K.

Table 2.3. Selected surface soil (0-15cm) chemical properties at the four experimental sites.

Site	Soil	pH	O.M.	P	K	Ca	Mg	Zn	Mn
			%	mg kg^{-1}					
I	Bojac	6.4	--	43	157	540	120	3	16
II	Wickham	5.8	--	16	148	348	74	2	16
III	State	6.1	2.0	40	157	564	116	4	16
IV	State	5.6	2.1	50	157	444	42	4	14

Table 2.4. Residual soil nitrate levels for five depths at the four experimental sites. Samples collected prior to early N sidedress.

Depth	Site I	Site II	Site III	Site IV
cm	mg kg^{-1}			
0-15	11	13	29	23
15-30	9	17	8	14
30-60	8	8	4	11
60-90	9	8	5	6
90-120	7	9	5	5

Table 2.5. Ear leaf N concentration as a function of late-season N fertilizer treatments at the four experimental sites.

	Tissue N Content			
	1999		2000	
N Rate	Site I	Site II	Site III	Site IV
kg ha^{-1}	g kg^{-1}			
0	25.0a†	23.5a	29.2a	28.1a
28	25.8ab	24.4ab	29.8ab	28.0a
56	25.6ab	24.6b	30.5ab	27.6a
84	26.1ab	24.7b	30.4ab	27.5a
112	26.8b	24.7b	30.8b	28.4a

† Within columns, means followed by the same letter are not significantly different according to Tukey's HSD (0.10).

Table 2.6. Ear leaf K concentration as a function of late-season K fertilizer treatments at the four experimental sites.

	Tissue K Content			
	1999		2000	
K Rate	Site I	Site II	Site III	Site IV
kg ha^{-1}	g kg^{-1}			
0	22.7a†	21.3a	23.5a	23.7a
28	22.6a	21.1a	23.8a	24.5a
56	22.1a	22.0a	23.7a	23.7a
84	21.9a	20.6a	23.5a	25.1a
112	21.7a	22.0a	24.0a	24.2a

† Within columns, means followed by the same letter are not significantly different according to Tukey's HSD (0.10).

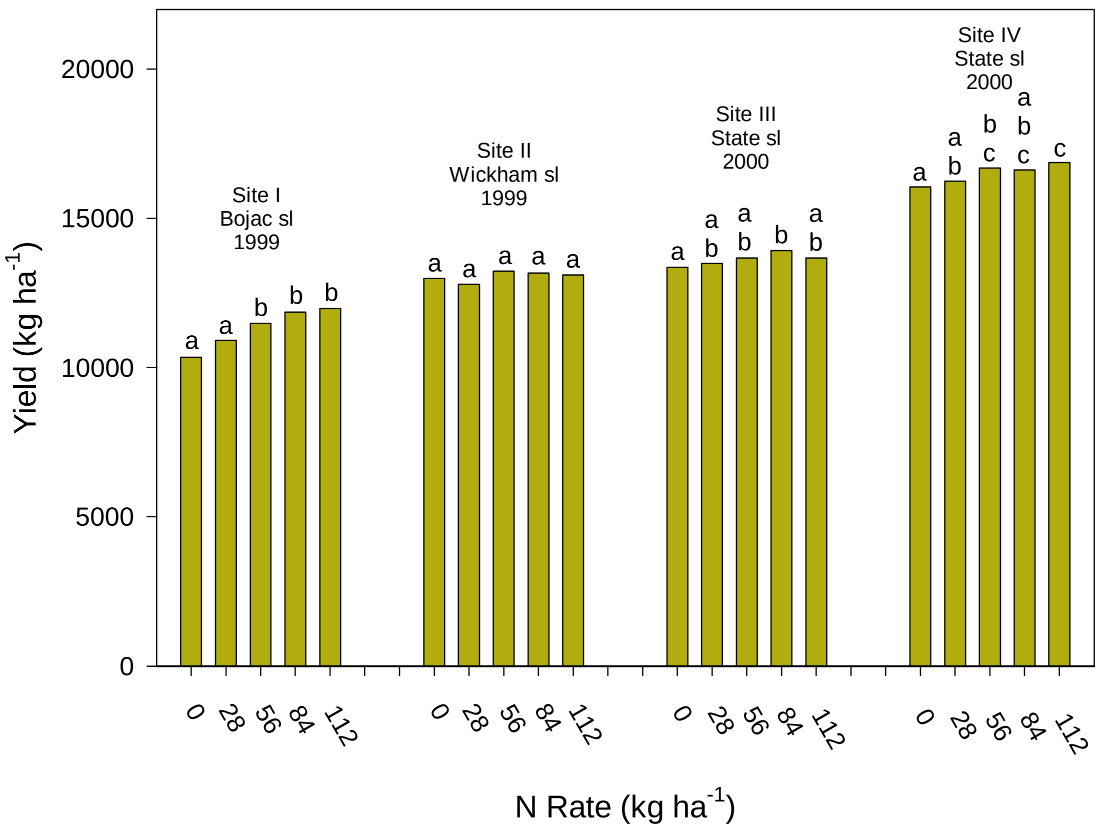

Fig. 2.1. Corn grain yield as a function of late-season N fertilizer applications at the four experimental sites. Within locations, bars containing the same letter are not significantly different according to Tukey's HSD (0.10).

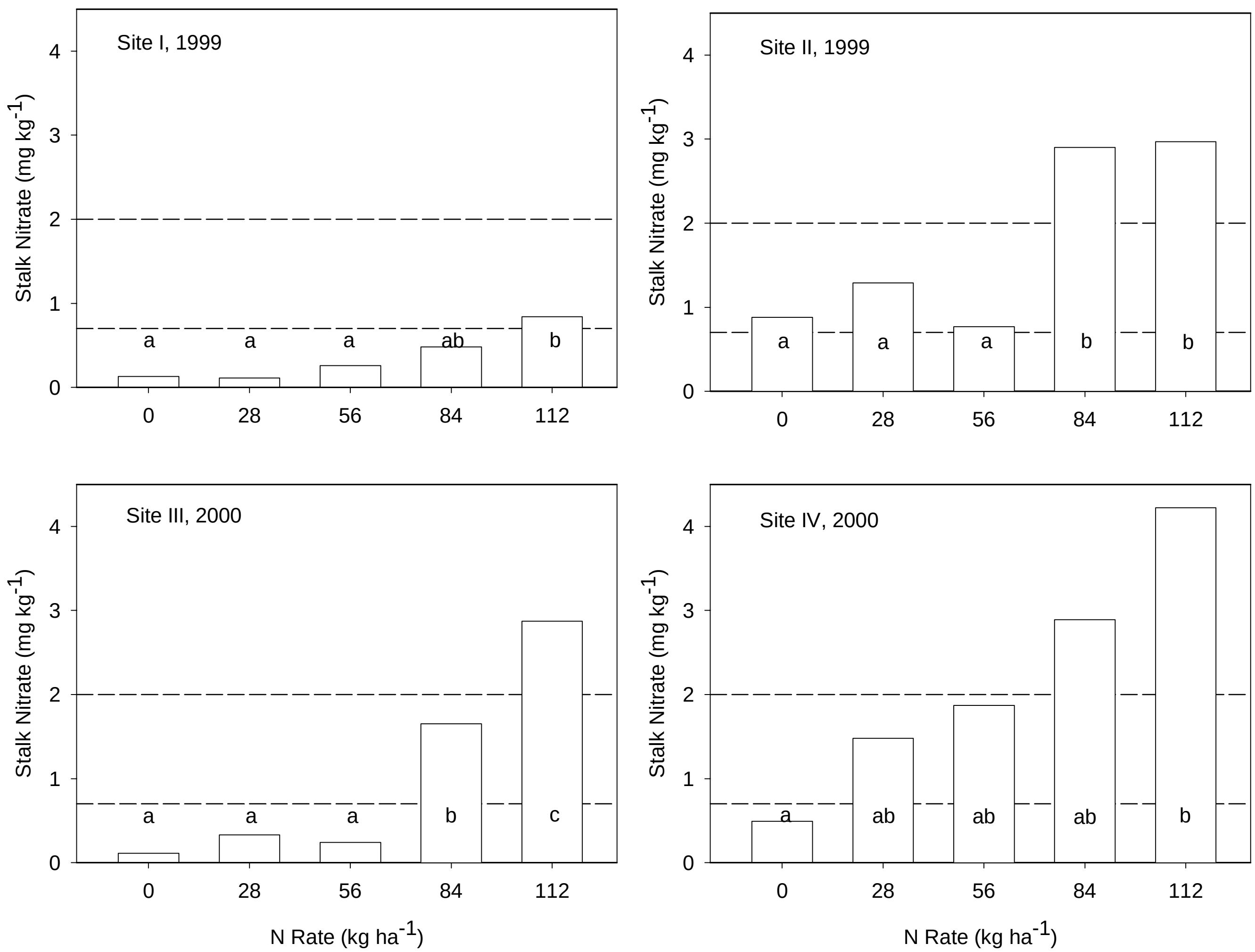

Fig. 2.2. Stalk nitrate content as a function of late-season N fertilizer treatments at the four experimental sites. Dotted lines indicate optimal nitrate concentration range. Within each graph, columns of the same letter are not significantly different according to Tukey's HSD (0.10).

Chapter 3 – Soil Moisture and Rainfall Pattern Analysis to Determine the Potential for Corn to Utilize Late-Season Nitrogen Fertilizer

ABSTRACT:

Corn (Zea mays L.) grain yields can be limited by nitrogen (N) availability on sandy coastal plain soils when soil moisture is adequate for high yields. Under rainfed conditions, N fertilizer management is generally based on realistic long-term average yields for each soil. The objective of this research was to evaluate the predictability of response to late-season N applications to corn based on soil moisture and rainfall probability. Two experiments in 2000 were established in the Virginia Coastal Plain to measure water use of high-yielding corn. Crop evapotranspiration during the two-week, moisture-sensitive critical period beginning at tassel was 0.9 and 1.7 times reference evapotranspiration at sites I and II, respectively. Significant drainage was suspected to have contributed to relatively high evapotranspiration measured at site II. Historical weather patterns, potential evapotranspiration of corn, and soil water holding properties were evaluated to estimate the conditions necessary to provide low-stress moisture to corn for the duration of a two-week moisture-sensitive critical period beginning at tassel. Soils must be near field capacity at the start of the two-week period and receive above-average (75^{th} percentile) rainfall during the period to provide low moisture stress conditions. Precipitation predictions necessary to make late-season N fertilizer application decisions are available from the National Weather Service and private weather services. Estimates of the duration of low moisture stress conditions can be based on predicted rainfall, potential ET, and soil moisture measurements.

