Determination and Manipulation of Leaf Area Index to Facilitate Site-Specific Management of Double-Crop Soybean in the Mid-Atlantic, U.S.A.

by

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In

Crop and Soil-Environmental Science

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Determination and Manipulation of Leaf Area Index to Facilitate Site-Specific Management of Double-Crop Soybean in the Mid-Atlantic, U.S.A.

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(Abstract)

Double cropping soybean after small grain harvest does not always allow sufficient canopy growth to maximize photosynthesis and seed yield. This is due to a shorter growing season and moisture deficits common to the Mid-Atlantic USA. Leaf area index (LAI) is the ratio of unit leaf area of a crop to unit ground area and is a reliable indicator of leaf area development and crop biomass. An LAI of 3.5 to 4.0 by flowering is required to maximize yield potential. Soybean LAI will vary within and between fields due to soil differences, cultivar selection, and other cultural practices. Site-specific management strategies such as varying plant population may be used to manipulate LAI and increase yield in leaf area-limited systems. Furthermore, methods to remotely sense leaf area are in order to facilitate such management strategies in large fields. The objectives of this research were to: i) determine the effect of plant population density on soybean LAI and yield; ii) determine the relationship between LAI measured at different reproductive stages and yield; iii) investigate and validate relationships between LAI and yield for two cultivars in three crop rotations across varying soil moisture regimes; iv) validate relationships found in previous work between soybean LAI and yield across soil moisture regimes in grower fields; and v) determine if normalized difference vegetation index (NDVI) values obtained from aerial infrared images can be used to estimate LAI and soybean yield variability. Increasing plant population increased LAI for cultivars at Suffolk in 2000 and 2001, but LAI increased with plant populations on soils with lower
plant available water holding capacity (PAWHC) at Port Royal in 2001. In 2000 at Suffolk, seed yield increased quadratically with increasing population and cultivar did not affect the response. In 2001, no relationship occurred between yield and plant population at either Suffolk or Port Royal, but the relationship of yield and LAI depended on soybean development stage at both sites. However, this relationship was not consistent between sites or years. In another study, crop rotation affected LAI and yield one out of two years. However, LAI and yield in both study years were negatively impacted on soil types with lower PAWHC. Where significant, a linear relationship was observed between yield and LAI for all soil types. Studies on grower fields showed similar linear relationships between yield and LAI. Remote sensing techniques showed promise for estimation of LAI and yield. When obtained at an appropriate development stage, vegetation indices correlated to both LAI and yield, and were observed to be effective as a predictor of LAI until plants achieved LAI levels of 3.5 to 4.0.
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Chapter 1 – Introduction and Justification

One of the most important commodities in Virginia is soybean (*Glycine max* (L.) Merr.). Soybean is planted on approximately 200,000 ha in Virginia with production exceeding 480,000 metric tons in 2000 (yielding an average of 2420 kg ha\(^{-1}\)). In 2000, soybean was the third most valuable row crop in Virginia, with total receipts of approximately $80 million (Virginia Agricultural Statistics Service, 2000).

Over one-half of Virginia’s soybean planting follows harvest of wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.), and is rotated with corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and peanuts (*Arachis hypogaea* L.). The ability to harvest three crops in two years, made possible by double-cropping soybean after small grains, has allowed Virginia producers to remain competitive in the world. However, this rotation restricts maximum potential yield of soybean by creating a shorter growing season. Furthermore, double-crop plantings frequently experience vegetative drought stress due to lower soil moisture reserves. Except in years of above average rainfall in July and August, double-crop soybean growth is reduced compared to full-season plantings.

The extent of soybean canopy development can be monitored using leaf area index (LAI), which is defined as the unit area of leaves per unit area of soil surface, and has been accepted as a method to quantify the amount of soybean canopy (Shibles and Weber, 1966). Soybean canopy is important for a variety of reasons, including light interception, photosynthesis, and biomass accumulation (Shibles and Weber, 1966; Klubertanz et al., 1996). Through these mechanisms there is a correlation between the
LAI of the canopy and yield. Previous research has shown the relationship of yield and LAI to be linear at the beginning pod (R3) to beginning seed (R5) development stage (development stages according to Fehr and Caviness, 1977) up to an LAI of approximately 3.5 to 4.0 (Hunt et al., 1994). After this level is reached, yield is not usually responsive to further LAI increases. Sharma et al. (1982) described a positive and highly significant correlation between net assimilation rate, LAI, and yield from time of pod development to physiological maturity. Reddy and Saxena (1983) conducted an experiment consisting of six soybean varieties on a clay loam soil in India, measuring LAI, leaf area ratio, and several other growth indicators. They saw a positive and significant correlation between LAI (at 20, 40, and 60 days after sowing) and grain yield and concluded that improvements in yield may be accomplished by increasing leaf area.

Typically, full-season soybean is able to attain the necessary LAI level required for maximum yield due to their longer growing season. Board and Hall (1984) found that full-season soybean was able to consistently reach the necessary 95% light interception required to maximize photosynthesis. Double-crop soybeans however are often unable to reach the critical leaf area for 95% light interception, usually at an LAI of 3.5 to 4.0 (Board and Hall, 1984). A number of cultural practices have been shown to increase the LAI of double-cropped soybean. Plant population and row spacing can affect leaf area and yield (Shibles and Weber, 1966; Boquet, 1990; Board and Harville, 1992). Determining the minimum population required to reach an optimum LAI and maximize yield for a specific environment is an economically important decision because seed cost can affect soybean profitability. Herbert and Litchfield (1984) used growth analysis techniques to look at the physiological basis of increased seed yield among narrow rows
and varying populations. Seed yield was increased 31% and 16% by decreasing the row width from 75 to 25 cm and 50 to 25 cm, respectively. They determined that narrow rows (25 cm) with higher densities (80 seeds m$^{-2}$) produced both higher LAI and more dry matter than narrow rows with lower densities (25 seeds m$^{-2}$), regardless of the yield loss that occurred from lodging at the higher densities. The increase in biomass production from the highly populated, narrow-row soybean occurred due to the timely closure of crop canopy that maximized light interception.

Work by Shibles and Weber (1966) in Iowa showed that optimal yield was obtained when the LAI was sufficient to reach approximately 95% light interception by the R5 development stage. In order to reach 95% light interception, however, plant population may have to be varied across different environmental conditions, i.e. the PAWHC of a soil. The PAWHC of a soil is an especially important consideration, because it is key to the amount of water available for the plant. Sandier soils may be unable to hold enough water for optimum soybean canopy development in many years in some environments.

The level and timing of moisture stress are important considerations for achieving maximum LAI (Ashley and Ethridge, 1978; Momen et al., 1979; Foroud et al., 1993). This may be especially important for double-crop soybean in the Mid-Atlantic, which may experience LAI-limiting drought stress during the R5 development stage due to lower levels of PAWHC brought about by high transpiration rates and low precipitation in July and August.

Knowledge of soil potential to provide available water to maximize LAI has promise to become a decision-making tool for producers to increase production efficiency through better planting strategy. The rate of leaf area development will change over soil moisture
regimes; therefore it will be necessary to know the relationship between soil moisture levels and LAI values. Unfortunately, there are several constraints that must be taken into consideration. Measurement of LAI is currently limited to research settings due to the high cost of the equipment, the labor intensity and the time required to take adequate readings. Time, labor, and equipment costs to intensively map soils, measure soil water content, and measure LAI across a field are barriers to determining soil-moisture/LAI relationships (Schnug et al., 1998). Remote sensing through aerial photography may provide a relatively inexpensive means of measuring LAI across a broad expanse.

Remote sensing research was conducted in Spain with durum wheat (*Triticum turgidum* L. subsp. *durum* (Desf.) Husn.), initially to provide a simpler method of genotype selection for breeding purposes (Aparicio et al., 2000). Utilizing infrared imaging techniques, these researchers calculated several spectral indices that were found to correlate strongly with LAI readings from the wheat. Research at North Carolina State University also examined aerial images and vegetation indices for tiller count estimates in soft red winter wheat (*Triticum aestivum* L.). Strong correlations were seen between tiller counts and spectral indices (Flowers et al., 2001). Correlations between spectral indices and LAI for soybean may also be possible. Remote sensing has also been utilized for soil type identification (Vanoverstraaten and Trefois, 1993; Ameskamp, 1997) and to reveal differences in soils and crops (Johannsen and Berglund, 1997) at a fraction of the cost of performing these operations on the ground.

This research focuses on viable options to effectively increase canopy coverage through manipulating leaf area in order to improve double-crop soybean yield through site-specific management. Specifically, the objectives of this experiment were to:
1. Determine the effect of plant population density on soybean LAI and yield;

2. Determine the relationship between soybean LAI measured at different reproductive development stages and yield;

3. Investigate and validate relationships between LAI and soybean yield for two soybean cultivars in three crop rotations across varying soil moisture regimes;

4. Validate, across soil moisture regimes in grower fields, relationships found in previous work between soybean LAI and yield;

5. Determine if NDVI values obtained from aerial infrared images can be used to estimate double-crop reproductive stage soybean LAI and yield variability.
REFERENCES


Chapter 2 - Double-crop Soybean Yield and Leaf Area Index

Responses to Multiple Plant Populations

ABSTRACT:

Leaf area index (LAI) of soybean \textit{Glycine max} (L.) Merrill] is related to yield in leaf area limited cropping systems. Double-crop soybean planted after small grains are often unable to develop the necessary canopy required for maximizing yield. It may be possible to increase yield of double-crop soybean by quickly obtaining full canopy coverage, as measured by LAI, via increasing plant density. The specific objectives of this research were to i) determine the effect of plant population density (PPD) on LAI and yield; and ii) determine the relationship between LAI measured at different reproductive stages and yield. Field studies were conducted in 2000 and 2001 in Suffolk VA on a Eunola sandy loam (fine-loamy, siliceous, thermic, Aquic Hapludults); and in Port Royal, VA on a Tarboro sand (mixed, thermic, Typic Udipsamments), a Bojac loamy fine sand (coarse-loamy, mixed, thermic, Typic Hapludults), and a Wickham loamy sand (fine-loamy, mixed, thermic, Typic Hapludults). An indeterminate maturity group (MG) III and a determinate MG V cultivar were planted to obtain final plant populations ranging from 120 to 815 thousand plants ha$^{-1}$. Increasing PPD from 120 to 815 thousand plants ha$^{-1}$ increased LAI by as much as 3.5 units for both cultivars in 2000 and 2001 at Suffolk. At Port Royal, LAI increased 0.3 to 0.4 units per 100 000 plants for the Tarboro and Bojac soils, but PPD did not affect LAI for the Wickham soil. Seed yield increased quadratically with PPD in 2000 at Suffolk, and maximum yield was reached at 494 thousand plants ha$^{-1}$. In 2001, neither cultivar nor PPD affected yield at Suffolk. At Port
Royal, higher yields were reflected by soils with higher plant available water holding capacity (PAWHC), but yield did not respond to PPD on any soil type. The relationship between yield and LAI was inconsistent among sites, but resulted in a linear relationship that increased yields 200 to 800 kg ha\(^{-1}\) for every unit increase in LAI. Only at the R2 development stage at Suffolk in 2000 did linear-plateau models describe the data. In these cases, LAI increased linearly until a level of 2.7 and 3.8 was reached for the MG III and MG V cultivar, respectively.
Double-crop Soybean Yield and Leaf Area Index

Responses to Multiple Plant Populations

Double-crop soybean planted in the Mid-Atlantic U.S.A. following winter wheat (Triticum aestivum L.) or winter barley (Hordeum vulgare L.) often produces lower yields than full-season plantings (Holshouser, 2001). Full-season soybean, due to earlier planting dates and a longer growing season, typically acquire the necessary vegetative growth for complete canopy coverage (Ball et al., 2000). Soybean sown following small grain harvest in a double-crop system frequently do not develop a closed canopy due to a shorter growing season and later planting date (Kane et al., 1997).

