

Chapter 2

Nitrogen Management in No Tillage Grain Sorghum Production. I. Rate and Time of Application.

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ABSTRACT

Research with grain sorghum (*Sorghum bicolor* L. Moench), a relatively low acreage crop to Virginia, has shown sorghum as a more water-use-efficient-crop than corn (*Zea mays* L.). Sorghum is grown in rotation with winter wheat (*Triticum aestivum* L.) and double crop soybeans (*Glycine max*). However, sufficient data on N fertilization of grain sorghum are not available for this region. The objective of this study was to evaluate the response of multi-rate N fertilization on dryland grain sorghum production. Treatments consisted of factorial combinations of four starter-band, and four side-dress N rates to supply a total of ten different N fertilization rates of 11, 34, 56, 78, 101, 123, 146, 168, 190, and 213 kg N ha⁻¹. A broadcast treatment of 67 kg N ha⁻¹ at planting was also included. Starter-band treatments were applied 5 cm to the side and below the seed at the time of planting. Side-dress N treatments were applied 35 days after emergence and grain yield data were taken at harvest. Grain yields over eight site-years ranged from 1.7 to 11.9 Mg ha⁻¹. Grain sorghum yields were highly responsive to N fertilizer applications at three sites, moderately responsive at one site, non-responsive at two sites, and negatively responsive at two study sites. Non-responsiveness of grain sorghum yields at four site-years was mainly due to high levels (> 85 kg N ha⁻¹) of soil profile residual mineral-N, and severe water stress conditions on low plant-available-water-holding capacity soils. Optimum rates of N fertilization to optimize grain yields therefore depend on soil mineral-N at planting. For soils testing high in mineral-N (≥ 30 kg N ha⁻¹ in the top 0.3 m of surface soil) at planting, zero starter-band-N should be applied in conjunction with side-dress-N applications of 130 kg N ha⁻¹ for optimum economic return to N fertilization. For soils testing low in mineral-N at planting, starter-band-N supplement of 40 kg N ha⁻¹ in

conjunction with 130 kg N ha^{-1} side-dress N should optimize the sorghum grain yields. Lack of yield response to N fertilization on four sites in 1995 and 1997, and to starter-band-N on three sites in 1996, prevented any extensive assessment of the efficiency of the fertilizer placement methods. Pre-plant broadcast N applications on one site however, were as efficient as starter-band-placed N. Sorghum grain yield of 4.0 Mg ha^{-1} in extremely dry year (1997) and 8.9 Mg ha^{-1} under good rainfall year (1996) are encouraging to the growing of grain sorghum. Grain sorghum therefore has potential to be used as an alternative grain crop to corn in Virginia.

INTRODUCTION

Grain sorghum (*Sorghum bicolor* L. Moench) is a relatively low acreage crop in Virginia. It has been recognized as a more drought tolerant crop (Bennett et al., 1990, Khosla et al., 1995) and an alternative to corn (*Zea mays* L.). Corn has suffered severe yield reduction during frequent droughts in Virginia in the last 15 years. Sorghum is grown on about 6,000 to 10,000 hectares in Virginia, mostly under no-tillage for erosion control and for more efficient use of available-soil-water. However, land area planted to sorghum has not increased partially because adequate production practices to increase yields in no-tillage systems are lacking.

One factor that continues to be a problem in high residue (no-till) farming systems is N fertilizer management (Lamond et al., 1991). No-till systems often exhibit suppressed yields because of lesser N availability (Rao and Dao, 1996). This occurs because of slower N mineralization (Phillips et al. 1980), greater N immobilization (Rice and Smith, 1984), denitrification (Rice and Smith, 1982), and NH₃ volatilization (Terman, 1979). Also, below optimum soil temperatures in no-till environment cause lower nutrient availability in the early part of the growing season (Gordon and Whitney, 1995). All these complexities with N fertilizer management in no-tillage systems suggest the need for more research for improved and efficient utilization of fertilizer N.

Opportunities to incorporate N fertilizer below the residue layers in reduced tillage systems are limited (Mengel et al., 1982). Consequently the most common application method used in no-tillage systems is broadcasting either solid ammonium nitrate or urea, or spraying urea ammonium nitrate (UAN) solutions on the soil surface immediately before or after planting (Mengel et al., 1982). However, surface application of N fertilizer can result in significant N losses through ammonia volatilization.

Several studies (Eckert, 1987; Fox and Piekielek, 1987; Fox et al., 1986; Maddux et al., 1984; Bandel et al., 1980 and 1984; Mengel et al., 1982) have examined placement methods for no-tillage corn production in the Corn Belt and Great plains. They reported that similar N application of broadcast UAN produced lower yields than either injected or surface-banded UAN. Possible N loss mechanisms noted with broadcast UAN includes volatilization and immobilization (Lamond et al., 1991). Much less work has been done on N fertilizer management for grain sorghum in no-tillage systems (Lamond et al., 1991).

Studies with grain sorghum (Lamond, 1987; Sweeney, 1989) have shown that knifed N-P-K applications at planting increased grain sorghum yields relative to broadcast applications in high residue systems. These results for grain sorghum, coupled with those reported for other crops, i.e. corn (Eckert, 1987; Fox and Piekielek, 1987; Fox et al., 1986; Maddux et al., 1984; Bandel et al., 1984; 1980; Mengel et al., 1982), barley (*Hordeum vulgare* L.) (Tomar and Soper, 1981; Malhi and Nyborg, 1990), and wheat (*Triticum aestivum* L.) (Deibert et al., 1985; Rao and Dao, 1992 and 1996) have consistently shown that surface-band applied N fertilizer is more efficient than surface broadcast. However, in the mid-Atlantic region, the majority of crops are grown on sandy coastal plain soils with low organic matter content (generally <2%) and sandy to sandy loam surface (Gilliam and Boswell, 1984). Therefore it is not advisable to band-apply the total amount of fertilizer N needed by the crop at the time of planting, because the potential for N leaching and de-nitrification losses are high in this region (Bundy and Malone, 1988).