Soil Moisture and Rainfall Pattern Analysis to Determine the Potential for Corn to Utilize Late-Season Nitrogen Fertilizer

INTRODUCTION

Corn grain yields can be limited by nitrogen (N) availability on sandy coastal plain soils when soil moisture is adequate for high yields. Under rainfed conditions, producers generally base N fertilizer management on realistic long-term average yields for each soil (Simpson et al., 1993). Recently, the 1996 and 2000 growing seasons provided exceptional rainfall for corn growth in the Virginia Coastal Plain (Table 3.1). Standard N fertilization programs were likely inadequate in many cases. However, increasing standard N application rates to meet higher crop demand may not be wise, since soil moisture conditions for the entire season cannot be reliably predicted. Excess N fertilization can reduce profits and result in the leaching of N to groundwater, especially on sandy soils.

Corn demand for N fertilizer has been reported to be 20.1 kg N Mg^{-1} under high-yield conditions (Flannery, 1986), and approximately 40% of the N requirement is taken up after the initiation of tassel (growth stage = GS VT) (Karlen et al., 1987; Ritchie et al., 1997). Researchers have measured significant positive grain yield response to late-season N fertilizer applications, especially when soil moisture is optimum for corn growth (Russelle et al., 1983; Evanylo, 1991; Binder et al., 2000). Thus, the potential for corn to utilize late-season (prior to GS VT) N applications in well-managed production systems is directly associated with the availability of soil water during pollination and grain fill.

Grain Yield Response to Late-Season N Applications

Effectiveness of late-season N applications to increase corn grain yield has been substantiated in numerous studies (Miller et al., 1975; Rhoads and Stanley, 1981; Elwali and Gascho, 1988; Evanylo, 1991; Binder et al., 2000). Fertilizer N is more directly partitioned to grain when N application is delayed, due to higher rates of uptake and translocation during reproductive growth (Bigeriego et al., 1979).

Grain yields are generally highest when N deficiency does not occur prior to late-season N applications (Rhoads and Stanley, 1981; Evanylo, 1991; Binder et al., 2000). Corn grain yield in Virginia increased by 4641 kg ha^{-1} on a Bojac loamy sand with 112 kg N ha^{-1} applied at GS V16 when adequate N (81 kg N ha^{-1}) was applied at GS V5 (Evanylo, 1991). Significantly decreased yields associated with lower early sidedress N fertilization rates were thought to be a result of N deficiency prior to the GS V16 fertilizer application. The magnitude of yield response to late-season N applications diminished with early sidedress rates greater than 81 kg N ha^{-1}, and the author suggested that yield is more closely associated with total N rate when N deficiencies do not occur prior to late-season fertilization. Similarly, corn grain yields decreased 1694 kg ha^{-1} as a total N fertilizer application rate of 270 kg N ha^{-1} was split from 6 to 12 weekly applications on a Troup loamy sand in Florida (Rhoads and Stanley, 1981). This was probably due to N deficiency resulting from inadequate N fertilization early in the growing season.

However, additions of late-season N have been observed to increase yield when N deficiency occurs prior to GS VT (Miller et al., 1975; Evanylo, 1991). Grain yield response to late-season N applications on a Sharpsburg silty clay loam in Nebraska was most significant when N was applied on or before GS R1.5 to corn that would have become N deficient (Binder et al., 2000). Yield increases to late-season N applications were most significant when N deficiency developed early, and the authors suggested that N deficiency is adequate justification for late-season N fertilizer applications to corn. Similarly, researchers measured significant positive corn grain yield response to a late-season (GS VT) application of 270 kg N ha^{-1} on two silt loam soils in Kentucky when N deficiency was apparent at the time of application (Miller et al., 1975).

Soil residual N also affects corn grain yield response to applied N (Onken et al., 1985; Oberle and Keeney, 1990; Evanylo and Alley, 1996; Karlen et al., 1998; Vyn et al., 1999). Soil residual N levels greater than 50 kg NO_3^- ha^{-1} in the 1.5-m profile were associated with a lack of response to N applied at GS V8 on both a Mt. Carroll silt loam and a Webster clay loam in Minnesota, though yields in excess of 9000 kg ha^{-1} were obtained (Jokela and Randall, 1989). Similarly, corn yielding 14,676 kg ha^{-1} did not respond to N fertilizer applications greater than 168 kg N ha^{-1} on a Nicollet silty clay loam in Iowa (Polito and Voss, 1991). The authors attributed the lack of response to residual soil N from a previous soybean crop.

Drought Stress Timing Influence on Corn Yields

Occurrence of a drought-sensitive critical period during tasseling and silking (GS VT - GS R1) has been observed in many studies (Denmead and Shaw, 1960; Claasen and Shaw, 1970; Hall et al., 1981; Stegman, 1986; Grant et al., 1989; NeSmith and Ritchie, 1992a; Lamm et al., 1994; Farré et al., 2000; Sadler et al., 2000a). Fertilized ovule number is determined during this period, and moisture stress results in dessication of silks and pollen grains, causing poor seed set (Ritchie et al., 1997).

Grain yield was reduced by 22% on a Ritzville sandy loam in Prosser, WA when moisture deficits of one to two days occurred during GS VT (Robins and Domingo, 1953). Similarly, longer moisture deficit periods of six to eight days were associated with 50% yield reductions. Deficits occurring after pollination resulted in lower yield reductions that were associated with the maturity of the seed when the stress began. Grain yield of corn grown on a Nicollet loam in Iowa was reduced 50% by drought stress induced at GS R1 (Denmead and Shaw, 1960). Stress induced during vegetative growth and grain fill reduced grain yields by 25% and 21%, respectively, and the authors suggested that the critical period does not extend beyond three weeks after GS R1. Stress during vegetative stages had an indirect effect on grain yield, due to a reduction of the photoassimilatory surface. However, it was also suggested that early moisture stress induces root growth and the subsequent ability of the plant to avoid damage from drought at later growth stages. This physiological adaptation has been witnessed in many crops, including corn (Boote et al., 1994).

Claasen and Shaw (1970) induced four days of drought stress at various growth stages to corn grown on a Nicollet loam in Iowa. Stress during early ear shoot and ovule development caused yield reductions of 12 to 15%, while stress during GS R1 caused yield reductions of 53%. Trends toward smaller yield losses with time were observed after silking, when stress resulted in kernel weight reduction. Corn grain yield on a Maury silt loam in Kentucky was increased by 559 kg ha^{-1} for each additional cm of plant available water during tasseling through grain fill (Hill and Blevins, 1973).

Grain yield response to a single irrigation on a Sherm silty clay loam in Texas was greatest when water was applied at GS VT (Shipley and Regier, 1976). An additional irrigation applied at GS R3 increased yield by 1570 kg ha^{-1}. In Bushland, TX, Musick and Dusek (1980) measured yield reductions of approximately 50% as a result of severe drought stress during grain fill. Moderate stress during GS R1 resulted in greater yield decreases than did similar stress during grain fill. At the same location, Eck (1984) reported yield reductions of 1.2% for each day of moisture stress during grain fill, though there was considerable variation in the data. On a Kendrick fine sand in Florida, Bennett et al. (1989) observed visible stress symptoms and yield reductions of 22% as a result of a ten-day drought stress treatment imposed at GS VT. Similarly, Grant et al. (1989) concluded that kernel number is most sensitive to drought stress during a 7-day period just after GS R1.

On a Spinks sand in Kalamazoo, MI, NeSmith and Ritchie (1992c) measured yield reductions of 15 to 25% following 18-21 day water deficits that occurred immediately prior to anthesis. Moisture stress treatments of 12 and 19 days during tasseling resulted in yield reductions of 22 and 46%, respectively (NeSmith and Ritchie, 1992a). Similarly, NeSmith and Ritchie (1992b) measured yield reductions of 21 to 23% when severe moisture stress occurred during grain fill.

Doorenbos and Kassam (1979) proposed a set of growth stage-specific crop stress coefficients that were later incorporated into CROPWAT, a crop growth simulation model (Smith, 1992). These coefficients indicate that drought stress during GS VT – R1 has 275% and 200% greater impact on yield than stress during vegetative stages and grain fill, respectively. Cavero et al. (2000) imposed drought stress treatments to grain corn at several growth stages, and found that CROPWAT accurately predicted yield reductions due to growth stage-specific moisture stress.

Though variation exists across the reported data, the trend is clear: corn yields are impacted most significantly by drought stress during anthesis (GS VT – R1), and to a lesser extent by stress during either late vegetative stages or late grain fill. The variation across experiments is most likely a result of severity, duration, and exact timing of water deficit treatments.

Quantitative Water Use of Grain Corn

Evapotranspiration (ET) rate is a function of multiple factors, including soil water status, insolation, leaf area, temperature, humidity, and wind (Ritchie, 1973; Jensen et al., 1990). However, Khosla and Persaud (1997) measured no significant differences in consumptive water use among populations of 37, 49, and 62 thousand plants ha^{-1} grown on an Uchee loamy sand in Virginia.

Water use of irrigated corn in Georgia is reported to be 6.4 to 8.1 mm day^{-1} during the critical period (GS VT – R1) (Congleton, 1983). Khosla and Persaud (1997) measured water use of corn in Virginia at 2 to 4 mm day^{-1} during anthesis, However, there was a 9-day period without rainfall during anthesis that resulted in water stress, and thus non-stress water use is probably greater. The authors reported water use during grain fill to be approximately 10 mm day^{-1}, though significant drainage due to several intense precipitation events may have caused error in measurements. Howell et al. (1997), reported water use of irrigated corn in Bushland, TX to be approximately 6 to 8 mm day^{-1} during the critical period of anthesis and early grain fill. Evapotranspiration rates during later stages of grain fill were in the same 6 to 8 mm day^{-1} range.

Variation in reported water use values of grain corn is probably due to the factors that influence ET. Use of evapotranspiration equations that include these factors allows reliable prediction of reference ET (ET_o) (Jensen et al., 1990). Specifically, the FAO-24 Blaney-Criddle method (Doorenbos and Pruitt, 1977) allows prediction of ET_o when only temperature data are available for a location. This is particularly useful, since reported or locally measured crop coefficients (K_c) can be used to predict potential ET of corn (Et_{crop}) based on ET_o (ET_{crop} = K_c

x ET_o) when soil moisture is not limiting transpiration (Doorenbos and Pruitt, 1977; Hansen et al., 1980; Jensen et al., 1990).