Canopy closure is prerequisite for maximal seed yield (Shibles and Weber, 1966). Greater canopy density enables a higher percentage of sunlight to be intercepted and converted into yield through photosynthesis. Because full-season soybean develops complete canopy coverage earlier than double-cropped soybean, a longer time period is available for maximum sunlight interception, and therefore a higher yield potential exists for full-season soybean (Board and Harville, 1992).

Increasing PPD affects canopy development in double-cropped soybean. Using higher PPD in narrower rows minimized yield losses from excessive delays in canopy closure in double-cropped systems, except where lodging occurred, (Ball et al., 2000). Herbert and Litchfield (1984) examined the growth responses of short-season soybean to variations in row spacing and plant density. They observed significantly greater accumulation of biomass and canopy density with increased plant densities. Other authors have noted relationships between increasing PPD and increasing yield of soybean. Boquet (1990)
concluded that for post-optimal planting dates, PPD above that required for optimal planting dates were needed to obtain the highest yields.

A measure of the density of canopy coverage for soybean is leaf area index (LAI). Leaf area index is defined as the ratio of unit leaf area of the crop to unit soil surface area (e.g. for an LAI of 3.5, there are 3.5 m$^2$ of leaves m$^{-2}$ of soil surface). Leaf area index has been shown to be a reliable predictor of crop yield. Shibles and Weber (1966) correlated LAI to dry matter production regardless of planting pattern. They concluded that maximizing light interception (LI) during seed formation is required for maximum yield.

An experiment on a clay loam soil in India measured LAI, crop growth rate, and other crop growth indicators (Reddy and Saxena, 1983). The authors observed a positive correlation of biomass with grain yield and correlation of LAI to grain yield 20, 40, and 60 days after sowing. Sharma et al. (1982) observed that yield plant$^{-1}$ was positively and highly correlated with LAI at time of pod development and at physiological maturity. However, they observed no relationship between yield and LAI at the vegetative and flowering stages.

Loss of LAI through defoliation has been observed to influence soybean yield. Seedling defoliation treatments resulted in soybean seed yield decreases of up to 12% (Hunt et al., 1994). The authors believed this to be a result of the failure of the soybean to reach the critical LAI of 3.5 until well into their reproductive stages, resulting in less LI and less dry matter accumulation. Another study experimented with defoliation at differing development stages (Klubertanz et al., 1996). Results indicated that leaf area remaining was a better indicator of final yield than leaf area removed. The authors observed a quadratic response of yield relative to increasing LAI. Biomass removal by
clipping resulted in a negative linear relationship with yield, and yield was observed to be lower at later clipping dates and with more frequent clipping (Singer, 2001). Malone (2001) observed a linear-plateau response of soybean yield to LAI and showed that defoliation of reproductive-stage soybean below a critical LAI of 3.5 to 4.0 caused significant decreases in seed yield. The critical LAI was determined by the point in the model, called the join point, at which yield began to decrease linearly.

The amount of light intercepted by a canopy is a function of LAI. Early research by Shibles and Weber (1965) demonstrated the obvious dependence of solar radiation interception on LAI. They observed that percent light interception (LI) increased with leaf area development of the plant communities and approached a maximum asymptotically. They defined the point of 95% LI to be the critical LAI level. Another study determined an effective LAI for a plant community to be that LAI which intercepts 90% of the available light (Sakamoto and Shaw, 1967). Jeffers and Shibles (1969) confirmed a photosynthesis response to LAI, stating that in an environment of low solar radiation, a genotype that terminates leaf production at the critical LAI would have an advantage in seed production over a genotype that produces excess foliage. Furthermore, these researchers recommended selection of genotypes and cultural methods that maximize LAI fastest in order to maximize seed yield. More recent research examining the critical LAI level concluded that the point of 90% LI occurs at an LAI of approximately 3.5 to 4.0 in soybean (Hunt et al., 1994). These authors stated that this critical level was established at approximately the beginning bloom (R1) development stages (based on scheme of Fehr and Caviness, 1977), above which point the rate of dry
matter accumulation does not increase. Board and Harville (1992) concluded that attaining LAI of 3.5 to 4.0 by development stage R1 is necessary to optimize yield.

It may be possible to increase the final grain yield of double-cropped soybeans by quickly and efficiently obtaining full canopy coverage via increasing the plant density. Furthermore, the development stage at which full canopy coverage for double-crop soybean is needed has not been clearly determined. The objectives of this research were to i) determine the effect of plant population density on soybean LAI and yield; and ii) determine the relationship between soybean LAI measured at different reproductive development stages and yield.

MATERIALS AND METHODS

Field studies were conducted in 2000 and 2001 on a Eunola sandy loam (Fine-loamy, siliceous, thermic, Aquic Hapludults) at the Tidewater Agricultural Research and Extension Center in Suffolk, Virginia (36°39’ N, 76°44’ W). An indeterminate maturity group (MG) III Southern States (Southern States Cooperative, Richmond, VA) cultivar RT-3975 and a determinate MG V Southern States cultivar RT-557N were planted no-till into wheat stubble on 5 July in 2000 and 26 June in 2001. Sufficient seeds were planted to obtain a final plant population of 123, 247, 371, 494, and 618 thousand plants ha$^{-1}$ in 2000 and 148, 222, 296, 370, 444, 519, 592, 667, 740, and 815 thousand plants ha$^{-1}$ in 2001. Plot size was five, 38-cm wide rows by 5-m long. Fertilizer was applied according to soil test recommendations, and weeds and insects controlled based on frequent scouting.
Experimental design was a randomized complete block in a split-plot arrangement with twelve and three replicates for 2000 and 2001, respectively. Main plots were soybean cultivar, and sub-plots were soybean population. In 2000, PPD was measured by counting the number of plants in 1 m of row at harvest. In 2001, in addition to the PPD determination at harvest, PPD was determined 25 days after planting (DAP) by placing an 85-cm diameter circular frame randomly two times into each plot, and counting the number of plants that fell within the frame. No PPD difference was observed between these two methods.

Leaf area index measurements were obtained with the LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE) at 35, 50, and 66 DAP in 2000, and 41, 55, 70, and 86 DAP in 2001. Leaf area index for each plot was determined from the average of four sets of LAI measurements. Each set of LAI measurements consisted of five readings. The first was a reading above the canopy to measure the total light the canopy was receiving. The remaining measurements took place below the canopy. The first reading was within the row, the second was in a diagonal transect approximately 25% of the distance to the adjacent row, the third reading fell in the middle of the two rows or 50% of the distance from the initial reading, and the final reading was approximately 75% of the distance from the initial within-row reading.

Leaf area index measurements were taken from sunrise until 1000 h, or 1500 h until sunset, either under complete cloud cover or with artificial shade provided by a 4 m by 2 m blue tarpaulin stretched onto a polyvinyl chloride rectangular frame held at an angle to shade the plots from the sun. The LAI measurements were taken in a manner such that the fish-eye detector lens never observed the frame. An opaque lens cap with a 45° view
opening was used to restrict the viewing space of the lens and to prevent the operator or frame from being detected. The four sets of LAI measurements that made up the mean LAI for each plot were taken with the view opening facing two directions: two measurements perpendicular to the rows and two measurements parallel to the row. This ensured accurate representation of the actual LAI of the plot. The above methods have been shown to accurately represent soybean LAI (Welles and Norman, 1991).

Soybean was harvested with a small-plot combine equipped with moisture tester and data logger 133 and 140 DAP in 2000 for the RT-3975 and RT-557N cultivars, respectively. In 2001, soybean were harvested 115 and 127 DAP for the RT-3975 and RT-557N cultivars, respectively. Yield, adjusted to 130 g kg$^{-1}$ moisture content, was measured by harvesting the three interior rows of each plot that had been end-trimmed to 5 m. Combined seed yield was converted to an area basis.

A separate study was initiated in 2001 at a private cooperator’s farm located near Port Royal, Virginia (38°09’ N, 77°08’ W). An indeterminate soybean cultivar, Southern States RT-3975 (MG III) was planted on 5 July 2001 into barley stubble on land containing three soil types: a Tarboro sand (Mixed, thermic, Typic Udipsammments), a Bojac loamy fine sand (Coarse-loamy, mixed, thermic, Typic Hapludults), and a Wickham loamy sand (Fine-loamy, mixed, thermic, Typic Hapludults). These soil types have different PAWHC: 5.0 cm m$^{-1}$ for the Tarboro, 7.3 cm m$^{-1}$ for the Bojac, and 11.8 cm m$^{-1}$ for the Wickham (USDA-NRCS Soil Survey Division, 2000 [Online]). Within each soil type, sufficient seeds were planted to obtain a final plant population of 297, 371, 445, 519, and 593 thousand plants ha$^{-1}$. Plot size was five, 38-cm wide rows by 7.3 m long.
Experimental design was a randomized complete block within each soil type. The five plant population treatments were replicated two times for the Tarboro, three times for the Bojac, and four times for the Wickham soil types. The different number of replications resulted from errors made in assigning planting treatments. Plant population was determined 25 DAP by counting the number of plants within an 85-cm diameter circular ring placed at two random locations within each plot. Leaf area index measurements were taken at 48 and 62 DAP by taking the average of four sets of readings within each plot, using the method previously described.