A possible means to increase the efficiency of fertilizer N for humid regions would be to split-apply the fertilizer N. The side-dress application, applying N fertilizer several weeks after corn emergence, has maximized the efficiency of fertilizer N

in most situations (Piekielek and Fox, 1992; Fox et al. 1986; Aldrich, 1984; Olsen and Kurtz, 1982). Also, the presence of plants at the time of side-dressing application reduces NH_3 volatilization loss by shading, and absorption of some of the evolved NH_3 (Harper et al., 1983).

The period of rapid growth and nutrient uptake by sorghum plants occurs about 35 days after emergence (Vanderlip, 1993) at the eight-leaf growth stage (Refer to Appendix A). Side-dress application at this stage is practically feasible and would be beneficial for the crop. However, the N fertilizer application at the time of planting sorghum under no-tillage cannot be ignored. The layer of crop residue on the soil reduces soil temperature, (Unger, 1978; Thomas et al., 1973) and may sometimes lower the nutrient availability in the early part of the growing season (Gordon and Whitney, 1995). Application of starter-band fertilizer N within the rooting zone of the young seedlings has been shown to be efficient and beneficial to the crop (Lamond and Whitney, 1991). In a more recent study, Gordon and Whitney (1995) reported an increase of 18% in the grain yields by application of fertilizer N in a starter-band. Similar research is lacking in the mid-Atlantic Coastal Plain region.

The objectives of this study were: (i) to determine the optimum rate of band-placed starter N fertilizer needed in combination with side-dress N applications to achieve economic grain yields, (ii) to determine if pre-plant broadcast N applications are as efficient as band-placed plus side-dress N applications, and (iii) to determine the estimated profit associated with N fertilization use as a function of starter-band-N rate and the side-dress N rate in these experiments.

MATERIALS AND METHODS

Multi-location field studies were conducted to study the rate and time of application of fertilizer N for no-till grain sorghum production over a period of three years (1995, 1996, and 1997). Experimental plots were selected each year on farmer's fields at different locations in the Virginia Coastal plain. The sites were representative of the soils (loamy sand or sandy loam, with low plant available water holding capacity and <2% organic matter) typical of soils widely used for grain sorghum production in Virginia. The plots were laid out in a randomized complete block design with four replicates of each treatment. Each experimental plot consisted of eight 0.15 m wide rows, 7.62 m in length. Appendix B shows the planting and harvesting dates for all the locations and other details of the field operations performed during the three years.

Soils used in these experiments were typical of those used for grain sorghum production in Virginia. Soil samples were taken at the time of planting to a depth of 0.9m at 0-0.15, 0.15-0.3, 0.3-0.6, and 0.6-0.9 m depth intervals. A "JMC Backsaver" probe was utilized to collect soil samples. A total of 16 cores for each depth increment were composited. Composite samples were extracted with 2M KCl and the extracts were analyzed for soil nitrate and ammonium by the Salicylate and Griess-Illosvay methods respectively, (Keeney and Nelson, 1982) on a Lachat QuikChem Analyzer. Soil mineral-N values were expressed as kg ha^{-1} using a bulk density estimate of 1.6 Mg m^{-3} , an average of numerous samples collected at various depths from these and similar coastal plain soils (Scharf, 1993). Chemical analyses of profile soil samples taken with depth from all locations at the time of sorghum planting are presented in Appendix C. The surface organic matter content ranged from 0.7% to 2.4% (average of 1.4% over eight locations) and is typical of Virginia coastal plain soils. The soil pH to a depth of 0.9 m ranged between 5.5 and 7.4, making it very suitable for crop root growth. All soils tested high ($>18 \text{ mg kg}^{-1}$) in phosphorus and medium to high in potassium, calcium, and magnesium (Donohue and

Heckendorn, 1994). Plant-available-water-holding capacity of these soils varied from low (Pamunkey sandy loam ~ 125 mm water m⁻¹ of soil) to very low (Bojac sandy loam ~ 50 mm water m⁻¹ of soil). These soils are deep and well drained and are susceptible to leaching of nitrates.

Nitrogen treatments consisted of factorial combinations of four starter-band and four side-dress N rates to supply a total of ten different N fertilization rates of 11, 34, 56, 78, 101, 123, 146, 168, 190, and 213 kg N ha⁻¹, and a broadcast rate of 67 kg N ha⁻¹ at the time of planting. Urea ammonium nitrate (30%) solution was used as the N fertilizer source. Starter-band treatments were applied 5 cm below and to the side of the seed with a carbon-dioxide pressurized system mounted on a John Deere Max Emerge 2 Conservation tillage planter. Phosphorus fertilizer solution (in the form of 10-34-0 ammonium poly-phosphate) was also placed with the starter-band-N. Potassium chloride was broadcast at each site, at a rate high enough to ensure adequate K availability.