Reduced water use, and thus moisture stress, due to limited soil moisture availability has been described as a logarithmic function of percent available soil water (Appendix D) (Burman et al., 1983; Haan et al., 1994; Sadler et al., 2000b). This is partially due to decreased hydraulic conductivity associated with more negative levels of soil matric potential (Black, 1984). Significantly reduced transpiration rates of many crops grown on soil types ranging from sand to clay loam have been measured when the root zone contains less than 50% available water and atmospheric demand is relatively high (Denmead and Shaw, 1962; Meyer and Green, 1980; Ritchie, 1983; Hook, 1985; Rosenthal et al., 1987). However, NeSmith and Ritchie (1992c) measured significant water stress below 85% available water on a deep sand in Michigan. The authors attributed this to the rapid depletion of available water from large pores.

When soil moisture is near field capacity, K_c of corn during anthesis is approximately 1.1 to 1.2 (Doorenbos and Pruitt, 1977; Jensen et al., 1990). Estimated historical ET_{crop} of tasseling corn at several sites in the Virginia Coastal Plain (Figs. 3.1 - 3.4), calculated from temperature records using the FAO-24 Blaney-Criddle method, varied with location. At all locations, ET_{crop} increased slightly from mid-June through early July, the period for tasseling and silking of most corn in the Virginia Coastal Plain.

Predicting Availability of Soil Water

Soils of the Virginia Coastal Plain were formed from alluvial deposits, are generally coarse-textured, and vary widely in their ability to hold water (Table 3.2). Coastal plain soils can supply moisture to tasseling corn for approximately 5 to 15 days before 50% of the available water has been depleted (Table 3.2). Therefore, rainfall must compensate soil water in order for late-season N applications to effectively increase corn grain yields. Historical rainfall patterns (Table 3.3) indicate that rainfall is enough to supplement stored soil water and prevent drought stress to corn in some years. Links to precipitation forecasts produced by the National Weather Service (NWS) are available online at http://www.nws.noaa.gov. Specifically, the Hydrometeorological Prediction Center produces daily precipitation forecasts for the seven-day period, and the Climate Prediction Center issues 6-10 and 8-14 day quantitative precipitation outlooks on a daily basis (Appendix E). Similarly, temperature outlooks are issued, and can be used to estimate ET_{crop} of corn for the period using the FAO-24 Blaney-Criddle method (Doorenbos and Pruitt, 1977). Measurements of soil water, rainfall probability, and ET_{crop} can be used to estimate soil water status during the critical period, and thus need for late-season N applications to corn.

The objective of this research was to develop a prediction system to determine potential for corn to utilize late-season N applications based on soil moisture. Phosphorus and potassium were not considered because they are generally immobile in soil systems and can be brought to levels that are not limiting to corn yields (Sharpley et al., 1994; Marschner, 1995; Lewis, 2001).

MATERIALS AND METHODS

Two experiments were established in the Virginia Coastal Plain to measure response of corn to late-season N applications and determine water use of high-yielding corn. Site I was located on a State sl in King William Co., VA (37º46'N, 77º18'W, 30m above sea level). Site II was located on a State sl in Westmoreland Co., VA (38º06'N, 76º44'W, 14m above sea level). The State sandy loam soils are fine-loamy, mixed, semiactive, thermic Typic Hapludults**.** Cultural practices and treatments are described in Chapter 2 of this thesis.

Rainfall, temperature, wind, and humidity were measured with a Spectrum Technologies Weather Monitor II™ solar-powered weather station equipped with a datalogger. To ensure accuracy in rainfall measurements, a separate tipping-bucket rain gauge with data logger was also employed. Soil moisture was measured with time domain reflectometry (TDR) probes (Moisturepoint™, Environmental Sensors, Inc.) at the following depths: 0-15cm, 15-30cm, 30-60cm, 60-90, and 90-120 cm. Four probes were used at Site I and two at Site II. Measurements were made on a regular basis throughout the growing season. Excavations were made at each site during grain fill to estimate effective rooting depth. Evapotranspiration plus drainage and runoff between each set of measurements was calculated using the equation:

$$ET + D + R = (S_f - S_i) + P + I \quad [1]$$

where:
- ET = evapotranspiration
- D = drainage
- R = runoff
- S_f = final soil water measurement
- S_i = initial soil water measurement
- P = precipitation
- I = irrigation

Eight intact soil cores to a depth of 1.2 m were removed from each site using a Concord™ 9300 soil sampler (CEE, LLC, Hawley, MN). Each 5 cm diameter core, contained in an acetate liner, was separated into sections using a band saw. The sections corresponded to TDR measurement depths. Smaller 1 cm subsamples were taken at random from each section, wetted, and subjected to equilibration on porous pressure plates at –10 and –1500 kPa, in order to estimate available water-holding capacity (AWC) (Klute, 1986). The remaining soil was composited by depth and subjected to routine particle size analysis (Day, 1965).

Four locations in the Virginia Coastal Plain were selected due to geographical distribution and availability of historical weather data from the National Weather Service. Historical ET_{crop} of tasseling and silking (GS VT – R1) corn at these locations was calculated from 30 years of climate data using the FAO-24 Blaney-Criddle method (Doorenbos and Pruitt, 1977) and summarized by week. Rainfall data was also summarized by week, in order to estimate the number of days soil water content can remain above 50% of AWC using equation [2]. The critical point of 50% was chosen due to significant plant stress and yield reductions measured by other researchers below this point (Denmead and Shaw, 1962; Meyer and Green, 1980; Ritchie, 1983; Hook, 1985; Rosenthal et al., 1987).

$$\text{Days} = (R + RAW) / ET_{crop} \qquad [2]$$

Where:

R = expected rainfall (mm)

RAW = readily available water (mm above 50% AWC)

ET_{crop} = calculated potential ET of corn in mm day^{-1}

RESULTS AND DISCUSSION

Field Experiments

Average yields at both sites were relatively high: Site I averaged 16,496 kg ha^{-1}, and Site II averaged 13,610 kg ha^{-1}, indicating that cultural practices were reasonable for high yields (Chapter 2). Soil moisture remained at or above the –10 kPa measured soil moisture retention levels (Table 3.4) at both sites for much of the growing season (Figs. 3.5 and 3.6), indicating that significant drainage may have occurred, especially at Site II (Fig. 3.6).

Water use calculations were performed to a depth of 90 cm, since excavations revealed no rooting activity below this depth. Measured ET plus drainage during the two weeks following late-season N applications was 4.2 and 8.6 mm day^{-1} at Sites I and II, respectively. These water use values correspond to calculated Blaney-Criddle K_c values of 0.9 and 1.7 at Sites I and II, respectively.

Drainage or runoff probably occurred at Site II, since the measured K_c of corn at this site was well above the range of K_c values (K_c = 1.1 – 1.2) found in the literature for corn during GS VT and R1 (Doorenbos and Pruitt, 1977; Jensen et al., 1990; Allen et al., 1998). Significant rainfall (99mm) and high initial soil water content (Fig. 3.6) at Site II during the two weeks following treatments further indicate that drainage occurred. Assuming a maximum K_c value of 1.2 (Doorenbos and Pruitt, 1977; Jensen et al., 1990; Allen et al., 1998), equation [1] was used to separate crop water use and drainage. The crop used approximately 86mm of water, while 34mm was estimated to be lost through internal drainage or runoff.

Lower measured K_c at Site I suggests that significant drainage did not occur on this soil. Lower total rainfall (76mm) and initial soil water content (Fig. 3.5) at Site I during the same two-week period further support the probability that drainage and runoff were not significant.

Predicting Soil Water Availability

Soil water availability over time is a function of moisture supply and demand. Historical ET_{crop} at the four selected sites varied slightly by location, but generally increased from mid-June through July (Figs. 3.1 – 3.4). Multiple predictions of the duration of low moisture stress conditions, estimated using equation [2], for the four locations in the Coastal Plain are presented in Tables 3.5 – 3.8. Rainfall and potential ET rates correspond to 25th and 75th percentile historical values outlined in Table 3.3 and Figures 3.1 – 3.4, respectively. These percentiles were selected to represent above- and below-average levels of precipitation and potential ET. Soil types for each location are representative of actively cropped soils in each locale. Two soil water contents (60% and 90% of AWC) were chosen to represent low and high levels of readily available water for each soil. The 60% of AWC level was chosen because it is near the 50% critical point for minimal moisture stress conditions (Denmead and Shaw, 1962; Meyer and Green, 1980; Ritchie, 1983; Hook, 1985; Rosenthal et al., 1987), while 90% was selected to represent a soil near field capacity.

The scenarios presented in Tables 3.5 – 3.8 indicate that, in order to remain above 50% of AWC for the two-week period, a soil must initially be near field capacity and rainfall levels must be above average. Historical rainfall patterns at Holland (Table 3.3), which were slightly higher than the other locations, suggest that 75th percentile rainfall at this location can supplement lower levels of stored soil water to meet crop demand for the two-week period (Table 3.6). Additionally, soils of higher AWC, near field capacity, can supply readily available water to the crop for a majority of the two-week period (Tables 3.5 – 3.8).

Corn yields are more likely to respond positively to additional N when there is minimal moisture stress during the two weeks immediately following tasseling. High yields may be achieved when soil water is less than 50% of AWC in the 0.9 m profile for part of the critical period, especially if root extension proceeds into lower depths that contain available water. Though some stress occurs above 50% of AWC (Burman et al., 1983; Ahuja and Nielsen, 1990; Haan et al., 1994; Sadler et al., 2000b), stress becomes more severe at soil matric potentials below this point (Denmead and Shaw, 1962; Meyer and Green, 1980; Ritchie, 1983; Hook, 1985; Rosenthal et al., 1987; Haan et al., 1994). Furthermore, 50% of AWC has been considered an acceptable soil water depletion limit for irrigated cropping systems management (Heermann et al., 1990). Under rain-fed conditions, the use of 50% of AWC as a critical point allows for a reserve of plant-available water during grain fill, when yield can be significantly impacted by drought stress.

Equation [2] must be used with some caution: soils of lower AWC are more likely to drain during major rainfall events, thereby losing available water for the corn crop. Also, soils of lower permeability are more likely to incur runoff during intense precipitation events, such as thunderstorms that are common in the Virginia Coastal Plain during the summer months.

Real-time potential ET for a given location can be calculated from available temperature forecasts using the FAO-24 Blaney-Criddle method. Similarly, quantitative rainfall forecasts can be employed to predict rainfall for the critical period. Soil moisture can be measured in a number of ways, including TDR, tensiometers, and simple gravimetric methods. Growers located near NWS monitoring sites can compare precipitation forecasts to historical patterns outlined in Table 3.3. Equation [2] can then be employed to estimate the number of days a soil will remain above 50% of AWC, as in Tables 3.5 – 3.8.