Soybean were harvested 103 DAP with a small-plot combine equipped with moisture tester and data logger. Yield, adjusted to 130 g kg<sup>-1</sup> moisture content, was measured by harvesting the three interior rows of each plot that had been end-trimmed to 5 m. Combined seed yield was converted to an area basis.

The MIXED procedure of SAS (SAS Institute, 1997) was utilized to examine significance of main effects and their interactions. The MIXED procedure uses a mixed linear model which permits data to exhibit correlation and non-constant variability, and can model not only the means of the data but their variances and covariances as well. The LSMEANS statement was used to compute the least-squares means of the fixed effects. The PDIFF option of the LSMEANS statement was used to request that the differences in LS-means be displayed for comparison. Leaf area index measurements were taken over time from the same experimental units, therefore the REPEATED statement within the MIXED procedure was used to test hypotheses about the LAI factors, and the interactions of LAI factors with PPD and yield. Mean separations were considered significant if p-values were ≤ 0.05.
The REG procedure of SAS (SAS Institute, 1997) was utilized to determine relationships between PPD and LAI, PPD and yield, and LAI and yield. A non-linear model known as a linear-plateau model was also tested using the NLIN procedure and the NEWTON method. The linear-plateau model is a manifestation of Liebig’s law of the minimum where the rate of change in plant responses to changes in the availability of a nutrient is constant until some concentration is reached at which other nutrients become limiting and the response attains a plateau (Schabenberger and Pierce, 2002). Linear-plateau models may also be applicable to the relationship of soybean yield to LAI (Malone, 2001). These models calculate the point at which the relationship is no longer linear, and this point is called the join point of the model. Significance of both the linear and non-linear regression models were tested, and models with the strongest coefficients of determination were fitted to the data.

RESULTS AND DISCUSSION

Figure 2.1 shows the LAI response of RT-3975 and RT-557N cultivars to variations in PPD at three developmental stages in 2000. Soybean LAI increased quadratically with PPD for both the RT-3975 and the RT-557N cultivars in 2000. LAI for the earlier maturing cultivar (RT-3975) increased until a population of 494 000 plants ha\(^{-1}\) was reached. Above this population, no significant increase in LAI was observed regardless of measurement date. A similar trend was observed for the later-maturing soybean (RT-557N). Although LAI of RT-557N was lower than RT-3975 at the earliest measurement date (Fig. 2.1a), no differences between cultivars were observed at the R2 and R3 stages (Fig. 2.1b), and the measured final leaf area of RT-557N was greater than the earlier-
maturing variety at all populations (Fig. 2.1c). No further increases in LAI were observed after the beginning pod development stage (R3) for any PPD with RT-3975 in 2000. However, LAI of RT-557N increased until late pod development stage (R4). The data are insufficient to show the development stage at which further LAI increases ceased since no measurements were taken after this stage. Leaf area index measurements taken at more frequent intervals may have shown a more detailed relationship.

In 2001, LAI was measured four times throughout the growing season for both cultivars (Fig. 2.2). Unlike 2000, LAI in 2001 responded linearly for both cultivars to increases in PPD except at the third and fourth measurement date, where no significant relationship could be detected due to variability in the data (Fig. 2.2c and d). At the initial measurement dates, cultivar did not affect LAI response to PPD and there was no difference between the LAI of the two cultivars (Fig. 2.2a and b). The RT-3975 cultivar began to experience a loss of leaf area during the full seed (R6) development stage, primarily due to crop senescence. The later-maturing RT-557N cultivar maintained a higher leaf area over time (leaf area duration) than the RT-3975 cultivar.

Increasing plant population increased yield for both cultivars in 2000 (Fig. 2.3a). In 2001, cultivar did not affect the response of yield to PPD and there was no difference between yield of the two cultivars. Yield increased in 2000 until a population of 494 000 plants ha\(^{-1}\) was reached. Above this population, no increase in yield was observed. These results tend to support previous research (Boquet, 1990; Ball et al., 2001); where increased yields of late-planted soybean were observed with increased PPD. However, in 2001, yield did not increase with increasing PPD (Fig. 2.3 b). Although LAI response to PPD was very similar between years during the first two measurement dates, the
similarity disappeared at the third measurement date (Fig. 2.1 and 2.2). More leaf area was obtained by R4 and R5 for RT-3975 and RT-557N, respectively, at the lowest PPD of 148,000 plants ha\(^{-1}\) in 2001 (Fig. 2.2c) than at this PPD in 2000 (Fig. 2.1c). This higher LAI may be partly responsible for the higher yields at lower PPD in 2001, and contributed to the lack of response of yield to PPD.

The relationship of soybean yield to LAI gives further insight into the yield response to PPD. Figures 2.4 and 2.5 show the relationship of yield to LAI for RT-3975 and RT-557N, respectively, at three development stages in 2000. LAI was measured at full bloom (R2), beginning pod (R3), and beginning seed (R5) stages for RT-3975, and late vegetative (V6), R2, and full pod (R4) stages for RT-557N. The relationship of yield to LAI of RT-557N at the V6 stage was linear, but by the R2 stage, both cultivars exhibited a linear-plateau relationship (Fig. 2.4a and 2.5b). This indicated that both cultivars reached an LAI at R2 that no longer limited yield. This LAI level, indicated by the join point of the model, was 2.71 and 3.83 for RT-3975 and RT-557N, respectively. Although the critical LAI level observed with RT-557N concurs with past research (Shibles and Weber, 1966; Hunt et al., 1994), a join point of 2.71 does not reflect values reported in the literature. As the crop matured to the R3 and R4 development stages for RT-3975 and RT-557N, respectively, the relationships became linear (Fig. 2.4b and 2.5c).

The model change from linear-plateau to linear can be related to the rate of LAI increase between development stages. Across the range of plant populations for both cultivars in 2000, the rate of LAI increase as the crop matured depended on PPD (Fig. 2.6a). For RT-3975, the rate of LAI increase between the R2 and R3 development stages
was faster at populations above 123,000 plants ha\(^{-1}\). However, as the crop matured from the R3 to R5 development stages, the rate of change became constant. This resulted in a LAI-dependent shift of data points along the x-axis from the R2 to R3 stage (Fig. 2.4a and b). Greater change in LAI for the higher PPD resulted in a mathematical transformation of the LAI:yield relationship from linear-plateau to linear (Fig. 2.4a and b). LAI did not change between R3 and R5 (Fig. 2.6a); therefore little change in the LAI/yield relationship occurred between these measurement dates (Fig. 2.4b and c).

The rate of LAI change between V6 and R2 for RT-557N was similar to the change between R2 and R3 for RT-3975 (Fig. 2.6b). The rate of increase in LAI was greater at higher PPD. This unequal change in LAI caused the data points to spread out among the x-axis and a linear plateau relationship was formed. The linear-plateau relationship accounted for more of the data variability (\(r^2 = 0.66\)) than the linear model that poorly related yield to LAI at V6 (\(r^2 = 0.44\)). It also indicated that maximum yield was reached with an LAI of 3.83 (Fig. 2.5b). But, between the R2 and R4 measurement dates, LAI for the lower PPD treatments increased at a faster rate than for the higher PPD treatments, as indicated by mean separation (Fig. 2.6b). Shifting the data points of the lower PPD to higher LAI levels while LAI of the higher PPD remained the same caused the relationship between yield and LAI to once again become linear.

Although the MG V data (Fig. 2.5b) support past research indicating that yield is optimized if an LAI of 3.5 to 4.0 is obtained by flowering (Board and Harville, 1992), yield was optimized at a much lower LAI for the MG III cultivar (Fig. 2.4a). Furthermore, although relationships between yield and LAI exist, additional investigation is needed on how these relationships change with development stage.
In 2001, yield generally increased with increasing LAI in a linear fashion for both cultivars at all measured development stages, except R5 and R4 for the RT-3975 and RT-557N cultivars, respectively, where the relationship was not significant (Fig. 2.7c and 2.8c). A critical LAI level at which no further yield increases occurred was not evident at any development stage for either cultivar.

Although a linear equation described the RT-3975 data, the fit was poor at R2 and R4 and non-existent at R5 (Fig. 2.7). Compared to 2000, the slope of this response was half or less. This is consistent with the lack of response of LAI at R5 or R6 and yield to PPD (Fig. 2.2 and 2.3). Because PPD had little effect on LAI or yield, the poor relationship between LAI and yield would be expected. Still, a significant relationship between yield and LAI indicated that LAI is a better indicator of yield than PPD. Furthermore, the linear relationship of yield to LAI for RT-3975 is reasonable since LAI levels at the R2 stage were generally less than the critical 3.5 to 4.0 levels reported in the literature at this development stage (Fig. 2.7a). The rate of change in LAI for all PPD remained constant between the remaining measurement dates; therefore the response changed very little. By R6, LAI decreased substantially due to beginning crop senescence, the slope of the curve increased by over 200 kg ha\(^{-1}\) per unit LAI, and the fit of the data as indicated by \(r^2\) was much better (Fig. 2.7d).

RT-557N did reach a LAI of 3.5 to 4.0 by the R2 development stage for several PPD in 2001 (Fig. 2.2b and 2.8b), but yield did not plateau at the higher LAI levels. The lack of a linear-plateau response at higher LAI levels may be related to an early frost that occurred on 9 October, causing some early leaf senescence (visually estimated at 10 – 20%) at the mid-R6 stage. It is possible that soybean yield did not decrease for those
soybean plots with higher LAI, especially those that had reached the critical LAI level of 3.5 to 4.0 by R2 and maintained adequate LAI after the frost to prevent yield losses. Malone (2001) determined that any leaf area above the critical 3.5 to 4.0 LAI level did not contribute to yield, therefore defoliation, whether via insects or frost, would not decrease yield in those cases of excess leaf area. If 20% of the leaves were removed by frost from plots with an LAI of 5.0, then an adequate LAI of 4.0 would still remain; yield would not be expected to decline. On the other hand, the same amount of defoliation to plots with an LAI of 4.0 would cause the leaf area to drop below the critical level, lowering yield. Lowering the yield of plots with lower LAI while the yield of the plots with higher LAI remained unchanged may cause the relationship of soybean yield to LAI at R2 to change from linear-plateau to linear. Therefore, the concept of a critical LAI level (Board and Harville, 1992; Shibles and Weber, 1966; Hunt et al., 1994) cannot be necessarily dismissed due to these data.