Side-dressing of the experimental plots was done approximately 35 days after planting at the eight-leaf growth stage of sorghum plants. The UAN solution was applied with a carbon-dioxide pressurized back-pack sprayer whose spray nozzles were fitted with Teejet “raindrop” tips. Flow rates for each tip size was measured at each experimental location prior to N application. Proper walking speed to obtain the desired application rate was calculated, and a stop-watch and metronome were used to calibrate and maintain proper walking speed during N application. Broadcast treatment application of 67 kg N ha⁻¹ was done in the same manner at the time of planting.

Sorghum grain yield was determined by harvesting the four middle rows of each plot with a plot combine. Grain moisture contents were measured on all samples with a Dicky John GAC II grain moisture meter. Grain yields are reported at 140 g kg⁻¹ moisture content.

On site weather data including daily rainfall, daily maximum and minimum temperatures were also recorded. For four locations (two locations in year 1996 and two in 1997) weather data was recorded with the Weather Monitor II™ automated weather systems (Spectrum Technologies, Inc., 1997). For other locations weather data was obtained from AgMaster Weather Service (Sky Bit, Inc., 1998).

Analysis of variance (ANOVA) was done as appropriate using the SAS software package (SAS Institute, 1993) to test for significant treatment effects. Mean separation was performed by the Duncan procedure when the ANOVA results indicated significant effects at the 0.05 probability level (SAS Institute, 1993). Data was further analyzed via regression procedures with SAS and Sigma-Stat (Jandel Scientific, San Rafael, CA) to determine the optimum rate of starter-band N fertilizer in combination with side-dress N applications, and to compare starter-band versus broadcast N application at planting. To determine the estimated profit associated with N fertilization use as a function of starter-band-N rate and the side-dress N rate, the least square quadratic response surface was calculated for each location. Profit was estimated as sorghum value (yield x grain price) - N fertilizer cost (total N rate x N price) - other production costs (estimated as \$345 ha⁻¹ for all experiments). Current grain price was taken as \$90.56 per metric ton of grain sorghum and N fertilizer price was taken as \$0.55 kg⁻¹.

RESULTS AND DISCUSSION

Climatic conditions varied during the 3 years of this project. Two out of three years were droughty. Rainfall was much below average in 1995 and 1997 (average rainfall ranges between 100-150 mm per month based on 30 years rainfall data, Norris, 1985). The early part of the growing season (May-June) in 1995 was conducive for germination, emergence and vegetative growth. Temperatures were above the critical temperature of ≥ 10 °C for grain sorghum growth (Anda and Pinter, 1994). Grain sorghum stands on both soils, Pamunkey sandy loam, and Conetoe loamy sand were excellent. However, the months of July and August were extremely hot and dry and plants were severely water stressed. Year 1997 was dry throughout the growing season with very little rainfall, 203 mm and 260 mm occurred on two soils, Atlee and Kempsville, respectively. Temperatures were below normal during the month of May and planting was therefore delayed until May 27th. However, on Bojac soil, temperatures stayed below or around the 10 °C critical level through the week after the emergence of sorghum. This initiated auxiliary tiller growth in sorghum later in the season, consequently increasing the water requirement of the crop. Water stress symptoms on plants were more prominent in 1995 and 1997 and were particularly evident on the plants growing on the Conetoe loamy sand, Bojac sandy loam, and Atlee very fine sandy loam. Year 1996 was good overall with normal to above average rainfall (≥ 550 mm) during the growing season at all four locations. (Climate data including rainfall distribution, daily maximum and minimum temperatures for the entire growing season during 1995, 1996, and 1997 are presented in Appendix D).

Grain yields over three years on eight different sites varied from as low as 1.7 Mg ha⁻¹ to as high as 11.9 Mg ha⁻¹ (Table 1). An overall average of the highest yield at eight locations was 7.98 Mg ha⁻¹ and is testimony to good cultural practices and fertility levels for other plant nutrients. The sorghum crop was highly responsive to N fertilizer applications

(the difference between the check yield and the highest yield was $>3 \text{ Mg ha}^{-1}$) at three sites, moderately responsive (yield response between 1 and 3 Mg ha^{-1}) at one site, non-responsive (no treatment yield more than 1 Mg ha^{-1} above the check yield) at two sites, and negatively responsive (treatments yields were below the check yield) at two sites. Figure 1 shows the yield response of grain sorghum to side-dress N applications and illustrates the above mentioned four categories of yield response similar to the method of Scharf (1993) with winter wheat.

Among the four responsive sites, grain yield reached the point of maximum yield response to applied N only at two soils, Suffolk and Appling-Cecil complex (Figures 2a & 2c). Beyond that the increases in the grain yields were not significant. Conversely, the grain yields did not reach its point of maximum yield response to applied N on the Bojac and Wheeling soils (Figures 2b & 2d). The grain yields were still increasing linearly in response to high applications of fertilizer N. This linear response of grain yield to applied N could be attributed to heavy rainfall (510mm) during the growing season that provided abundant plant-available soil moisture for plant growth and at the same time may have caused leaching of nitrates.

Review of the yield response surface curves in Figure 2, reveals that the crop reached its maximum economic yield (MEY) at starter-band and side-dress N application rates of 39 and 134 kg N ha^{-1} on the Suffolk soil, 0 and 135 kg N ha^{-1} on the Bojac soil, 0 and 106 kg N ha^{-1} on the Appling-Cecil complex, and 0 and 129 kg N ha^{-1} on the Wheeling soil (Figures 2a, b, c, & d, respectively). Zero level of starter-band-N indicates that grain yields at these sites did not respond to starter-band-N applications. This is logical because at planting, the Bojac and Wheeling soils had $\geq 70 \text{ kg N ha}^{-1}$ of mineral N in the top 0.3 m surface soil, out of a total $>105 \text{ kg N ha}^{-1}$ of profile mineral N (Table 2). This level of residual mineral-N evidently provided sufficient N to support the early season growth of the sorghum plants prior to side-dressing. Conversely, grain yields on Suffolk fine sandy loam

Table 1. Treatment number, pre-plant broadcast N, starter band N, side-dress N and sorghum grain yields on various soil types used at study-sites over three years 1995, 1996, and 1997.