For example, a Tetotum loam near field capacity at Warsaw, VA contains approximately 52 mm of available water above the 50% critical point on June 24 (Table 3.5). Corn growing on this soil is near the GS VT stage, and weather forecasts for the two-week period call for conditions that are cooler and wetter than average. Therefore, rainfall totals of approximately 55 mm would be expected, and potential ET of corn would be approximately 5.7 mm day^{-1} (Tables 3.3, 3.5, Fig. 3.1). Applying equation [2], the estimated duration of low moisture stress conditions exceeds two weeks (Table 3.5). A late-season application of N fertilizer may improve corn grain yields on this soil. Conversely, a Nansemond fine sandy loam near the 50% critical point at Holland can supply approximately 10 mm of readily available water to a growing corn crop (Table 3.6). Weather forecasts indicate hot, dry conditions for the two-week period beginning June 24. Thus, total rainfall and potential ET could be approximated at 12 mm and 6 mm day^{-1}, respectively (Tables 3.3, 3.6, Fig. 3.3). Applying equation [2], the total duration of low moisture stress conditions is estimated to be less than 4 days (Table 3.6). An application of late-season N fertilizer to corn growing on this soil would not likely improve yields, and could cause adverse environmental impacts. This is a simple, effective method that growers can employ when making late-season N application decisions, since the tools needed are publicly and commercially available.

Additional considerations for efficacy of late-season N applications include residual soil N, soil moisture availability during grain fill, population density, and hybrid selection. Yield response will be greater when soil N status is limiting higher yields, though threshold levels of residual N have not been determined for late-season applications. Similarly, yield response to late-season N applications will likely be significant when long-range precipitation forecasts are not indicative of drought conditions during grain fill. Also, yield potential is greater for higher plant populations and “flex-ear” hybrids that can respond to optimal growing conditions by increasing ear size.

CONCLUSIONS

Three experiments over two years have shown that the potential exists for late-season N fertilizer applications to increase corn yields when adequate moisture is available (Lewis, 2001). Measurements of water use were not successful in refining crop coefficient values for GS VT – R1 corn in the Virginia Coastal Plain, due to significant drainage associated with above-average precipitation. However, calculations of readily available soil water as a function of initial soil water status and predicted rainfall indicate that many soils can remain above 50% of AWC when initial soil water content is near field capacity and above-average rainfall is expected during the two-week critical period. These results indicate that soil moisture is adequate for efficacy of late-season N applications to corn in some years. Furthermore, the prediction system outlined in this chapter allows growers to evaluate the potential for late-season N applications to improve corn yields based on soil moisture measurements and precipitation forecasts.

Moreover, the potential for corn to utilize late-season N has been substantiated in numerous irrigation experiments in other regions. More research is needed to determine the level of N deficiency at which late-season N fertilization will significantly improve corn grain yields, as well as establish K_c values for corn in the region.

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Table 3.1. Total June and July precipitation and deviation from 30-year average at four National Weather Service sites in the Virginia Coastal Plain, 1996 and 2000.

Location and Month	30-Year Average	1996 Precipitation	1996 Deviation	2000 Precipitation	2000 Deviation
	mm				
Corbin					
June	88	77	-11	176	88
July	112	146	34	173	61
Holland					
June	89	114	25	155	66
July	140	232	92	110	-30
Painter					
June	77	99	22	91	14
July	111	365	254	211	100
Warsaw					
June	84	132	48	139	55
July	118	172	54	198	80

Table 3.2. Selected Virginia soils, available water-holding capacities (AWC) to 0.9 m, and maximum days of low-stress water availability to tasseling corn.

Soil	AWC† Low	AWC High	Days‡ Low	Days High
	—— mm ——			
State sil	113	164	9	13
Norfolk ls	71	112	6	9
Craven sil	110	137	9	11
Sassafras sl	98	184	8	15
Conetoe ls	64	109	5	9
Pamunkey fsl	121	176	10	14
Wickham sl	107	152	9	12
Bojac lfs	66	131	5	11
Munden sl	73	146	6	12
Nansemond fsl	80	126	6	10
Eunola lfs	96	142	8	12
Tetotum l	104	157	8	13

† AWC Low and AWC High correspond to the reported range in available water holding capacity for each soil. Source: USDA-NRCS Soil Survey Division. 2001. National MUIR database download [Online]. Available at http://www.statlab.iastate.edu/cgi-bin/dmuir.cgi

‡ Assuming ET = 6mm day^{-1} and low-stress water = 50% of AWC.

Table 3.3. Thirty-year weekly median, 25th percentile, and 75th percentile rainfall at four National Weather Service sites in the Virginia Coastal Plain.

	Total Rainfall for Week Beginning				
Site and Percentile†	June 17	June 24	July 1	July 8	July 15
	mm				
Corbin					
25th	4.6	6.6	10.4	4.1	3.0
Median	13.3	18.0	17.4	17.8	10.9
75th	27.4	28.4	26.1	35.2	22.5
Holland					
25th	11.7	4.8	7.2	2.1	6.6
Median	17.3	12.4	16.5	17.7	19.2
75th	32.9	29.7	36.0	54.4	38.7
Painter					
25th	2.3	4.1	5.7	1.1	0.6
Median	13.5	11.4	9.8	12.2	7.5
75th	33.5	25.5	23.4	22.7	33.2
Warsaw					
25th	6.9	5.9	3.7	7.7	1.0
Median	21.6	12.7	19.9	13.0	13.6
75th	34.0	22.6	32.4	42.5	37.9

† 25th, 25th percentile; 75th, 75th percentile

Table 3.4. Soil water holding properties at the two experiment sites, 2000.

Site	Depth	Texture	-10 kPa	-1500 kPa	Available Water Capacity
	cm		% Volumetric Water		cm cm^{-1}
I					
	0 – 15	sl	18.68	8.31	0.10
	15 – 30	sl	19.29	8.63	0.11
	30 – 60	sl	20.68	11.77	0.09
	60 – 90	sl	22.04	14.86	0.07
II					
	0 – 15	sl	19.58	10.85	0.09
	15 – 30	l	19.13	11.75	0.07
	30 – 60	sl	22.89	15.55	0.07
	60 – 90	sl	15.65	10.62	0.05

Table 3.5. Days of readily available water as a function of soil water status, expected rainfall, and potential evapotranspiration at Warsaw, VA, June 24 – July 7.

Soil	Water Status†	Total Expected Rainfall‡	PET§	Days Above 50% AWC¶
		mm	mm day^{-1}	
Bojac lfs (AWC = 98mm)	60% of AWC (10mm above 50% of AWC)	10	5.7	3.5
			6.0	3.3
		55	5.7	11.4
			6.0	10.8
	90% of AWC (39mm above 50% of AWC)	10	5.7	8.6
			6.0	8.2
		55	5.7	16.5
			6.0	15.7
Tetotum l (AWC = 130mm)	60% of AWC (13mm above 50% of AWC)	10	5.7	4.0
			6.0	3.8
		55	5.7	11.9
			6.0	11.3
	90% of AWC (52mm above 50% of AWC)	10	5.7	10.9
			6.0	10.3
		55	5.7	18.8
			6.0	17.8

† AWC, available water holding capacity – average of reported range (Table 3.2)
‡ Selected rainfall amounts correspond to 25th and 75th percentile historical rainfall totals (Table 3.3)
§ PET, potential evapotranspiration of corn – Selected PET values correspond to 25th and 75th percentile historical PET values for the period (Fig. 3.1)
¶ Assumes no drainage

Table 3.6. Days of readily available water as a function of soil water status, expected rainfall, and potential evapotranspiration at Holland, VA, June 24 – July 7.

Soil	Water Status†	Total Expected Rainfall‡	PET§	Days Above 50% AWC¶
		mm	mm day^{-1}	
Nansemond fsl (AWC = 103mm)	60% of AWC (10mm above 50% of AWC)	12	5.7	3.9
			6.0	3.7
		66	5.7	13.3
			6.0	12.7
	90% of AWC (41mm above 50% of AWC)	12	5.7	9.3
			6.0	8.8
		66	5.7	18.8
			6.0	17.8
State sil (AWC = 139mm)	60% of AWC (14mm above 50% of AWC)	12	5.7	4.6
			6.0	4.3
		66	5.7	14.0
			6.0	13.3
	90% of AWC (56mm above 50% of AWC)	12	5.7	11.9
			6.0	11.3
		66	5.7	21.4
			6.0	20.3

† AWC, available water holding capacity – average of reported range (Table 3.2)
‡ Selected rainfall amounts correspond to 25^{th} and 75^{th} percentile historical rainfall totals (Table 3.3)
§ PET, potential evapotranspiration of corn – Selected PET values correspond to 25^{th} and 75^{th} percentile historical PET values for the period (Fig. 3.3)
¶ Assumes no drainage

Table 3.7. Days of readily available water as a function of soil water status, expected rainfall, and potential evapotranspiration at Corbin, VA, June 24 – July 7.

Soil	Water Status†	Total Expected Rainfall‡	PET§	Days Above 50% AWC¶
		mm	mm day^{-1}	
Bojac lfs (AWC = 98mm)	60% of AWC (10mm above 50% of AWC)	17	5.6	4.8
			5.9	4.6
		54	5.6	11.4
			5.9	10.8
	90% of AWC (39mm above 50% of AWC)	17	5.6	10.0
			5.9	9.5
		54	5.6	16.6
			5.9	15.8
Wickham sl (AWC = 130mm)	60% of AWC (13mm above 50% of AWC)	17	5.6	5.4
			5.9	5.1
		54	5.6	12.0
			5.9	11.4
	90% of AWC (52mm above 50% of AWC)	17	5.6	12.3
			5.9	11.7
		54	5.6	18.9
			5.9	18.0

† AWC, available water holding capacity – average of reported range (Table 3.2)

‡ Selected rainfall amounts correspond to 25th and 75th percentile historical rainfall totals (Table 3.3)

§ PET, potential evapotranspiration of corn – Selected PET values correspond to 25th and 75th percentile historical PET values for the period (Fig. 3.2)

Table 3.8. Days of readily available water as a function of soil water status, expected rainfall, and potential evapotranspiration at Painter, VA, June 24 – July 7.