Figure 2.9 shows the LAI response of RT-3975 to PPD for a Tarboro sand, Bojac loamy sand, and Wickham fine sandy loam near Port Royal, VA in 2001. For all PPD, LAI was greater for the Wickham soil than for either the Bojac or Tarboro soil types. At both the late vegetative (V4) and beginning pod (R3) development stages, LAI increased with increasing PPD for the Bojac and Tarboro soils, but PPD did not affect LAI on the Wickham. For all soil types, LAI was observed to increase between the V4 and R3 development stages.

Plant population density had no affect on yield at Port Royal in 2001 (Fig. 2.10). Within each of the five plant population treatments, the Wickham soil had a significantly higher yield than either the Bojac or Tarboro soils.
A significant, but weak ($r^2 = 0.20$ to 0.40) linear relationship between yield and LAI existed (Fig. 2.11). Although yield and LAI differences existed between soil types, no differences in the slope of the yield:LAI relationship could be discerned via regression analysis. The LAI and yield differences were primarily due to PAWHC differences. The Wickham had the greater PAWHC and the crop was able to utilize this stored water for longer periods throughout their growing season. Although LAI was greater than 3.5 for most PPD at V4 and for all PPD at R3, soybean yield on the Wickham soil was not observed to plateau at any LAI measurement. These data were similar to the case of RT-557N at Suffolk in 2001. However, in this instance, the early frost should not have affected the results because the RT-3975 cultivar at Port Royal was mature when the frost occurred. Although a linear-plateau response or a critical LAI level have been documented in the literature, these data indicate that such a response may not occur in all situations. In addition, when a response occurred, it only occurred at one development stage.

**CONCLUSIONS**

Three experiments over two study years measured inconsistent relationships between double-crop soybean LAI, plant population, and yield. In Suffolk, increasing plant population increased LAI for both soybean cultivars RT-3975 and RT-557N and higher populations were able to reach a LAI of 3.5 to 4.0 earlier. This level has been reported to be the level above which no further yield increases occur. Likewise, LAI increased with increasing PPD for cultivar RT-3975 at Port Royal for two of three soil types. Although
LAI did not increase with increasing PPD for the Wickham soil, which had the highest PAWHC, LAI was above 5.0 by the R3 stage, regardless of PPD.

Soybean yield increased with increasing plant population in a quadratic fashion and maximum yield was reached at 494 000 plants ha\(^{-1}\) at Suffolk in 2000. But in 2001, yield was not affected by PPD. Relatively higher LAI for the lower PPD is likely the reason for the lack of response of yield to PPD. However, LAI levels could not always account for lack of response in all locations.

The relationship between soybean yield and LAI was inconsistent among study sites in 2000 and 2001. At Suffolk in 2000, yield of both the MG III and V cultivars responded to LAI in a linear-plateau fashion by the R2 development stage. However, at later development stages, the models became linear. This model change from linear-plateau to linear was likely due largely to PPD-dependent increases in LAI between measurement dates. Because of this, one should not necessarily assume that there is a critical LAI level in which no further increases in yield would occur. As these data reflect, the dependence of yield on LAI is related to the development stage in which LAI is measured. In addition to this phenomenon, the relationship between yield and LAI was linear at both locations on all soils in 2001. Yield was not observed to plateau at any LAI level. This could be explained by the lack of the MG III cultivar to reach an LAI greater than 3.5 to 4.0, an early frost affecting the MG V results, or data variability. But, the lack of a clearly defined critical LAI level leads this author to conclude that LAI alone measured at a specific development stage may not be the only factor controlling yield of leaf area limited soybean systems. Soils and MG were shown to affect this relationship in these experiments.
Further study investigating the effects of PPD on LAI and yield across varying environmental conditions will be necessary before site-specific recommendations for PPD can be made. Studies need to account for differences in soil plant available water, precipitation, and evapotranspiration. The relationships between soybean seed yield and LAI must be measured for more environments in order to determine the LAI levels at which no further yield increases occur. Also, more frequent observations of LAI will be needed to determine the most appropriate growth stages to measure the relationship of LAI and yield.
REFERENCES


Fig. 2.1 a, b, and c. LAI response of two soybean cultivars to plant population at three developmental stages in 2000 at Suffolk, VA. Vertical bars represent ± standard error of the mean.
Fig. 2.2 a and b. LAI response of two soybean cultivars to plant population at two developmental stages in 2001 at Suffolk, VA. Vertical bars represent ± standard error of the mean.
Fig. 2.2 c and d. LAI response of two soybean cultivars to plant population at two developmental stages in 2001 at Suffolk, VA. Vertical bars represent ± standard error of the mean.
Fig. 2.3 a and b. Yield response of two soybean cultivars to plant population at Suffolk, VA in a) 2000 and b) 2001. Vertical bars represent ± standard error of the mean.
Fig. 2.4 a, b, and c. Relationship of yield to LAI for soybean cultivar RT-3975 at three developmental stages in 2000 at Suffolk, VA.
Fig. 2.5 a, b, and c. Relationship of yield to LAI for soybean cultivar RT-557N at three developmental stages in 2000 at Suffolk, VA.
Fig. 2.6 a and b. LAI differences between developmental stages for plant populations of a) RT-3975 and b) RT-557N cultivars in 2000 at Suffolk, VA. Means with the same letter are not significantly different at the 0.05% level as determined by Fisher’s protected LSD.
Fig. 2.7 a and b. Relationship of yield to LAI for soybean cultivar RT-3975 at two developmental stages in 2001 at Suffolk, VA.
Fig. 2.7 c and d. Relationship of yield to LAI for soybean cultivar RT-3975 at two developmental stages in 2001 at Suffolk, VA.
Fig. 2.8 a and b. Relationship of yield to LAI for soybean cultivar RT-557N at two developmental stages in 2001 at Suffolk, VA.
Fig. 2.8 c and d. Relationship of yield to LAI for soybean cultivar RT-557N at two developmental stages in 2001 at Suffolk, VA.
Fig. 2.9 a and b. LAI response of RT-3975 cultivar to plant populations at two developmental stages for three soil types in 2001 at Port Royal, VA. Vertical bars represent ± standard error of the mean.
Fig. 2.10. Yield response of RT-3975 cultivar to plant populations for three soil types in 2001 at Port Royal, VA. Vertical bars represent ± standard error of the mean.
Fig. 2.11 a and b. Relationship of yield to LAI for soybean cultivar RT-3975 at two developmental stages on three soil types at Port Royal, VA in 2001.
Chapter 3 – Double-Crop Soybean Leaf Area and Yield Responses to 
Mid-Atlantic Soils and Cropping Systems

ABSTRACT:

Leaf area index (LAI) of soybean \([Glycine \text{ max} \ (L. \text{ Merrill})]\) is related to yield. Achieving adequate leaf area development is necessary to maximize potential soybean yield. Cropping system, available soil moisture, and cultivar will affect leaf area development. Soils can vary greatly within a field in the Mid-Atlantic region, and site-specific management tactics may increase leaf area. However, the relationship between cropping system, cultivar, and soil type to LAI and yield must first be documented on field-scale environments. The specific objectives of this study were to: i) investigate and validate relationships between LAI and yield for two soybean cultivars in three crop rotations across varying soil moisture regimes; and ii) validate, across soil moisture regimes in grower fields, relationships found in previous work. For the first objective, maturity group (MG) III and MG IV cultivars were planted double-crop in three cropping systems on a Bojac loamy sand, a Bojac sandy loam, and a Wickham fine sandy loam. These soils range in plant-available water holding capacity (PAWHC) from 7.3 cm m\(^{-1}\) to 11.8 cm m\(^{-1}\). Leaf area index was measured with a LAI-2000 plant canopy analyzer at 53 and 73, and at 41, 54, and 69 days after planting (DAP) in 2000 and 2001, respectively. Soil moisture was measured with time domain reflectometry (TDR) probes placed across the site. Soybean was harvested at maturity with production scale equipment outfitted with yield monitors and global positioning systems (GPS). For objective 2, soybean cultivars ranging from MG III to MG VII were planted double-crop on soils common to the coastal plain of Virginia and North Carolina. At each site, LAI was measured at two
to three reproductive development stages and yield was determined with production scale combines equipped with yield monitors and GPS. There was no effect of cropping rotation on either LAI or final soybean yield in 2000, but soil type impacted LAI and yield. The Wickham soil type accumulated more leaf area and produced greater yield than the Bojac2 soil. In 2001, the Wickham soil had greater LAI and seed yield than the Bojac2 soil for all crop rotations. LAI of the 4 crops in 3 years rotation was significantly lower than LAI of the 3 crops in 2 years or the 4 crops in 2 years rotation. In 2000 neither soil type nor crop rotation affected a linear relationship between LAI and yield. In 2001, a similar linear yield-LAI relationship was not affected by crop rotation, but was by soil. Data from these experiments failed to show LAI to be a limiting factor to yield. Relationships on grower fields were similar. However, soil type affected LAI at only two of five sites, and yield at only one of five sites. At the site where LAI and yield were affected by soil, a Tarboro sand consistently produced yields less than either a Wickham fine sandy loam or a Bojac loamy sand. Regardless of soil type, yield was observed to increase linearly with increases in LAI. Relationships between LAI and yield in grower fields were not consistent with past research.
Double-Crop Soybean Leaf Area and Yield Responses to Mid-Atlantic Soils and Cropping Systems

In the Mid-Atlantic U.S.A., soybean is commonly grown in a double-cropped system following the harvest of small grains, primarily wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) (Wesley, 1999). From 1999 to 2001, double-crop soybean hectares in Virginia ranged from 45 to 65% of total (D. Holshouser, personal communication, 2002). Double-crop soybean is planted at post-optimal planting dates, often resulting in lower seed yield than in mono-cropped soybean systems (Egli, 1976; Wesley, 1999). Seed yield has been shown to decline rapidly as planting is delayed into late June in the northern hemisphere (Pendleton and Hartwig, 1973; Kluse et al., 1976; Johnson, 1987; Heatherly, 1988). In many instances, double-crop soybean planting is often delayed to mid or late July (Caviness and Collins, 1985; Flack and Boerma, 1976; Weaver et al., 1991), causing even greater yield reductions (Lewis and Phillips, 1976).

Yield reduction of late planted, double-crop soybean has been attributed to a lack of sufficient vegetative growth (Boerma et al., 1982). Ball et al., (2000) examined the effects of plant population density for increasing vegetative growth on late-planted soybean. They observed that in short seasons, decreased potential for producing fertile nodes per plant was partially compensated for by increasing plant population. Herbert and Litchfield (1984) examined the growth effects of row spacing and plant density on short-season soybean. They observed significantly greater accumulation of biomass and canopy coverage with increased plant density.