----- Treatment Description -----				----- Soil Types -----							
Treatment	Pre-plant Broadcast N	Starter Band-N	Side-dress N	Pamunkey sl	Conetoe ls	Suffolk fsl	Bojac sl	Wheeling sl	Cecil-Appling complex	Atlee vfsl	Kempsville fls
				----- Year 1995 -----		----- Year 1996 -----			----- Year 1997 -----		
	----- kg ha ⁻¹ -----			----- Mg ha ⁻¹ -----							
1	0	11	0	6.9	3.4	4.9	6.6	5.2	7.2	4.1	6.2
2	0	11	45	7.5	4.0	6.1	7.1	6.2	10.1	4.3	5.7
3	0	11	90	7.4	3.4	7.8	8.7	6.7	11.2	4.1	6.3
4	0	11	134	7.8	3.1	8.4	9.0	5.2	10.4	4.8	5.6
5	0	34	0	7.5	3.8	5.3	6.6	4.6	9.0	4.7	4.9
6	0	34	45	7.7	3.3	6.8	7.7	6.3	9.0	4.4	6.2
7	0	34	90	7.4	3.3	8.5	7.8	6.7	10.6	4.4	6.7
8	0	34	134	7.9	3.8	8.9	8.6	7.2	11.1	4.9	5.1
9	0	56	0	7.7	3.4	6.0	6.6	5.8	9.1	4.6	6.0
10	0	56	45	7.7	2.2	7.3	7.7	6.7	10.2	4.8	6.2
11	0	56	90	7.5	3.8	8.3	7.6	6.3	9.5	4.0	5.5
12	0	56	134	7.8	1.7	8.7	8.3	6.7	9.6	3.8	5.3
13	0	78	0	7.5	2.0	6.6	6.8	6.3	8.9	4.2	6.0
14	0	78	45	7.4	2.7	8.0	7.7	6.9	8.9	4.6	5.6
15	0	78	90	7.6	2.6	8.5	9.2	7.1	11.9	4.6	7.8
16	0	78	134	6.8	2.8	9.1	9.5	5.5	8.7	4.0	6.7
17	67	11	0	7.3	3.0	6.5	6.6	5.9	9.8	6.1	5.6
18	67	11	45	7.5	3.0	7.7	7.4	6.2	10.7	4.3	6.8
19	67	11	90	7.0	2.8	9.0	8.9	6.8	10.0	4.4	6.2
20	67	11	134	7.3	2.4	8.6	9.9	5.3	10.3	4.2	6.1

*Grain yields are reported at 14% moisture and are average of 4 replicates.