Soil	Water Status†	Total Expected Rainfall‡	PET§	Days Above 50% AWC¶
		mm	mm day^{-1}	
Bojac lfs (AWC = 98mm)	60% of AWC (10mm above 50% of AWC)	10	5.7	3.5
			6.1	3.3
		49	5.7	10.4
			6.1	9.7
	90% of AWC (39mm above 50% of AWC)	10	5.7	8.6
			6.1	8.0
		49	5.7	15.4
			6.1	14.4
Munden sl (AWC = 109mm)	60% of AWC (11mm above 50% of AWC)	10	5.7	3.7
			6.1	3.4
		49	5.7	10.5
			6.1	9.8
	90% of AWC (44mm above 50% of AWC)	10	5.7	9.5
			6.1	8.9
		49	5.7	16.3
			6.1	15.2

† AWC, available water holding capacity – average of reported range (Table 3.2)
‡ Selected rainfall amounts correspond to 25th and 75th percentile historical rainfall totals (Table 3.3)
§ PET, potential evapotranspiration of corn – Selected PET values correspond to 25th and 75th percentile historical PET values for the period (Fig. 3.4)

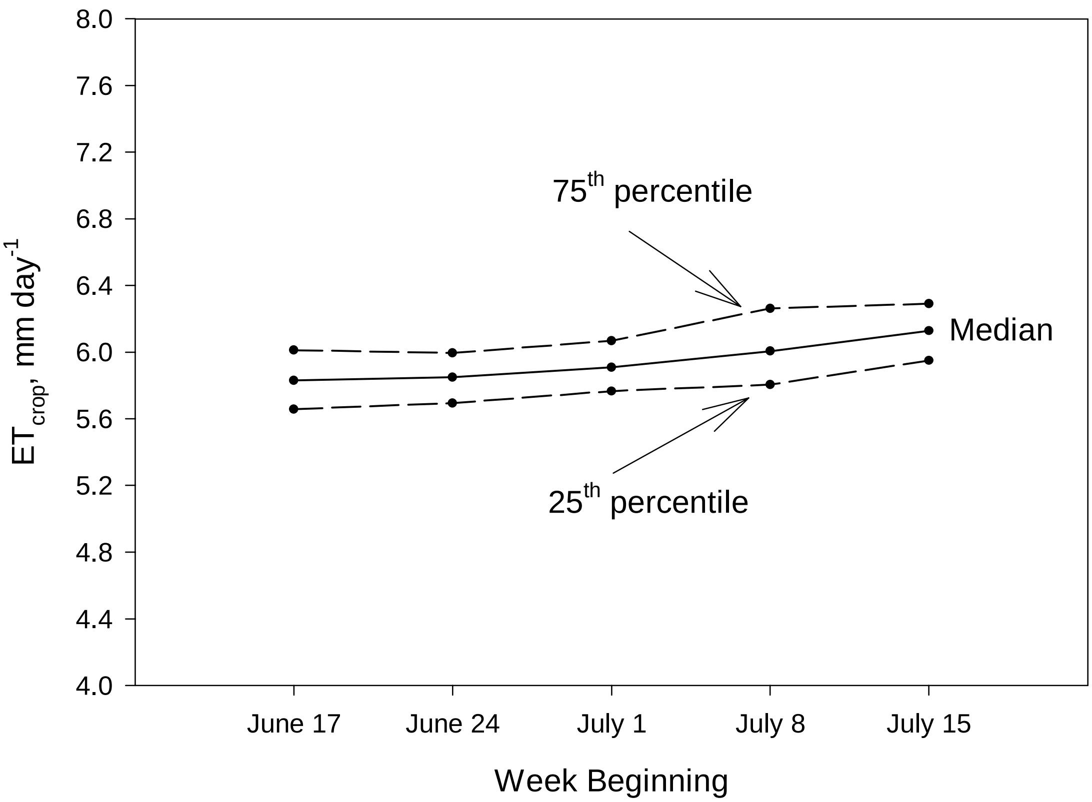


Fig. 3.1. Estimated 30-year weekly median, 25th percentile, and 75th percentile potential evapotranspiration of corn at Warsaw, VA. Calculated using the FAO-24 Blaney-Criddle method.

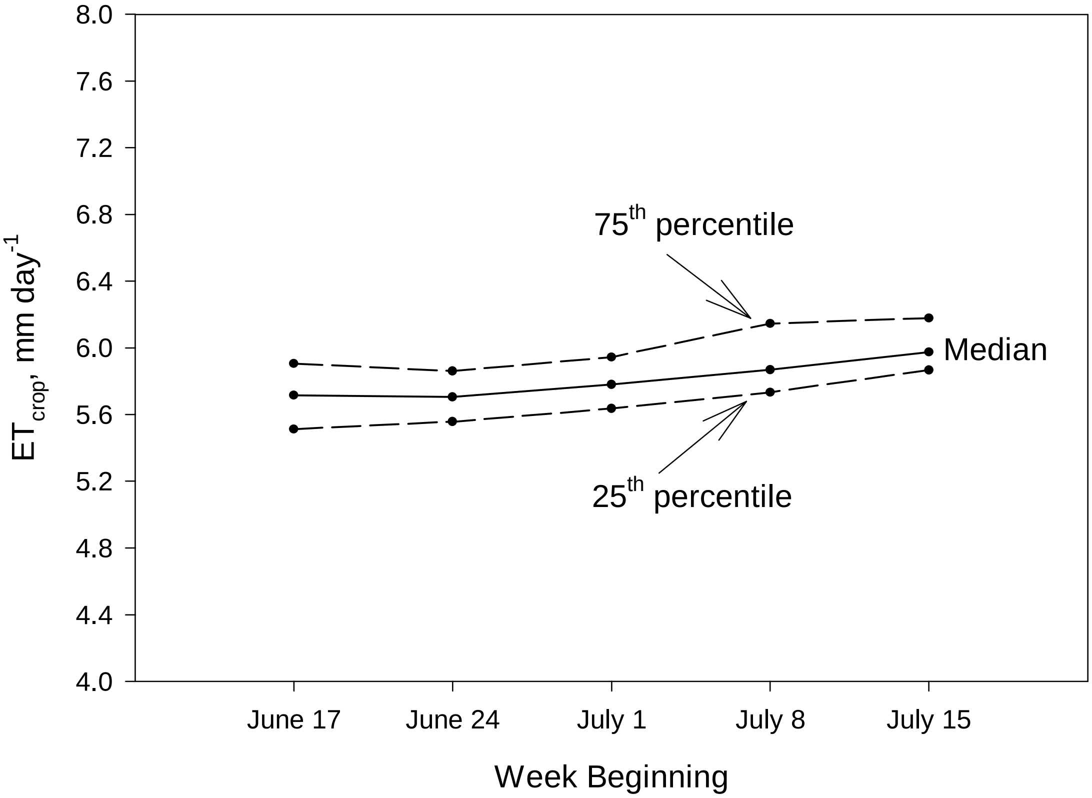


Fig. 3.2. Estimated 30-year weekly median, 25th percentile, and 75th percentile potential evapotranspiration of corn at Corbin, VA. Calculated using the FAO-24 Blaney-Criddle method.

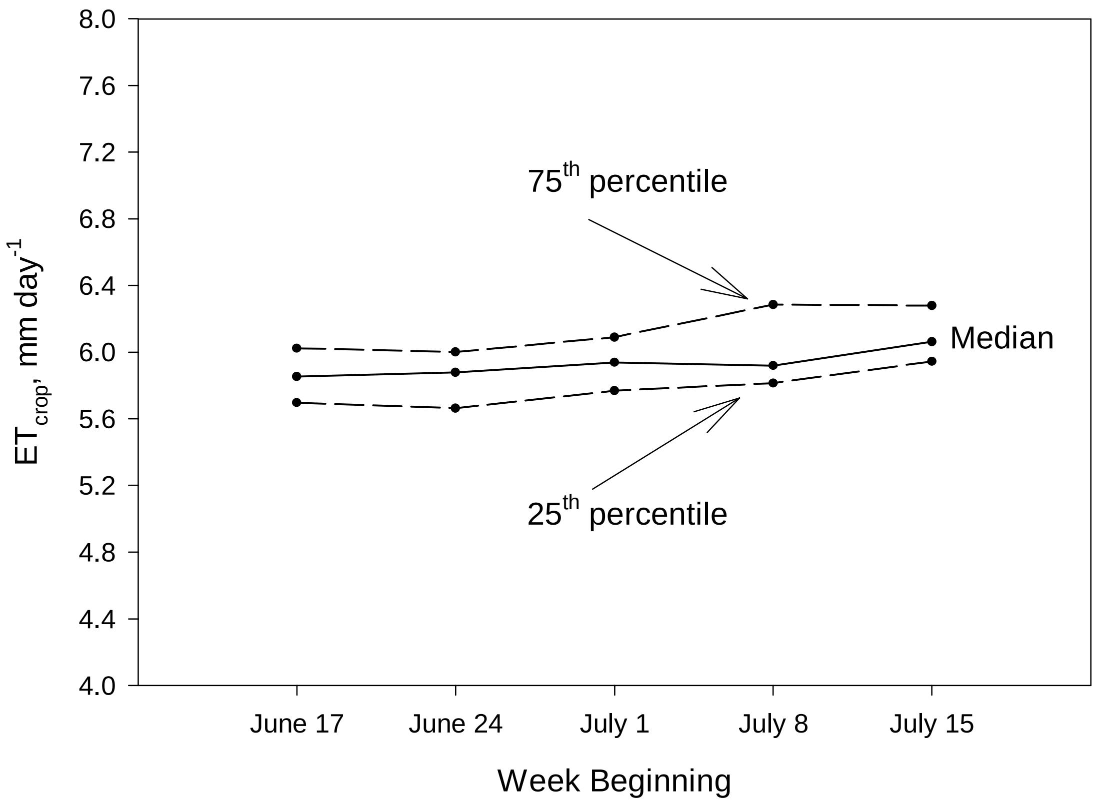


Fig. 3.3. Estimated 30-year weekly median, 25th percentile, and 75th percentile potential evapotranspiration of corn at Holland, VA. Calculated using the FAO-24 Blaney-Criddle method.