Increasing leaf area to maximize light interception (LI) is the primary reason that increased biomass is associated with higher yields in late-planted soybean (Wells, 1991;...
Board et al., 1992; Board and Harville, 1993). Greater LI in narrow rows was more pronounced at late compared with optimal plantings for a short-season cultivar compared to a full-season cultivar in Louisiana (Board and Harville, 1992). Decreasing row spacing from 100- to 50-cm increased both LI and yield for soybean planted in late July in Louisiana (Board et al., 1992). Board et al. (1990) attributed yield increases in narrow compared to wide rows as being due to increases in LI and biomass accumulation. They observed that during the late vegetative and early reproductive periods, LI increased 63% and 27% for 25- and 50-cm row spacing, respectively.

In soybean, LI has been related to the amount of leaf area on a plant, as measured by leaf area index (LAI) (Wells, 1991; Board and Harville, 1992). Leaf area index is the ratio of unit leaf area of the crop to unit soil surface area and is highly correlated with crop biomass. Canopy photosynthetic rates have been shown to increase as leaf area increases (Westgate, 1999). A number of researchers have concluded that the maximum rate of canopy photosynthesis occurs when between 90 and 95% of available solar radiation is intercepted by the canopy (Shibles and Weber, 1965; Shibles and Weber, 1966; Christy and Williamson, 1985; Westgate, 1999). The LAI necessary to achieve 90-95% light interception, termed the critical LAI by Sakamoto and Shaw (1967), was observed to occur when sufficient leaf area was present to cover the ground approximately four times (LAI = 4.0) (Christy and Williamson, 1985).

The development stage at which critical LAI is reached is also important. Westgate (1999) stated that, in order to take advantage of a variety’s yield potential, it was essential that the canopy reach critical LAI by the beginning bloom stage (R1). Egli (1988) observed that indeterminate soybean varieties lose yield potential if they fail to achieve
95% LI by first flower. Photosynthetic source restriction experiments confirmed these results. Christy and Porter (1982) observed that a 38% decrease in canopy photosynthesis during vegetative growth had little impact on seed number, size, or yield. However, a similar decrease in photosynthesis during flowering caused yield to drop approximately 17%. Jiang and Egli (1995) shaded plants to reduce photosynthesis from emergence to R1 and for varying periods during flowering and pod set. They observed that shade during any part of flowering and pod set reduced seed number in both field and greenhouse studies.

Cultivar selection can affect leaf area development. Later-maturing cultivars are more likely to meet minimum leaf area requirements than early maturing cultivars. In an experiment to determine the relationship of LAI to plant population and yield of two cultivars of differing maturity group (MG), higher LAI was reached with the later maturing cultivar at the R2 development stage (Jones, 2002). Holshouser and Whittaker (2002) also observed this phenomenon when comparing MG III and IV cultivars in the Mid-Atlantic coastal plain of Virginia. In an experiment in Kentucky with narrow row spacing, Egli (1993) observed increasing length of vegetative growth period and plant size (total nodes plant$^{-1}$ and maximum vegetative mass) as MG increased from 00 to V, indicating higher LAI potential of later-maturing soybean.

Lack of moisture can impact leaf area development. Ball et al. (2000) observed recommended populations for optimum planting dates were insufficient for late-planted soybean because of the failure of these populations to achieve optimal light interception, especially in years of low rainfall. Similarly, in an early soybean production system, higher populations were required to maximize yield only where drought stress limited
leaf area production (Holshouser and Whittaker, 2002). In this study, soils with higher water holding capacity, therefore less susceptibility to drought, were able to achieve critical leaf area requirements at an earlier stage and at lower populations. Therefore, it would be expected that leaf area development would proceed at different rates on soils of differing water holding capacities.

Double-cropped soybean yield may be impacted by soil moisture deficits during critical crop development stages because late plantings can shift reproductive growth into environments less conducive to maximum yield (Egli and Bruening, 1992). Soil moisture levels in the mid-South U.S.A. generally decline as the growing season progresses, thus the potential for yields to be reduced by moisture stress is greater with delayed planting (Tanner and Hume, 1978). However, in the Mid-Atlantic region, early-season intermittent drought is common (Holshouser and Whittaker, 2002), therefore moisture stress is likely to also affect early season vegetative growth and leaf area development.

Cropping system, available soil moisture, and cultivar may all affect the attainment of critical LAI by flowering and thus influence the maximum potential soybean yield (Egli, 1988; Westgate, 1999). Because soils can vary greatly within a field in the Mid-Atlantic region, site-specific management tactics to increase leaf area may possibly be a means to increase field-average yields. But, the relationship of cropping system, cultivar selection, and soil type to LAI and yield must first be documented in field-scale environments. The objectives of this study were to: i) investigate and validate relationships between LAI and soybean yield for two soybean cultivars in three crop rotations across varying soil moisture regimes; and ii) validate, across soil moisture regimes in grower fields, relationships found in previous work between soybean LAI and yield.
MATERIALS AND METHODS

Cropping Systems Experiment

Field studies were conducted in 2000 and 2001 at Camden Farms in Port Royal VA (38°09’N, 77°08’W). The site was part of the larger Mid-Atlantic Regional Cropping Systems Project (Alley and Roygard, 2001), a long-term study evaluating three Mid-Atlantic crop rotations under rain-fed conditions. Upon initiation of the study in 1997, Natural Resource Conservation Service scientists conducted an Order I soil survey of the site. Soil types as mapped were a Bojac1, Bojac2, Wickham3, and Wickham4. The Bojac1 and Bojac2 soils are a sandy loam and loamy sand, respectively (coarse loamy, mixed, thermic Typic Hapludults), and are relatively low in PAWHC (10.6 and 7.3 cm⁻¹ PAWHC respectively). The Wickham soils are both sandy loams (fine loamy, mixed, thermic Ultic Hapludalfs), and would be considered more productive soils (11.8 cm⁻¹ PAWHC). Due to the similarities between the Wickham soil types, they were combined for analysis purposes.

Crop rotation 1 is a standard rotation used throughout much of the Mid-Atlantic region and consists of 3 crops in 2 years: no-till corn (*Zea mays* L.), conventional-till wheat, and no-till double-crop soybean. Crop rotation 2 is a rotation of 4 crops in 3 years used to a lesser extent in the Mid-Atlantic region: no-till corn (*Zea mays*), no-till full-season soybeans, no-till wheat (*Triticum aestivum* L), and no-till double-crop soybean. Crop rotation 3 is an experimental rotation of 4 crops in 2 years: no-till wheat, no-till double-crop soybeans, no-till barley, and no-till double-crop corn.
Experimental design of the study is a randomized complete block, with seven treatments divided among the three crop rotations in order to enable data collection for each phase of each rotation encountered each year. Specifically, there are two treatments for rotation 1, three treatments for rotation 2, and two treatments for rotation 3. Each of the seven treatments is replicated three times, resulting in a total of 21 treatment strips. Table 3.1 lists the crops and year planted for each rotation and treatment since the beginning of the experiment. Each plot is 610-m long and 18-m wide.

Data were collected from treatment rotations that included double-crop soybean during the growing seasons of 2000 and 2001 (Table 3.1). Two soybean cultivars were used for the study years. Rotation 1 (3 crops / 2 years) and rotation 2 (4 crops / 3 years) were planted no-till with Pioneer brand (Pioneer, a DuPont Co., Johnston, IA) ‘9492’ soybean (MG IV) on 25 June in 2000 and 29 June in 2001 following conventionally-tilled wheat harvest. Rotation 3 (4 crops / 2 years) was planted no-till with Asgrow (Monsanto, St. Louis, MO) brand ‘AG3701’ soybean (MG III) following no-till wheat harvest on 25 June in 2000 and on 29 June in 2001. An earlier maturing cultivar was needed in this rotation to enable timely barley planting immediately after soybean harvest. All soybean planting was accomplished with a 23-row John Deere brand JD 1780 Max-Emerge II (Deere and Company, Moline, Illinois) no-till planter using a 38-cm wide row spacing.

In 2000, seeding rates were increased as soil PAWHC decreased in an attempt to increase leaf area development. Seeding rates were 465 000, 554 000, and 640 000 seed ha\(^{-1}\) for the Wickham, Bojac 1, and Bojac 2 soils, respectively. In 2001, seeding rate was only 395 000 seed ha\(^{-1}\) for all soils due to miscommunication to the producer.
Within each crop rotation, 30 randomly selected locations were established to measure plant stand, LAI, and yield. Figure 3.1 shows the locations of measurements within soil types on the cropping systems study for 2000 and 2001. The 30 measurement locations were arranged so that 10 locations were taken from each of the three treatment replications. Variability in the area of soil types across the treatment strips resulted in an unequal number of measurement locations being assigned to each soil type. In 2000, Bojac1 had a total of 16 locations, Bojac2 had 30, and Wickham had 20. Some data points in 2000 were lost due to measurement error. Therefore, only 66 out of 90 assigned total measurements were recorded in 2000. In 2001 however, a total of 90 measurements were recorded, 30 for each rotation. Bojac1 had a total of 9 measurements, Bojac2 had 39, and Wickham had 42. The relatively low number of measurements for the Bojac1 in both study years is because of the smaller area that this soil type covers in the cropping systems experiment, versus the larger areas of the Bojac2 and Wickham soil types.

Latitude and longitude were determined for all sample locations using a differential global positioning system (DGPS) receiver with 1-m accuracy (Trimble AG 132, Trimble Navigation, Sunnyvale, CA). Stand, LAI, and yield were measured at the same geo-referenced locations within the field, allowing relationships between these variables to be established.

Stand counts were taken at the pre-established geo-referenced locations. Stands were measured 20 to 26 days after planting (DAP) by placing an 85-cm diameter circular frame randomly three times within 2 m of the pre-established and geo-referenced measurement location and counting the number of plants that fell within the frame.
Leaf area index was measured at the same geo-referenced locations with a LAI-2000 plant canopy analyzer following sampling methods described by LI-COR (1992, p. D1-3) and Welles and Norman (1991). The LAI-2000 uses the relationship between fractions of direct and indirect radiation intercepted by the canopy and canopy structure, or gap fraction analysis, to estimate LAI (Welles and Norman, 1991). This requires that both the sensor and the plants in the plot be shaded to generate an accurate LAI value. Therefore, all readings were taken on a cloudy day or in the early morning or late afternoon with a constructed shade that prevented direct sunlight from reaching the sensor or plants in the plot. In 2000, LAI was measured at 53 and 73 DAP. In 2001, LAI was measured at 41, 54, and 69 DAP.