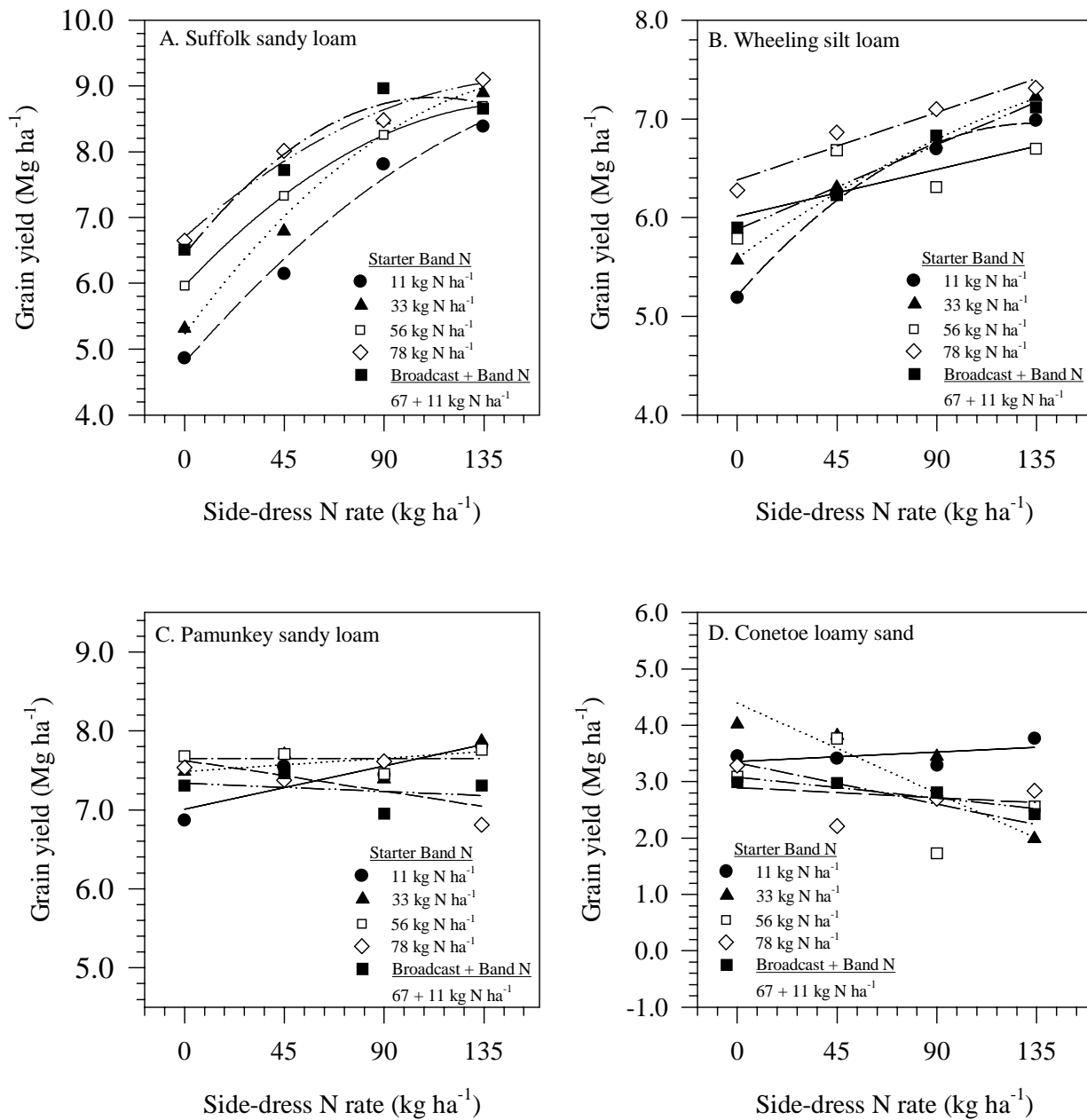


Figure 1. Sorghum grain yield responses to side-dress N applications on different soil types. Plot A is characterized as highly responsive, B as moderately responsive, C as non-responsive, and D as negatively responsive.

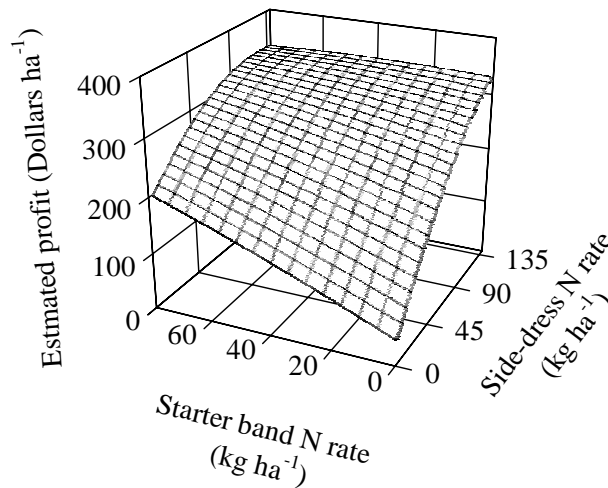
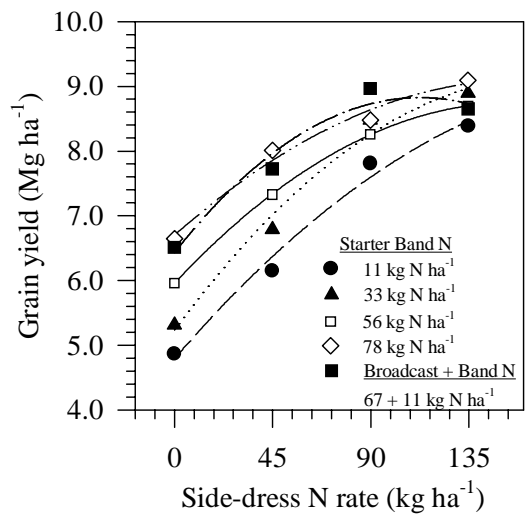


Figure 2a. Suffolk fine sandy loam, James City.

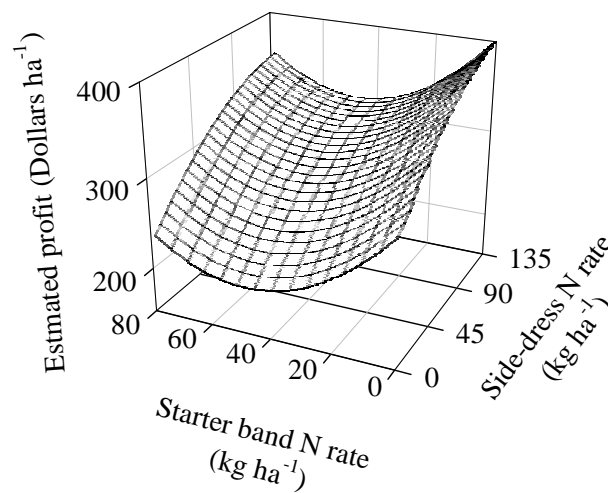
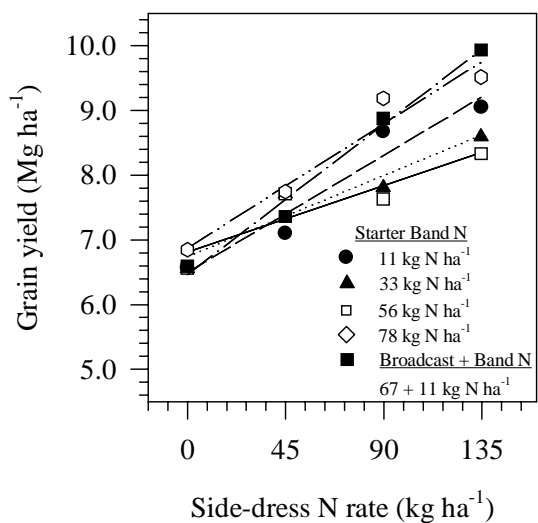


Figure 2b. Bojac sandy loam, New Kent.