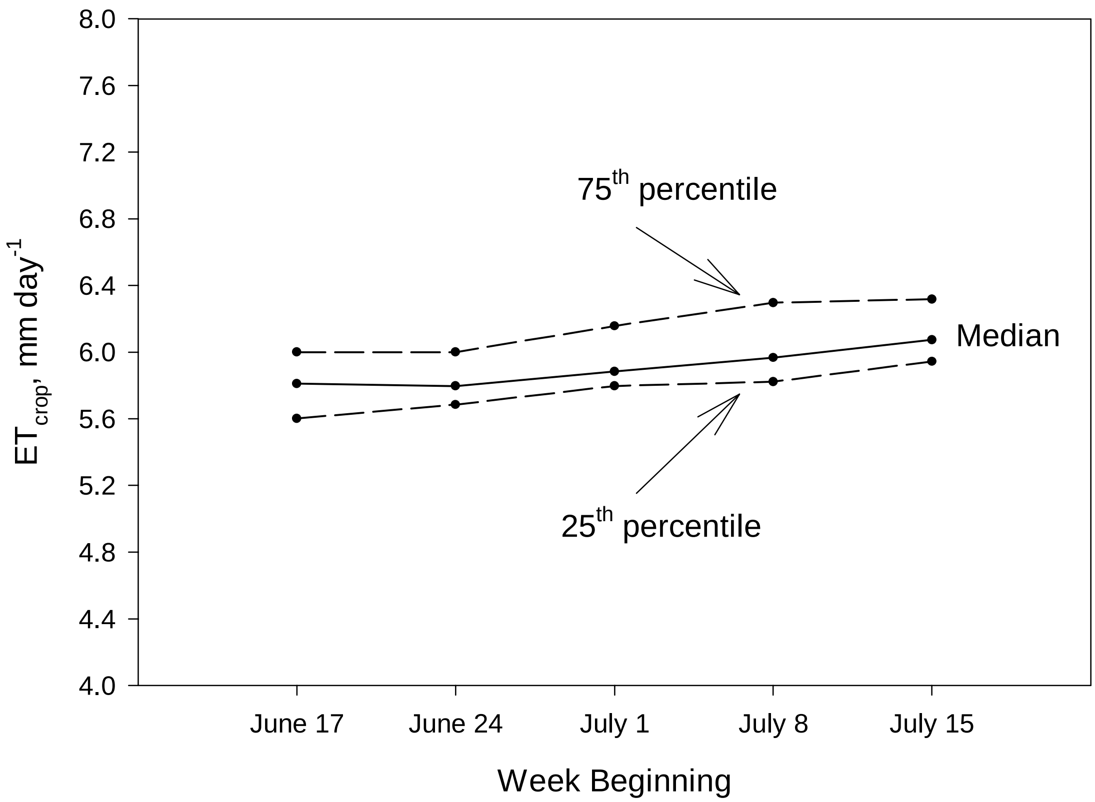


Fig. 3.4. Estimated 30-year weekly median, 25th percentile, and 75th percentile potential evapotranspiration of corn at Painter, VA. Calculated using the FAO-24 Blaney-Criddle method.

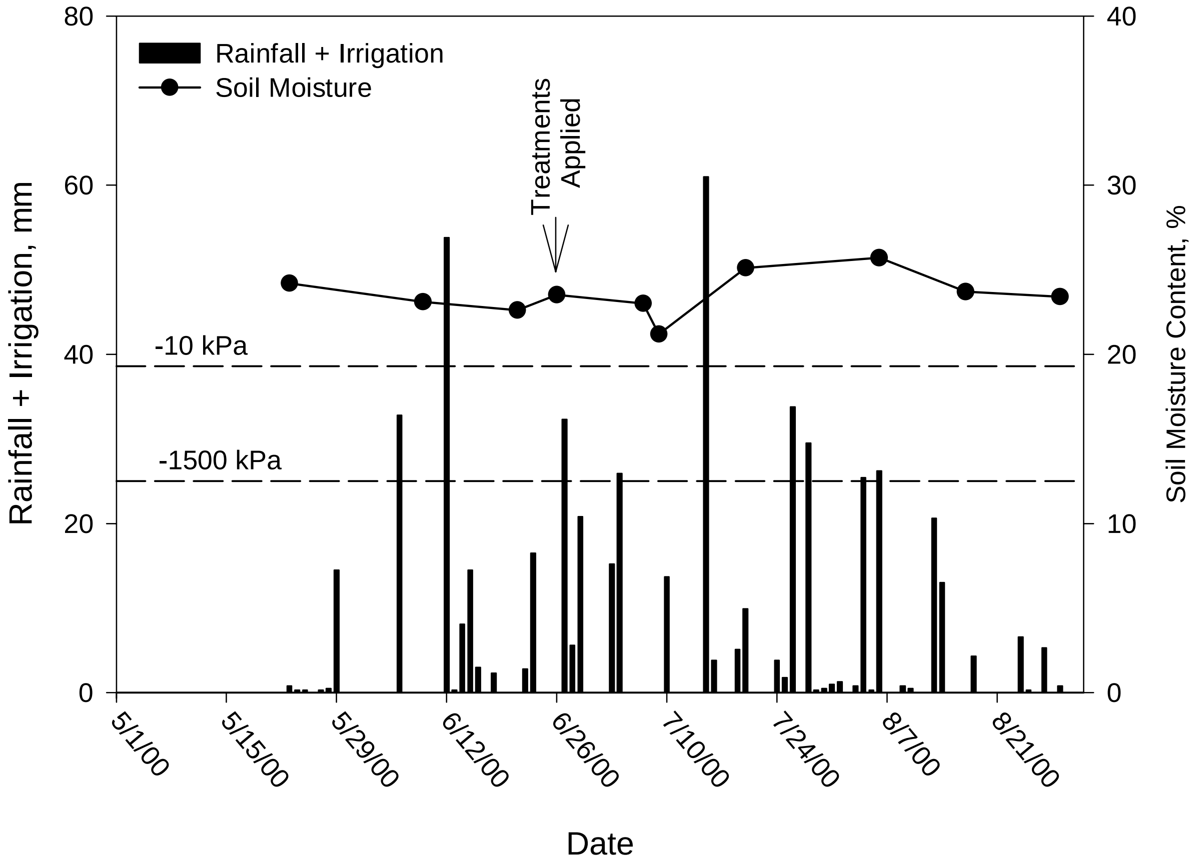


Fig. 3.5. Rainfall and irrigation, and soil moisture content at Site I, 2000.

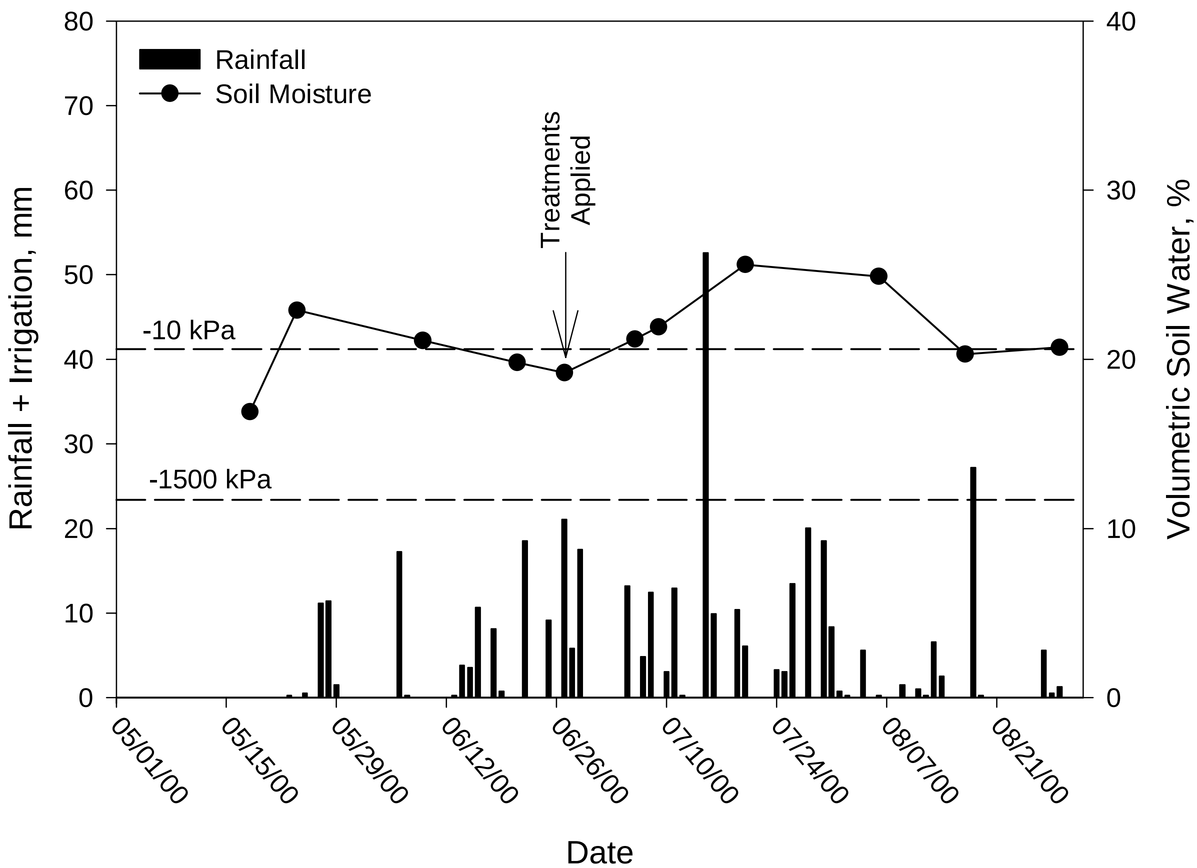


Fig. 3.6. Rainfall and irrigation, and soil moisture content at Site II, 2000.

Chapter 4 – Summary

Four experiments over two years have indicated that late-season (immediately prior to tassel) nitrogen (N) applications to corn can improve grain yields significantly. Relatively high grain yields were obtained in all four experiments with average grain yields ranging from 11,290 to 16,495 kg ha^{-1}. Grain yield increased by as much as 1130 kg ha^{-1} with a late-season application of 56 kg N ha^{-1}. Late-season applications of potassium (K) did not affect grain yields, and there were no interactions between N and K. These results suggest that K from standard pre-plant applications is sufficient to maximize yields, even on sandy soils.

In 2000, water use of high-yielding corn at two experimental locations was measured to evaluate evapotranspiration rates for corn under Virginia climatic conditions. Significant drainage due to above-average rainfall prohibited accurate measurement of evapotranspiration. Water use plus drainage during the two-week critical period beginning at tassel was 4.2 and 8.6 mm day^{-1} at sites I and II, respectively. These values corresponded to crop coefficients of 0.9 and 1.7 times reference evapotranspiration at sites I and II, respectively. Assuming a maximum crop coefficient of 1.2 at site II, approximately 86 mm of water was used by corn, while 34 mm was lost to drainage or runoff during the two-week period.

Historical weather patterns, potential evapotranspiration of corn, and soil water holding properties were evaluated to estimate the conditions necessary to provide adequate moisture to corn for the duration of a two-week moisture-sensitive critical period beginning at tassel. Soils must be near field capacity at the start of the two-week period and receive above-average (75^{th} percentile) rainfall during the period. Soils near a critical point of 50% of available water holding capacity, supplemented with below-average (25^{th} percentile) rainfall, generally can supply adequate moisture to corn for only several days of the two-week critical period.