Daily rainfall measurements were obtained from a weather station located at Camden Farms. Cumulative rainfall was calculated throughout the growing seasons of 2000 and 2001. Potential evapotranspiration rates were calculated using the FAO reference Penman-Monteith equation (Allen et al., 1998). The FAO Penman-Monteith equation determines the evapotranspiration from a reference grass surface and provides a standard to which evapotranspiration from other crops can be related (Alley and Roygard, 2001).

The method utilizes weather data to calculate a reference evapotranspiration (ET<sub>o</sub>) (Equation 1, from Allen et al., 1998).

\[
\text{ET}_o = \frac{0.408 \Delta ( R_n - G ) + \gamma \left( \frac{900}{T + 273} \right) u_2 ( e_s - e_a )}{\Delta + \gamma \left( 1 + 0.34 u_2 \right)}
\]
Where:

$\text{ET}_o$  reference evapotranspiration (mm day$^{-1}$)

$R_n$  net radiation at the crop surface (MJ m$^{-2}$ day$^{-1}$)

$G$  soil heat flux density (MJ m$^{-2}$ day$^{-1}$)

$T$  air temperature at 2-m height ($^\circ$C)

$u_2$  windspeed at 2-m height (m s$^{-1}$)

$e_s$  saturation vapor pressure (kPa)

$e_a$  actual vapor pressure (kPa)

$e_s - e_a$  saturation vapor pressure deficit (kPa)

$\Delta$  slope vapor pressure curve (kPa $^\circ$C$^{-1}$)

$\gamma$  the psychrometric constant (kPa $^\circ$C$^{-1}$)

Soil profile water content was measured with TDR probes (Moisturepoint, Environmental Sensors Inc, Victoria, B.C., Canada). Time domain reflectometry probes were arranged such that, for each study year, there were at least two probes for each soil type within each crop rotation. Due to the rotation, sites were in different locations in the two years of the study. Probes were inserted vertically to a depth of 1.2 m. Volumetric water content measurements were recorded weekly using a Moisturepoint soil moisture measurement instrument (Model MP-917, Environmental Sensors Inc., Victoria, B.C., Canada). Measurements were made downward along the probe in 15 cm increments for the first 30 cm, after which measurements were made along the probe in 30 cm increments until a depth of 120 cm.
In 2000, soybean cultivars AG3701 (4 crops/2 years) and 9492 (3 crops/2 years and 4 crops/3 years) were harvested 12 October and 13 November, respectively. In 2001, an early freeze occurred on 9 October, terminating soybean growth. As a result, all soybean plots were harvested on 20 October. Harvest was accomplished with a John Deere 9610 combine equipped with a yield monitor (Greenstar™) and GPS with satellite differential correction. All yield data were geo-referenced by the combine at time of harvest. This allowed yield data to be compared with geo-referenced plant population density and LAI data.

The MIXED procedure of SAS (SAS Institute, 1997) was utilized to examine significance of main effects and their interactions. The MIXED procedure uses a mixed linear model which permits data to exhibit correlation and non-constant variability, and can model not only the means of the data but their variances and covariances as well. The LSMEANS statement was used to compute the least-squares means of the fixed effects. The PDIFF option of the LSMEANS statement was used to request that the differences in LS-means be displayed for comparison. Leaf area index measurements were taken over time from the same experimental units, therefore the REPEATED statement within the MIXED procedure was used to test hypotheses about the LAI factors, and the interactions of LAI factors with soil types and yield. Mean separations were considered significant if p-values were ≤ 0.05.

The REG procedure of SAS (SAS Institute, 1997) was utilized to determine relationships between LAI and yield. A non-linear model known as a linear-plateau model was also tested using the NLIN procedure and the NEWTON method. The linear-plateau model is a manifestation of Liebig’s law of the minimum where the rate of
change in plant responses to changes in the availability of a nutrient is constant until some concentration is reached at which other nutrients become limiting and the response attains a plateau (Schabenberger and Pierce, 2002). Linear-plateau models may also be applicable to the relationship of soybean yield to LAI (Malone, 2001). These models calculate the point at which the relationship is no longer linear, and this point is called the join point of the model. Significance of both the linear and non-linear regression models were tested, and models with the strongest coefficients of determination were fitted to the data.

**Leaf Area Index – Seed Yield Relationships in Grower Fields**

Field studies were conducted in 2000 and 2001 on commercial farms in the coastal plain of Virginia and North Carolina. In 2000, two sites from Virginia (Prince George and Hanover Counties) and one site from North Carolina (Washington County) were selected. In 2001, one field from Virginia (Caroline County) and one field from North Carolina (Lenoir County) were selected. These sites ranged in latitude from northernmost Caroline Co., VA (38°09’N, 77°08’W) to southernmost Lenoir Co., NC (35°22’N, 77°33’W).

An intensive Order I soil survey was performed on all fields to determine soil types and locations following either a grid or the topography of the fields. Geo-referenced soil maps were created showing soil type boundaries for each field. Soil types and their respective PAWHC at each site are listed in Table 3.2.

Soybean was planted in a double-crop rotation following either wheat or barley in all study fields. The Prince George site was planted on 17 June 2000 with NK (Novartis
Seeds, Minneapolis, MN) brand cultivar S-53Q7 (MG V) at a row spacing of 38-cm following harvest of wheat. The Hanover site was planted on 12 June 2000 with Asgrow brand AG4501 (MG IV) at a row spacing of 19-cm following wheat harvest. The field in Washington County was planted on 22 June 2000 with Pioneer brand cultivar 9641 (MG VI) at a row spacing of 19-cm following the harvest of wheat. In 2001, the site in Caroline County was planted on 4 June with Pioneer brand cultivar 9492 (MG IV) at a row spacing of 38-cm following barley harvest. This planting date was three to four weeks after the average barley harvest date for this area, but the planting date was within the average soybean planting window following wheat harvest. The Lenoir County site was planted on 20 June with Hartz (Monsanto, St. Louis, MO) brand cultivar H7550RR (MG VII) at a row spacing of 19-cm following wheat harvest.

All fields were seeded with the rate that the grower normally used for that field and year. Stand counts were performed between 20 and 30 DAP to determine the plant populations of each of the fields. Plant populations averaged 447 ± 36; 286 ± 15; 413 ± 23; 272 ± 9; and 423 ± 23 thousand plants ha\(^{-1}\) for the Hanover, Prince George, Washington, Caroline, and Lenoir sites, respectively. Latitude and longitude were determined for each stand count location using a DGPS receiver with 1-m accuracy (Trimble AG 132, Trimble Navigation, Sunnyvale, CA).

At each location where plant population density was measured, LAI was estimated using the procedures described in the previous section. In 2000, LAI was measured 61 and 82 DAP at the Prince George Co. site, 66 and 87 DAP at the Hanover Co. site, and 76 and 105 DAP in Washington Co. In 2001, LAI was measured 56, 71, and 93 DAP in Caroline Co., and 42 and 56 DAP in Lenoir Co. Soybean at all sites was harvested at
maturity using production-scale combines equipped with yield monitoring and GPS technology.

Mean soybean yields and LAI values were compared between soil types for each site independently using the LSMEANS statement of the MIXED procedure of SAS. Differences between LAI measurements over time were obtained using REPEATED statements in MIXED, as described previously. Mean differences were considered significant if \( p \leq 0.05 \). Relationships between LAI and seed yield were determined with linear and non-linear regression procedures in SAS, as previously described.

RESULTS AND DISCUSSION

Cropping Systems Experiment

Daily rainfall, cumulative rainfall, and cumulative evapotranspiration rates are shown in Fig. 3.2. Rainfall rates remained consistent with or exceeded potential evapotranspiration (\( \text{ET}_o \)) rates early in 2000. Nearly half of the total rainfall was received within one month of planting. Rainfall was below average in August 2000 and \( \text{ET}_o \) was greater than cumulative rainfall. Some smaller rainfall events were observed until late September (93 DAP; R6 soybean stage), and no further rainfall occurred prior to harvest on 12 October (109 DAP) or on 13 November (141 DAP) for AG3701 and 9492, respectively. This indicates that soybean were using the soil moisture reserves, as well as the rainfall, during the seed filling stages.

Cumulative rainfall shown on Fig. 3.2 does not fully represent the 2001 year. Of the total rainfall 308 mm was received during the first 52 DAP, until 19 August. From 19 August until harvest on 20 October (114 DAP) only 43 mm of rainfall occurred. Rainfall
exceeded ET₀ until the late pod to early-seed development stages, for the MG III and IV cultivars, respectively. However, lack of rainfall in late September and October resulted in a deficit of cumulative rainfall compared to ET₀.

Final plant population densities for the cropping systems project in 2000 and 2001 are shown in Table 3.3. In 2000, seeding rate was varied by soil type following Virginia Tech extension recommendations (D. Holshouser, personal communication, 2000). Stand counts showed that plant populations as measured were very near target population densities for all soil types. However, miscommunication between research and producer resulted in a single plant population used for all soil types in 2001. Stand counts revealed that final plant population densities were all lower than target populations, regardless of soil type or rotation. No obvious reason was evident at that time to explain why the target populations were not reached. There were no differences in plant population between rotation or soil types, eliminating plant density as a factor in either LAI development or yield.

There was no effect of cropping rotation on either LAI measurements or yield in 2000. The cropping rotation study has been in effect since 1997. Rotational effects due to tillage and management practices may take several years before differences are observed. However, soil type was observed to impact LAI and yield (Table 3.4). Leaf area index responded similarly to differences in soil type for both sets of LAI measurements. The Wickham soil, with the higher PAWHC, had a greater LAI for all cropping system rotations than the Bojac2 soil type. An identical response was observed for the second LAI measurement. Leaf area index increased over time. The Wickham soil type
produced greater yields than the Bojac2 soil. Yield for the Bojac1 was intermediate to
the Wickham and Bojac2.

Cropping rotation significantly affected both LAI and yield in 2001 (Table 3.5). As in
2000, LAI increased over time for all cropping rotations regardless of soil type. The
Wickham soil type had both greater LAI and seed yield than the Bojac2 soil in all
cropping rotations for all LAI measurement dates. In 2001, there was essentially no
rainfall during seed filling for either cultivar (Fig. 3.2b). It is likely, then, that the greater
PAWHC of the Wickham soil greatly contributed to final seed yield. Soybean planted on
the drier Bojac2 soil type used the available soil water early, and thus very little was
available when conditions became droughty.