Figure 2 a&b. Yield response to side-dress N applications and response surface curves describing estimated relative profit due to N applications (starter band-N and side-dress N) on Suffolk fine sandy loam and Bojac sandy loam in Virginia, 1996.

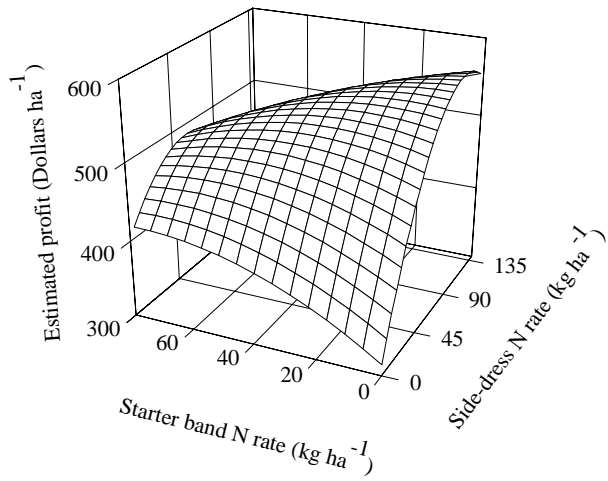
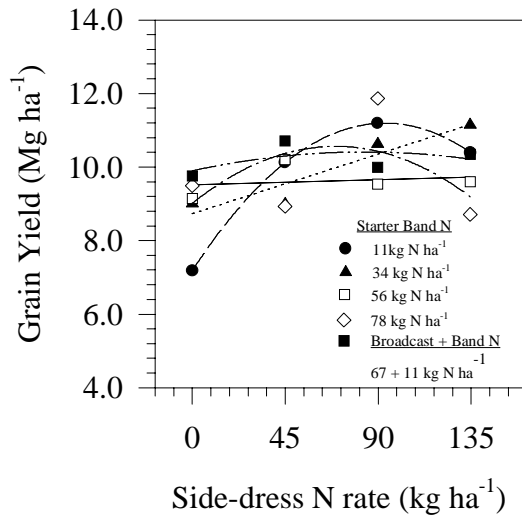


Figure 2c. APpling-Cecil complex, Amelia.

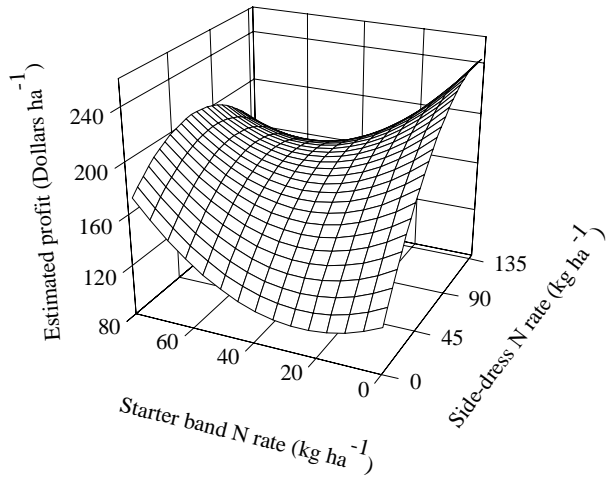
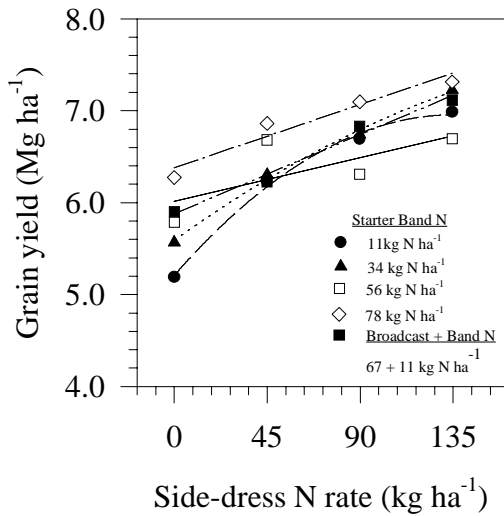


Figure 2d. Wheeling silt loam, Whitethorn.

Figure 2c&d. Yield response to side-dress n applications and response surface curves describing estimated relative profit due to N applications (starter band-N and side-dress N) on APpling-Cecil complex and Wheeling silt loam in Virginia, 1996.

Table 2. Residual soil mineral-N (NO₃-N plus NH₄-N) by depth present at grain sorghum planting for eight experimental sites.