A prediction system is proposed that allows producers to determine need for late-season N applications based on soil moisture supply and demand. Using this system, growers can predict the duration of low moisture stress conditions for the corn crop during the critical period by measuring soil water and estimating rainfall from weather forecasts. The estimate of readily available water can be divided by potential evapotranspiration of corn, in order to predict the duration of low moisture stress conditions. When the expected duration of low moisture stress conditions approaches or exceeds the end of the two-week critical period, late-season applications of N fertilizer are more likely to improve corn grain yields.

The potential for corn to utilize late-season N has been substantiated in numerous irrigation experiments in other regions. More research is needed to determine the level of N deficiency at which late-season N fertilization will significantly improve corn grain yields, as well as establish crop coefficients for corn water use in the Virginia Coastal Plain region.

APPENDIX A

GROWTH STAGES OF A CORN PLANT

Vegetative Stages	Reproductive Stages
VE emergence	**R1 silking**
V1 first leaf	**R2 blister**
V2 second leaf	**R3 milk**
V3 third leaf	**R4 dough**
•	**R5 dent**
•	**R6 physiological maturity**
V(n) nth leaf	
VT tasseling	

Source: Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1997. How a corn plant develops. Spec.Rep. 48. Rev. ed. Iowa State Univ. Coop. Ext. Serv., Ames.

APPENDIX B

CORN GRAIN YIELD AS A FUNCTION OF LATE SEASON N FERTILIZER APPLICATIONS AT THE FOUR EXPERIMENTAL SITES, 1999 AND 2000

Corn grain yield as a function of late-season N fertilizer applications at the four experimental sites, 1999 and 2000.

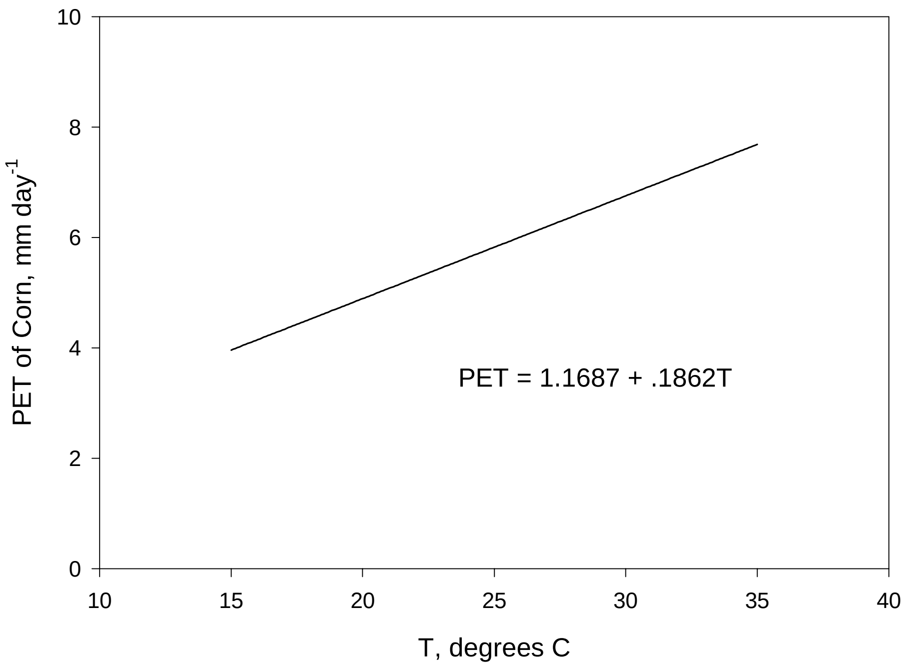
N Rate	Average Corn Grain Yield‡			
	Site I	Site II	Site III	Site IV
	kg ha^{-1}			
0	10 349a†	12 983a	13 359a	16 056a
28	10 913a	12 795a	13 485ab	16 244ab
56	11 478b	13 234a	13 673ab	16 684bc
84	11 854b	13 171a	13 924b	16 621abc
112	11 980b	13 108a	13 673ab	16 872c

† Within columns, means followed by the same letter are not significantly different according to Tukey's HSD (0.10).

‡ Yields for each N rate are averaged across K rates, due to lack of response to late-season K applications.

APPENDIX C

FAO-24 BLANEY-CRIDDLE PREDICTED POTENTIAL EVAPOTRANSPIRATION OF CORN AS A FUNCTION OF AVERAGE DAILY TEMPERATURE



FAO-24 Blaney-Criddle predicted PET of corn as a function of average daily temperature.

Methodology and assumptions:

$$ET_{crop} = K_c * ET_o$$

Where:

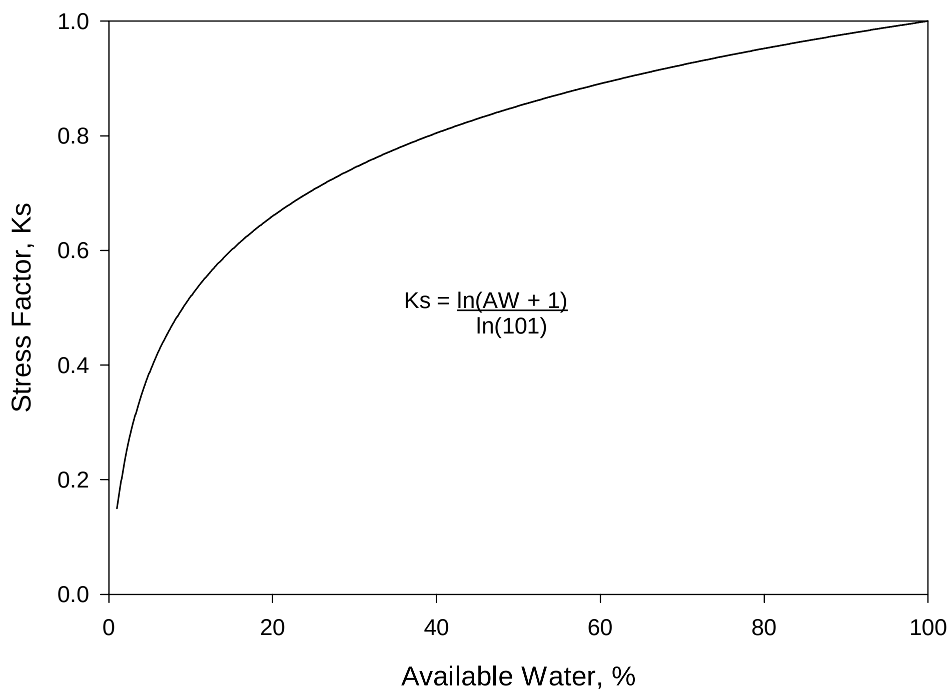
Kc	= crop coefficient (for tasseling/silking corn, approximately 1.15)
ET_o	= reference crop evapotranspiration in mm day^{-1} = c[p(0.46T + 8)]
T	= mean daily temperature in degrees C
p	= mean daily percentage of total annual daytime hours = .32 during June and July at 35º N Latitude
c*	= adjustment factor dependent upon relative humidity, sunshine hours, and daytime wind estimates.

* Assuming minimum relative humidity of 70%, medium sunshine hours, and medium wind speed, c takes the form of the equation: $ET_o = 1.1x – 1.8$. Where: x = p(.46T + 8).

Source: *Doorenbos, J. and W.O. Pruitt. 1977. Guidelines for Predicting Crop Water Requirements. FAO Irrig. And Drain. Paper 24, 2nd ed. FAO, Rome. 156pp.*