Within soil types, LAI response to cropping rotation and soybean cultivar varied
according to time of LAI measurement. Initially on the Wickham soil type, there was no
difference in LAI between crop rotations. By the second and third measurement dates,
however, LAI was greater in rotation 1 (3 crops / 2 years) and rotation 2 (4 crops / 3
years) than in rotation 3 (4 crops / 2 years). This was expected since an earlier maturing
cultivar was used in rotation 3. At 54 DAP, AG3701 was in the late pod development
stage (R4), where leaf area development is slowing. In contrast, 9492 was in the
beginning pod development stage (R3), where the rate of leaf area development had not
yet slowed. For the Bojac1 soil type, a difference in LAI between rotations was not
observed until the third measurement date. At this time, double-crop soybean in both
rotations 2 and 3 were observed to have a lower LAI than in rotation 1. The response for
the Bojac2 soil was quite different. For all LAI measurements, LAI was lowest for
rotation 2 (4 crops / 3 years). No difference between rotations 1 and 3 were observed
until the last measurement date, which can be explained by differences in maturity as described above.

A number of explanations could account for the lower LAI of rotation 2 as compared to rotations 1 and 3. Rotation 2 is 4 crops in 3 years: no-till corn, no-till full season soybean, no-till wheat, followed by no-till double-crop soybean. In this rotation, double-crop soybean is planted only one year after full-season soybean, and since initiation of the study in 1997 this has required two previous soybean plantings. This is compared to rotations 1 and 3 (3 crops / 2 years and 4 crops / 2 years) where soybean plantings are two years apart. Since initiation of the study, there has been only one previous soybean planting in these rotations. It is possible that an unknown plant pathogen or nematodes infected the planting in 2001. Nematode infestations and other pathogens are common in cropping systems that leave little time between plantings, and especially in the longer growing season that full-season planting affords. Both cultivars are race 3 and 14 nematode resistant varieties, but race 1 has also been documented in Virginia (P.A. Phipps, personal communication, 2002).

Soil quality is another possibility. As part of the cropping systems study, an intensive study of soil quality indicators was undertaken in July 2001. Soil quality factors measured included bulk density, aggregate stability, and infiltration rate. Comparisons were made between the three crop rotations and the two most diverse soil types, the Wickham and the Bojac2. Sampling was completed on wheat/double-crop soybean strips between soybean planting and emergence. At depths from 1 to 10 cm, bulk density of rotations 2 and 3 were higher than that of rotation 1 (Alley and Roygard, 2001). This is likely due to the conventional tillage systems of rotation 1, versus no-till in rotations 2
and 3. The rotation 1 plots were disked the previous fall after corn harvest and before wheat planting. The higher bulk density of rotation 2 may have contributed to prohibitive early-season root growth and lower LAI. Bulk density in rotation 3 (4 crops / 2 years) was also higher than the rotation receiving tillage and no differences in LAI occurred until the last measurement date. Therefore bulk density differences alone cannot be justified as the sole cause of this discrepancy.

Soybean yield differences between cropping rotations in 2001 are more straightforward (Table 3.5). A premature killing frost occurred on 9 October. The earlier maturing cultivar AG3701 had already reached full maturity by this time. However, the later maturing ‘9492’ was in the late seed-filling stage. The frost caused premature leaf death, which likely had a negative impact on seed yield of the MG IV cultivar, especially those areas of the field with lower LAI. Differences in yield between rotations 1 and 2 could therefore be related to LAI differences between the rotations. Although frost affected both rotations the greater LAI on the Bojac soils of rotation 1 helped to maintain yield. Frost likely affected the two rotations equally on the Wickham soil since LAI did not differ.

The relationship between soybean yield and LAI is shown in Fig. 3.3 and 3.4. In 2000, no relationship was evident for any soil or crop rotation at either measurement date (Fig. 3.3). It should be noted that LAI was usually above 3.5 to 4.0. Previous research has proposed that LAI no longer becomes a limiting factor in soybean yield at these levels or above (Hunt et al., 1994; Malone, 2001). But, more importantly, up to two-fold variation in yield at a specific LAI was observed. Such variation indicates that factors unrelated to LAI are affecting yield in this large field. This experiment covered a total
land area of 24 ha and the distance between data collection locations ranged from 15 to 50 m. It is not unexpected to see large yield variation over such a large area when all sources of yield variation are unknown.

In 2001, crop rotation had no impact on the yield:LAI relationship for any measurement date, but soil type affected the relationship (Fig. 3.4). Leaf area index was measured at the V7, R2, and R4 stages for 9492, and at the R1, R3, and R5 stages for AG3701. At the first and second measurement dates (Fig. 3.4a and b), as LAI increased, yield increased for the Bojac2 soil type, but no relationship between yield and LAI existed for the Wickham or Bojac1 soils. As the crop matured (Fig. 3.4c), differences between soils still existed and a relationship between LAI and yield was observed on the Bojac1 soil. For both Bojac soils, yield increased with increasing LAI at the same rate regardless of soil type. No relationship between LAI and yield was observed at any date for the Wickham soil and LAI was greater than 3.5 in most instances by the R2 and R3 stages. Past research indicated that if a LAI of 3.5 to 4.0 could be reached by flowering then further increases in LAI would not increase in yield (Christy and Williamson, 1982). This was the case for the MG IV cultivar (Fig. 3.4b), but not for the MG III cultivar (Fig. 3.4a). Still, by the R3 stage, AG3701 had largely exceeded an LAI of 3.5 (Fig. 3.4b). Furthermore, yield in 2001 varied less than yield in 2000 (Fig. 3.3), and less variation in yield resulted in a stronger linear fit of the data.

**Leaf Area Index - Seed Yield Relationships in Grower Fields**

Table 3.6 shows plant population, yield, and LAI differences between soil types for the study sites in 2000 and 2001. No differences in plant population were observed
between any soils within any study site. This is to be expected, because all of these sites were seeded using production scale equipment with a single plant population density that the producer would normally use for that field and environment. It is interesting to note that the higher plant populations were achieved in 19-cm wide row spacing with a seed drill. On average, the plant density of the Hanover, Washington, and Kinston sites was 150,000 plants ha\(^{-1}\) greater than that of the Port Royal or Prince George sites, which were planted in 38-cm wide rows.

Seed yield was relatively high for all sites in both study years versus 5-year state averages of 1640 and 1780 kg ha\(^{-1}\) for VA and NC, respectively (D. Miller, Personal Communication, 2002). No differences in yield were observed between soil types within any site except for Port Royal in 2001. This site contained the very sandy Tarboro series with a low PAWHC (Table 3.2). It was on this soil series where the lowest yields were observed for the experiment. Low yields of this soil are probably due to PAWHC.

Differences in LAI were observed within several sites. With the exception of Prince George, leaf area at all sites in 2000 was measured at the R3 and R5 development stages. Measurements at the R5 stage were not taken at Prince George due to lodging through the field that would have resulted in unreliable LAI measurements. At R3 in Hanover, LAI of the Caroline soils was observed to be higher than the Duplin soil type, but by R5, the differences ceased to exist. Leaf area of the Washington site was not different between soil types at either R3 or R5. However, LAI at R5 was lower than at R3. Reasons for this are unclear, but may be attributed to the lodging noted at this site.

In 2001, LAI was different between soil types at Port Royal for all measurements (R2, R4, and R6), but was not observed to be different at the Kinston site for either
measurement. In Port Royal, leaf area attained on the Tarboro soil was lower than either 
the Wickham or Bojac at all measurements. LAI of the Wickham and Bojac soils was 
not different except at the R2 stage, where the Wickham had the highest LAI. These 
differences in leaf area are due to the PAWHC of the respective soils. The Wickham soil 
has a relatively high PAWHC of 11.8 cm\(^1\) m\(^{-1}\). This is compared to the Bojac and 
Tarboro soils, which have PAWHC of 7.3 and 5.0 cm\(^1\) m\(^{-1}\), respectively (Table 3.2). 
Even with lower PAWHC, soybean growing on the Bojac soil was able to achieve LAI 
equal to the soybean grown on the Wickham by R4. The Tarboro sand, however, only 
reached a maximum LAI of 3.92, and this was not until the R6 stage. Water is a major 
limitation to leaf area development, and a limitation is clearly revealed in the data. 

No relationship between seed yield and LAI was observed for either measurement date 
at the Hanover site in 2000 (Fig. 3.5). Soybean at the Hanover site had apparently 
developed sufficient leaf area for that environment necessary to maximize yield, and LAI 
was not a limiting factor to yield. Similar observations were observed at the Washington 
site in 2000 (Fig. 3.6). A significant linear relationship occurred between yield and LAI, 
but the relationship was very weak (\(r^2 = 0.28\) and 0.37 for the R3 and R5 stages, 
respectively). Leaf area index was usually above 4.0 by R3 for all soil types and soils did 
not affect yield (Table 3.6). As stated earlier, other factors may be more responsible for 
yield variation once LAI, measured by R2, increases to levels above 3.5 to 4.0 (Hunt et 
al., 1994; Malone, 2001). Of note in this data however, is the significant decline in LAI 
as the crop matured. This may be explained by the significant amount of lodging 
observed at the site by R5. Lodging often causes lower LAI to be measured because of 
the irregularity in the canopy structure.
The relationship between yield and LAI at Kinston in 2001 is shown in Fig. 3.7. Yield was not related to LAI for either development stage, nor did soil type affect the relationship. By R1, LAI was greater than 3.5 in most areas of the field. Lodging occurred at this site and was likely caused by a dense population on soils with high PAWHC. High LAI in addition to lodging likely prevented the measurement of any yield:LAI relationship.

Figure 3.8 shows the relationship of soybean yield to LAI at three development stages at Port Royal in 2001. LAI was measured at the R2, R4, and R6 development stages, which consisted of the previously described Tarboro, Bojac, and Wickham soils. Yield responded in a positive linear fashion to increases in LAI for all measurement dates. Although LAI and yield varied with soil type, soil type did not alter the relationship between LAI and yield at any measurement date. These data do not support research that indicates that little relationship exists between yield and LAI (measured at R2) if LAI is greater than 3.5 to 4.0. Yield increased as LAI increased for all soils (Fig. 3.8). However, an early frost occurred in 2001 at this site. While resulting in lower final yield for all soybean, it is likely that the frost did not affect yield of high LAI locations as much as those where LAI was just at or below the critical level of 3.5 to 4.0. Because of the excess LAI, defoliation resulting from the frost might not have been great enough to impact yield. This phenomenon is explained in detail in Chapter 2. On the other hand, yield areas with lower LAI were likely reduced because of the lower LAI present at the time of the frost. Had yield not been affected by the frost, the slopes between soil types may have been different.
CONCLUSIONS

At the cropping systems study, there was no effect of cropping rotation on either LAI or yield in 2000. But, soil type was observed to impact both LAI and yield. The Wickham soil had greater LAI and yield for all crop rotations than the Bojac2 soil. Leaf area index and yield for the Bojac1 was intermediate between the Wickham and Bojac2 soils. In 2001, soil type and crop rotation affected LAI and yield. Leaf area index and yield differences were expected between crop rotations containing different maturing varieties due to less time available for leaf area production for the earlier MG. However, lower LAI and yield was also observed on the Bojac soils for the rotation in which soybean was grown more frequently. The reason for the lower LAI in this rotation could not be determined, but could possibly be related to higher bulk density of the top 10 cm of soil of this continuous no-till rotation, or to an unknown disease or nematode infestation due to more frequent soybean plantings of this rotation. Yields of the Wickham and Bojac 1 soils of the 3 crop in 2 year and 4 crop in 2 year rotations were higher than yields on the Bojac 2 soil. Only in the 4 crop in 3 year rotation were the yield of the Bojac 1 reduced below that of the Wickham.