Soil Depth	Residual Soil Mineral-N							
	Pamunkey sl	Conetoe ls	Suffolk fsl	Bojac sl	Wheeling sl	Cecil-Applying complex	Atlee vfls	Kempsville fls
	----- 1995 -----		----- 1996 -----			----- 1997 -----		
----- m -----	----- kg ha ⁻¹ -----							
0.0 - 0.15	45	44	27	49	46	32	15	24
0.15 - 0.3	35	22	17	27	24	19	23	14
0.3 - 0.6	39	25	19	18	17	29	8	15
0.6 - 0.9	28	21	20	13	27	51	45	19
0.9 +	*	*	*	*	*	*	38	15

* samples not taken or analyzed

did respond to starter-band N (Figure 2a). Residual mineral N of 45 kg N ha⁻¹ in the top 0.3 m of soil at planting, evidently was not sufficient to provide N support to the crop until it received side dressing at 35 DAP. Also heavy rainfall (607mm) during the season on the sandy textured Suffolk soil may have caused leaching of nitrates. The Appling-Cecil complex had similar amount of residual mineral-N at planting (51 kg N ha⁻¹) as the Suffolk soil. However, the Appling-Cecil complex is a heavy texture clay loam soil underlying the sandy loam surface horizon and the leaching potential of this soil is relatively much lower (L.W. Zelazny, personal communication) than for the Suffolk soil. This is apparent to some extent because the grain yield did not respond to starter-band-N and also the point of maximum yield on the Appling-Cecil complex occurred at 106 kg N ha⁻¹ side-dress N rate as compared to ≥ 130 kg N ha⁻¹ side-dress N rate on other lighter textured soils. Also the total profile mineral N on the Appling-Cecil complex was 131 kg N ha⁻¹ that is 48 kg N ha⁻¹ higher than the level in the Suffolk soil (Table 2).

Residual mineral-N present in the top 0.3 m of soil at planting is crucial in deciding whether or not starter-band N should be applied. In this study residual mineral N levels of >45 kg N ha⁻¹ in the top 0.3m of soil were found to be sufficient to support the crop growth until side-dressing. Optimum rate of starter-band-N fertilizer needed in combination with side-dress N applications to optimize grain yields would therefore depend on soil mineral-N at planting. Based on the data from these experiments, for soils testing high in mineral-N (≥ 50 kg N ha⁻¹ in the top 0.3 m of surface soil) at planting, zero starter-band-N should be applied in conjunction with side-dress-N applications of 130 kg N ha⁻¹. For soils testing low (<50 kg N ha⁻¹ in the top 0.3m of surface soil) in mineral-N at planting, starter-band-N supplement of 40 kg N ha⁻¹ in conjunction with 130 kg N ha⁻¹ side-dress N should optimize the sorghum grain yields under conditions similar to these studies.

The efficiency of pre-plant broadcast N applications as compared to starter-band-N plus side-dress N applications could not be evaluated extensively in this

study. Lack of yield response to N fertilization on four sites in 1995 and 1997, and to starter-band-N on three out of four sites in 1996, prevents any assessment of the efficiency of the fertilizer placement methods. However, the Suffolk fine sandy loam experiment conducted in 1996 showed that the grain yields response to broadcast N applications and starter-band applications were almost identical (Table 1). The average grain yield from starter-band N and broadcast N was 8.05 and 7.95 Mg ha⁻¹, respectively, suggesting that broadcast N applications were as efficient as band placed and side-dress N applications. This contradicts the findings reported in literature by other workers (Lamond, 1987; Sweeney, 1989; Malhi and Nyborg, 1990; Lamond and Whitney 1991; Lamond et al., 1991; Rao and Dao, 1996). However finding on Suffolk soil can probably be attributed to significant rainfall that occurred soon after planting and continued for the next several days. Consequently little or no NH₃ volatilization losses would be expected. The successfulness of broadcast N applications therefore greatly depends upon occurrence of rainfall. Chichester and Morrison (1995) reported similar results from their two-year study in Temple, TX. However, should there be a dry period after planting, volatilization losses would be significant and the broadcast efficiency would be low compared to starter-band N as reported in other studies (Lamond, 1987; Sweeney, 1989; Malhi and Nyborg, 1990; Lamond and Whitney 1991; Lamond et al., 1991; Rao and Dao, 1996).

Response surfaces describing the estimated profit due to N application as a function of N fertilizer rates at planting (starter-band) and side dressing are shown for four experimental locations (Figure 2). The highest point on the response surface for Suffolk soil (Figure 2a) corresponds to maximum estimated profit of \$341 ha⁻¹, obtained at a starter-band and side-dress N fertilizer combination of 39 and 135 kg N ha⁻¹ respectively. Figure 2 shows that there is an increasing trend in the yield response to applied fertilizer N for both starter-band and side-dress applications on Suffolk soil (Figure 2a). Conversely, on the Bojac soil there is a decreasing trend in the estimated

profit with the increase in the application rates of starter-band fertilizer (Figure 2b). Although grain yields were increasing with increasing starter-band rate, yield increases were not great enough to cover the cost of the added fertilizer N. However, each additional application of fertilizer N as side-dress application significantly increased the estimated profit. The highest point on the response surface corresponds to the maximum estimated profit of \$402 ha⁻¹ obtained in this experiment at starter-band and side-dress N fertilizer combination of 0 and 135 kg N ha⁻¹, respectively (Figure 2b). Similar trends in estimated profit as those reported for the Suffolk and Bojac soils were found for the Appling-Cecil complex and Wheeling soils, respectively (Figures 2c & 2d).

Non-responsiveness or negative-response of grain sorghum yields in four out of eight site-years of this study can be attributed to high levels of residual mineral-N present in the soil profile at planting. Also, erratic rainfall patterns that promoted early season luxuriant crop growth on low plant-available-water holding capacity soils caused severe water stress conditions later in the season. These conditions translated growth into early leaf senescence and poor head development and grain filling. Consequently the grain yields were lower and non-responsive to applied N fertilizer.