APPENDIX D

WATER STRESS OF CORN AS A FUNCTION OF PERCENT AVAILABLE SOIL WATER

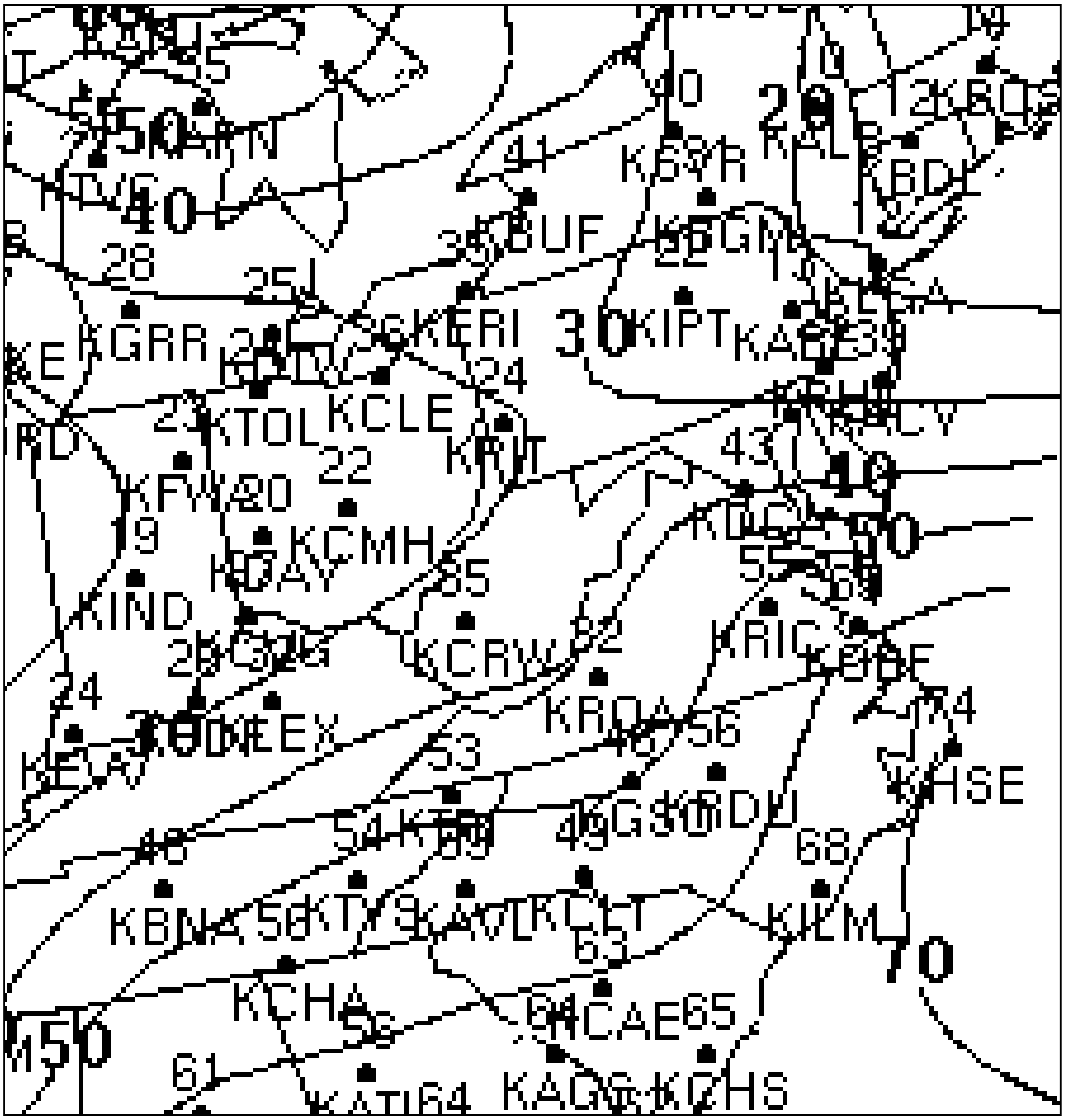


Water stress of corn as a function of percent available soil water

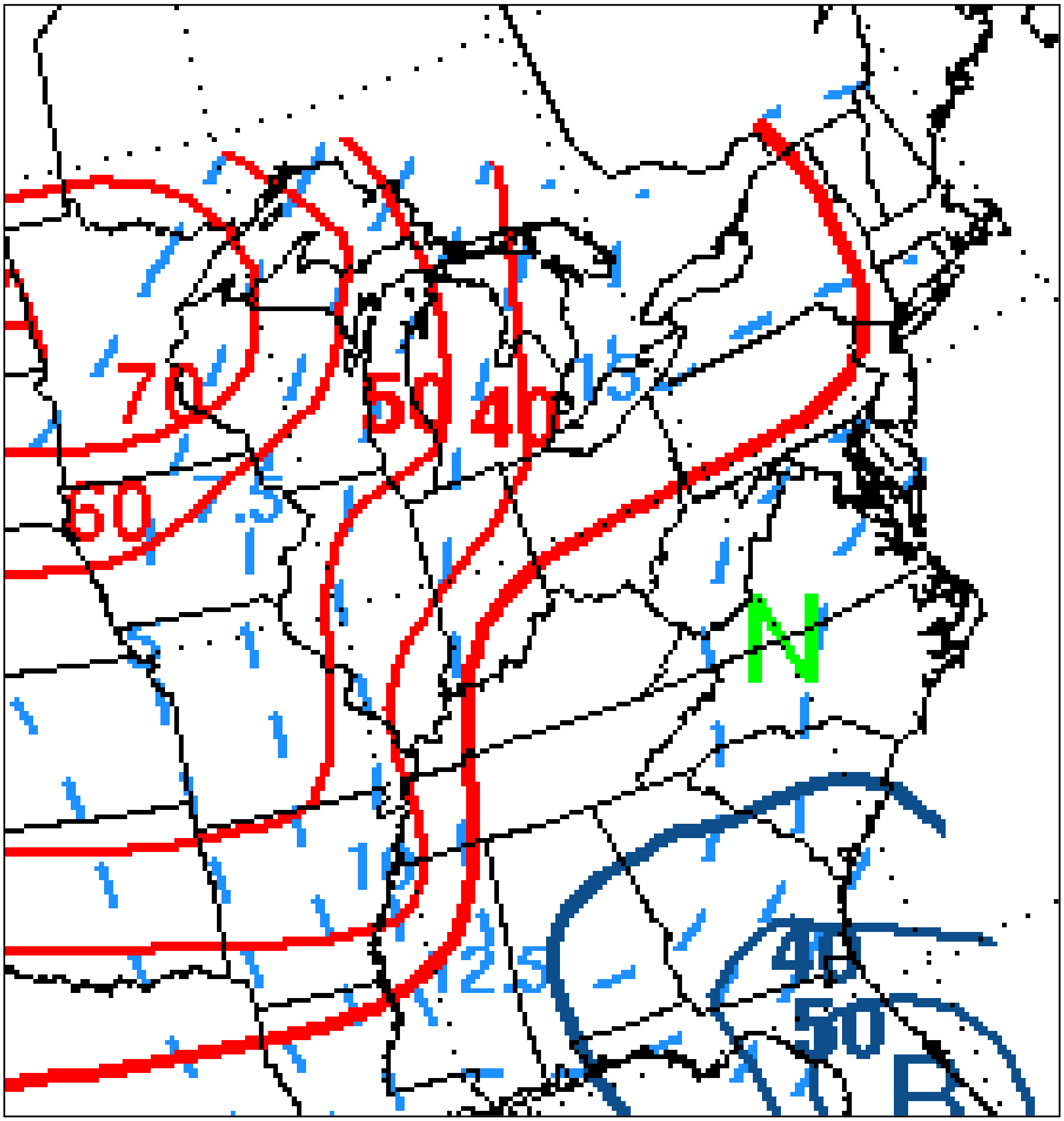
Source: *Haan, C.T., B.J. Barfield, and J.C. Hayes. 1994. Design hydrology and sedimentology for small catchments. Academic Press, San Diego.*

APPENDIX E

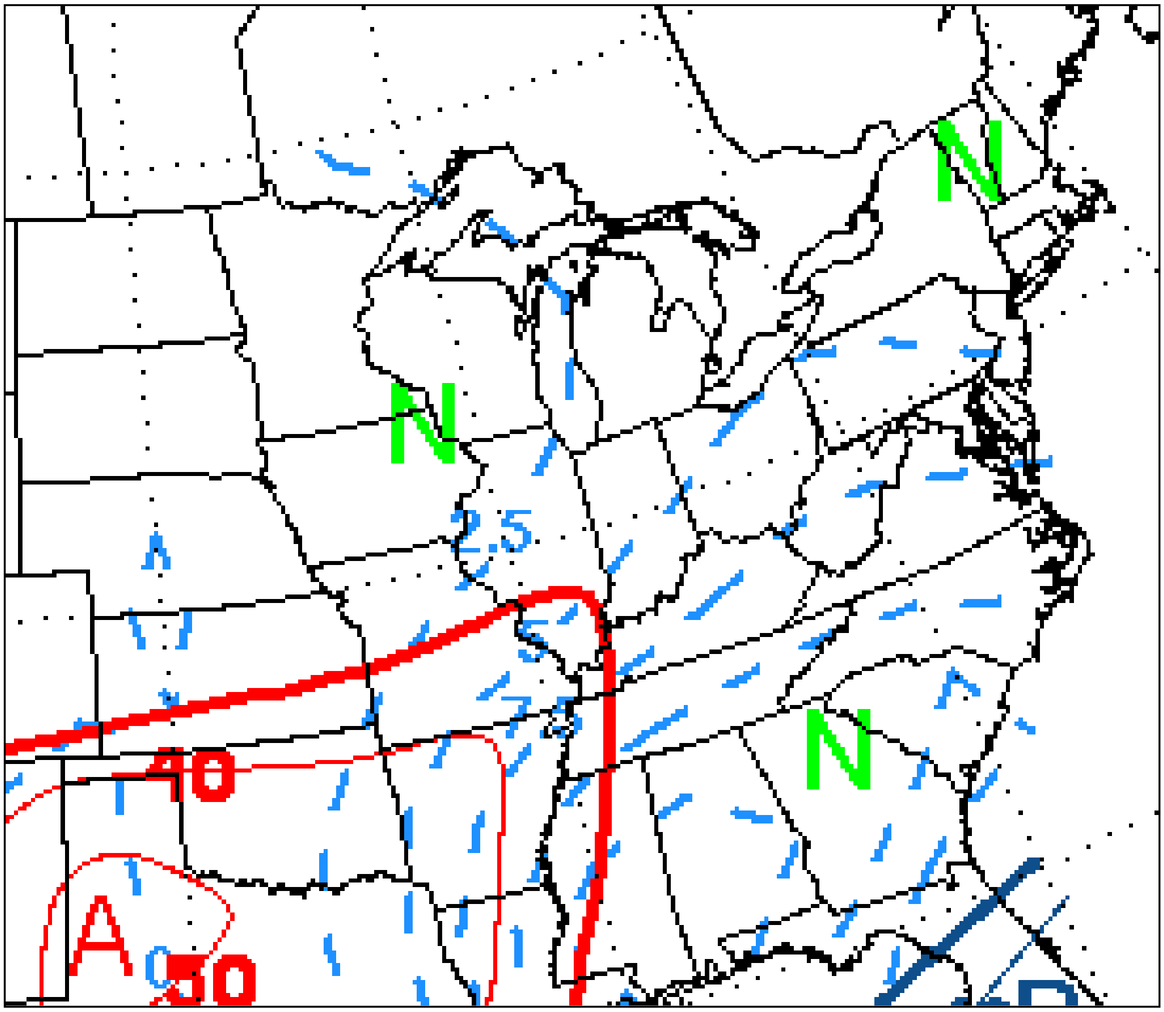
EXAMPLES OF NATIONAL WEATHER SERVICE PRECIPITATION FORECASTS



Example NWS Hydrometeorological Prediction Center daily precipitation forecast. Isolines indicate percent probability of measurable precipitation. Individually numbered points indicate probability of precipitation at the specific location. Actual amounts are not specified by this forecast. Source: *www.nws.noaa.gov*



Example NWS Climate Prediction Center 6-10 day precipitation forecast. Dashed blue lines indicate total expected rainfall (0.1 inches). Solid lines indicate probabilities associated with quantitative forecast. Solid blue lines are associated with below-normal precipitation, and red lines with above-normal precipitation.
Source: *www.nws.noaa.gov*



Example NWS Climate Prediction Center 8-14 day precipitation forecast. Dashed blue lines indicate total expected rainfall (0.1 inches). Solid lines indicate probabilities associated with quantitative forecast. Solid blue lines are associated with below-normal precipitation, and red lines with above-normal precipitation.
Source: *www.nws.noaa.gov*

Vita

Matthew Aaron Lewis

The author was born in Richmond, Virginia on July 8, 1977. He is the son of Larry and Joyce Lewis of Callao, Virginia. Matt graduated from Northumberland High School in June of 1995 and attended Rappahannock Community College for one year, while working on a large grain and beef cattle farm. He transferred to Virginia Polytechnic Institute and State University (Blacksburg, VA), where he pursued a B.S. in Crop and Soil Environmental Sciences. After graduating magna cum laude in May of 1999, he enrolled in graduate school at Virginia Tech, where he worked towards a Masters Degree in Crop and Soil Environmental Science under the guidance of Dr. Marcus M. Alley.