Residual mineral-N is usually neglected in the humid mid-Atlantic region in making fertilizer N recommendations due to the widely accepted perception that over-winter soil mineral-N losses are high, (Bundy and Malone, 1988; Gilliam and Boswell, 1984). However, residual soil mineral-N was found in significant amounts in the top 0-0.9 m of the soil profile at planting for four non-responsive sites. In light of the above mentioned results it would therefore be unwise to ignore soil residual mineral-N at planting. There were 147 and 112 kg of mineral-N ha⁻¹ in the Pamunkey and Conetoe soils, respectively, in 1995. Similarly there were 129 and 87 kg of mineral-N ha⁻¹ in the Atlee and Kempsville soils, respectively, in 1997. These high residual N levels probably reflect N that mineralized from the previous soybean crop. Mineral-N in the deeper (0.6 - 0.9m)

horizon could mostly have come from previous nitrogen applications. Lack of yield response to applied N is therefore reasonable in light of residual mineral-N levels that were present at these four sites at the time of planting. These agronomically significant levels of soil profile mineral-N warrant consideration in developing improved and more efficient N fertilizer recommendations for no-till grain sorghum production on sandy soils in Virginia. A system to incorporate soil mineral-N as an integral part of the N recommendation system for no-till grain sorghum is presented in Chapter 4 of this dissertation.

Nitrogen-use of crops under dryland conditions depends largely on plant-available-soil-water, which is a direct result of rainfall and soil texture. Both years 1995 and 1997, in which the research sites were non-responsive, were droughty. Total rainfall during the growing season was much below the 30-year average rainfall. Also, a significant proportion of rainfall (32% of the total) occurred within 28 days after planting (DAP) on the two sites in 1995, causing luxurious vegetative crop growth early in the season. Luxurious crop growth with high leaf area would be expected to have high water requirement. High demand for soil water by plants cause severe water stress. Grain sorghum yields were severely limited by plant-available-soil-water in 1995 (average yield $\sim 3.02 \text{ Mg ha}^{-1}$). A yield response of grain sorghum to applied-N was not observed and cannot be expected under these conditions.

The challenge with dryland grain sorghum production in Virginia therefore is to synchronize the plant N need with plant-available-water. This perhaps can be achieved by partitioning the N application of the crop into several doses. Apply little ($\leq 30 \text{ kg N ha}^{-1}$) or zero starter-band-N on soils testing high ($\geq 50 \text{ kg N ha}^{-1}$) in residual mineral-N at the time of planting, and later apply smaller amounts of side-dress N applications at various growth stages of the crop. This would restrict plants from accumulating excessive biomass early in the season and may perhaps reduce the risk of severe water stress later in the season. Side-

dress N in this experiment was applied at the eight-leaf growth stage that occurs about 35 DAP. Another period of rapid growth and nutrient uptake in sorghum occurs at the mid-bloom growth stage, around 60 days after emergence (Vanderlip, 1993). Should rainfall occur during this period, side-dress N application to the crop at mid-bloom stage can be applied with a high clearance applicator. Although the window of opportunity that exists at this stage is relatively short, it could promote proper head development, and enhance grain yield and N-use efficiency of the crop. To evaluate this hypothesis, another study was conducted in 1996 and 1997, on five experimental sites and is presented in Chapter 3 of this dissertation.

CONCLUSIONS

Climatic conditions over 3 years of research work were variable. Two out of three years were droughty. This is not atypical of the climatic conditions of Virginia in the last 10 to 15 years. Grain yields on eight different study sites varied from 1.7 Mg ha⁻¹ to 11.9 Mg ha⁻¹. The sorghum crop was highly responsive to N fertilizer applications at three sites, moderately responsive at one site, non-responsive at two sites, and negatively responsive at two study sites.

Optimum rate of starter-band-N fertilizer needed in combination with side-dress N applications to optimize grain yields depends on soil residual mineral-N at planting. Little or zero starter-band-N should be applied in conjunction with side-dress-N applications of 130 kg of N ha⁻¹ for soils testing high in mineral-N (≥ 50 kg N ha⁻¹ in the top 0.3m of surface soil) at planting. A starter-band-N supplement of 40 kg N ha⁻¹ in conjunction with 130 kg N ha⁻¹ side-dress N should optimize the sorghum grain yields for soils testing low in mineral-N at planting. In the presence of significant levels of soil mineral-N (≥ 50 kg N ha⁻¹ in the top 0.3m of surface soil) at planting, sorghum has responded consistently well to later side-dress N applications. The challenge therefore is to synchronize the N applications with plant N need in conjunction to plant-available-soil-water.

Lack of yield response to N fertilization on four sites in 1995 and 1997, and to starter-band-N on three out of four sites in 1996, prevents any assessment of the efficiency of the fertilizer placement methods on seven site-years. However, broadcast N applications were as efficient as band placed and side-dress N applications at one experimental site at which rainfall occurred soon after planting.

Non-responsiveness of grain sorghum yields at four site-years of this study was mainly due to high levels ($> 85 \text{ kg N ha}^{-1}$) of soil profile residual mineral-N, and severe water stress conditions on low plant-available-water holding capacity of soils. Based on the results obtained in this study it would be prudent to utilize soil profile mineral-N at the time of planting. Agronomically significant levels of soil profile mineral-N warrant consideration in developing improved and more efficient N fertilizer recommendations for no-till grain sorghum production on sandy soils in Virginia.

Sorghum grain yield of 4.0 Mg ha^{-1} in an extremely dry year (1997) and 8.9 Mg ha^{-1} in an adequate rainfall year (1996) and the estimated profit associated with N fertilization are encouraging to the growing of grain sorghum. Grain sorghum therefore has potential to be used as an alternative grain crop to corn on low water holding capacity soils in Virginia.

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