In 2000, no relationship between LAI and yield was observed even though LAI differences between soils existed and many LAI measurements were less than 4.0 on the Bojac2 soil. Other factors unrelated to LAI likely contributed to variability in this large field, therefore any relationship between LAI and yield could not be distinguished. In 2001, yield responded linearly to increases in LAI, and crop rotation had no effect on this relationship. Therefore, one can conclude that LAI differences between crop rotations noted in the above paragraph were the reasons for the crop rotation yield differences.
Soil type also altered the yield-LAI relationship. More areas of the field in 2001 had lower LAI values, therefore unlike 2000, LAI influenced yield to a greater degree. Data from these experiments failed to recognize an LAI level at which yield no longer responds. This does not reflect current literature that states that yield is not responsive to LAI if a critical LAI level, generally stated to be approximately between 3.5 and 4.0, is reached by flowering (Christy and Williamson, 1985; Westgate, 1999).

Validation studies on large-scale grower fields revealed similar responses. Only at the Port Royal site where dramatic differences in the PAWHC between soils occurred did soil type affect the results. At this site, LAI and yield on the Tarboro soil (low PAWHC) was consistently less than that of the Wickham or Bojac2 soils (higher PAWHC). There were significant differences in the leaf area between soils at the Hanover site in 2000, but no other sites revealed any differences. No difference in yield between soils at these sites occurred and was probably related to little growth differences, as revealed by LAI measurements, between soil types. A linear relationship between yield and LAI was revealed only at the Port Royal location, but an LAI level where no further yield increases occurred could not be discerned.

Although these data reveal valuable information on soil effects on soybean leaf area development and yield, the relationship of LAI and yield was inconsistent. A critical LAI level in which no further leaf area-related increases in yields could not always be distinguished. In order to better quantify and understand the relationships of LAI and yield in large field settings, future work will require that other non-LAI variability within grower fields be measured and accounted for. Furthermore, determining the impact of plant available water, as determined by evapotranspiration rates and precipitation, on this...
relationship will be necessary. Site-specific management practices that attempt to maximize leaf area for double-cropping soybean systems in the Mid-Atlantic state must consider variations in plant available water over different soils.

Finally, current methods of measuring the amount of leaf area are costly and time constraining. More adequate methods of measuring LAI in large-field settings must be developed before large-scale determination of leaf area, and accurate determination of LAI-yield relationships, can become a reality.
REFERENCES


Table 3.1. Soybean rotation for each treatment in 2000 and 2001 at the cropping systems study in Port Royal, VA.

<table>
<thead>
<tr>
<th>Season</th>
<th>Rotation 1 (3 crops/2 years)</th>
<th>Rotation 2 (4 crops/3 years)</th>
<th>Rotation 3 (4 crops/2 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Treatment 1</td>
<td>Treatment 2</td>
<td>Treatment 3</td>
</tr>
<tr>
<td>Spring 1997</td>
<td>FS† Corn</td>
<td>FS Corn</td>
<td>FS Corn</td>
</tr>
<tr>
<td>Fall 1997</td>
<td>CT Wheat</td>
<td>Fallow</td>
<td>NT Wheat</td>
</tr>
<tr>
<td>Spring 1998</td>
<td>NT DC Soy</td>
<td>NT FS Corn</td>
<td>NT DC Soy</td>
</tr>
<tr>
<td>Fall 1998</td>
<td>Fallow</td>
<td>CT Wheat</td>
<td>Fallow</td>
</tr>
<tr>
<td>Spring 1999</td>
<td>NT FS Corn</td>
<td>NT DC Soy</td>
<td>NT FS Corn</td>
</tr>
<tr>
<td>Fall 1999</td>
<td>CT Wheat</td>
<td>Fallow</td>
<td>Fallow</td>
</tr>
<tr>
<td>Spring 2000</td>
<td>NT DC Soy</td>
<td>NT FS Corn</td>
<td>NT FS Soy</td>
</tr>
<tr>
<td>Fall 2000</td>
<td>Fallow</td>
<td>CT Wheat</td>
<td>NT Wheat</td>
</tr>
<tr>
<td>Spring 2001</td>
<td>NT FS Corn</td>
<td>NT DC Soy</td>
<td>NT DC Soy</td>
</tr>
<tr>
<td>Fall 2001</td>
<td>CT Wheat</td>
<td>Fallow</td>
<td>Fallow</td>
</tr>
</tbody>
</table>

† FS = full season; DC = double crop; NT = no till; CT = conventional till
Table 3.2. Soil series and average PAWHC in top 1 m of soil from Order 1 soil surveys of sites in 2000 and 2001.

<table>
<thead>
<tr>
<th>Season</th>
<th>Site</th>
<th>Soil Series</th>
<th>PAWHC in top 1 m of soil</th>
</tr>
</thead>
<tbody>
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<td>Hanover</td>
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<tr>
<td></td>
<td>Caroline</td>
<td>Fine sandy loam, <em>Fine, mixed, subactive, thermic Typic Paleudults</em></td>
<td>20.58</td>
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<tr>
<td></td>
<td>Duplin</td>
<td>Fine sandy loam, <em>Fine, kaolinitic, thermic Aquic Paleudults</em></td>
<td>17.31</td>
</tr>
<tr>
<td></td>
<td>Norfolk</td>
<td>Fine sandy loam, <em>Fine-loamy, kaolinitic, thermic Typic Kandiudults</em></td>
<td>12.47</td>
</tr>
<tr>
<td>2001</td>
<td>Washington</td>
<td>Augusta fine sandy loam, <em>Fine-loamy, mixed, semiaactive, thermic Aeric Endoaquults</em></td>
<td>19.18</td>
</tr>
<tr>
<td>County</td>
<td>Soil Type</td>
<td>Percentage</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>------------------------------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>Caroline</td>
<td>Bojac loamy sand</td>
<td>7.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Fine, mixed, semiactive, thermic Typic Endoaquults</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tarboro sand</td>
<td>5.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Mixed, thermic Typic Udipsamments</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wickham sandy loam</td>
<td>11.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Fine-loamy, mixed, thermic Ultic Hapludalfs</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lenoir</td>
<td>Goldsboro fine sandy loam</td>
<td>13.63</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Fine-loamy, siliceous, thermic Aquic Paleudults</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lynchburg fine sandy loam</td>
<td>15.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Norfolk fine sandy loam</td>
<td>12.47</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Fine-loamy, kaolinitic, thermic Typic Kandiudults</em></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† PAWHC data was obtained from the respective county soil surveys.
Table 3.3. Average plant population density for crop rotations at the cropping systems study at Port Royal, VA in 2000 and 2001.

<table>
<thead>
<tr>
<th>Season</th>
<th>Rotation</th>
<th>Cultivar</th>
<th>Plant Population Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Soil Type</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bojac 1</td>
<td>Bojac 2</td>
</tr>
<tr>
<td>2000</td>
<td>3 crops / 2 years DC</td>
<td>9492</td>
<td>487</td>
</tr>
<tr>
<td></td>
<td>4 crops / 3 years DC</td>
<td>9492</td>
<td>460</td>
</tr>
<tr>
<td></td>
<td>4 crops / 2 years DC</td>
<td>AG3701</td>
<td>450</td>
</tr>
<tr>
<td>2001</td>
<td>3 crops / 2 years DC</td>
<td>9492</td>
<td>278</td>
</tr>
<tr>
<td></td>
<td>4 crops / 3 years DC</td>
<td>9492</td>
<td>274</td>
</tr>
<tr>
<td></td>
<td>4 crops / 2 years DC</td>
<td>AG3701</td>
<td>289</td>
</tr>
</tbody>
</table>
Table 3.4. Mean LAI and seed yield for each soil type at the cropping systems study at Port Royal, VA in 2000.

<table>
<thead>
<tr>
<th>Season</th>
<th>Soil Type</th>
<th>LAI @ 53 DAP</th>
<th>LAI @ 73 DAP</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Wickham</td>
<td>5.0a†</td>
<td>5.7a</td>
<td>3230a</td>
</tr>
<tr>
<td></td>
<td>Bojac 1</td>
<td>4.7ab</td>
<td>5.5ab</td>
<td>3030ab</td>
</tr>
<tr>
<td></td>
<td>Bojac 2</td>
<td>3.9b</td>
<td>4.6b</td>
<td>2750b</td>
</tr>
</tbody>
</table>

† Denotes mean differences between soil types for each LAI measurement. Means with the same letter are not significantly different at the 0.05% level as determined by Fisher's protected LSD.
Table 3.5 Mean LAI and yield for each measurement date and soil type within each cropping rotation at the cropping systems study at Port Royal, VA in 2001.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Soil Type</th>
<th>Rotation &amp; Soybean Cultivar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3 crops/2 years (9492)</td>
</tr>
<tr>
<td>LAI @ 41 DAP</td>
<td>Wickham</td>
<td>2.0a†A‡</td>
</tr>
<tr>
<td></td>
<td>Bojac 1</td>
<td>1.5ab A</td>
</tr>
<tr>
<td></td>
<td>Bojac 2</td>
<td>1.1b A</td>
</tr>
<tr>
<td>LAI @ 54 DAP</td>
<td>Wickham</td>
<td>4.4a A</td>
</tr>
<tr>
<td></td>
<td>Bojac 1</td>
<td>3.9a A</td>
</tr>
<tr>
<td></td>
<td>Bojac 2</td>
<td>2.6b A</td>
</tr>
<tr>
<td>LAI @ 69 DAP</td>
<td>Wickham</td>
<td>6.1a A</td>
</tr>
<tr>
<td></td>
<td>Bojac 1</td>
<td>5.6a A</td>
</tr>
<tr>
<td></td>
<td>Bojac 2</td>
<td>4.2b A</td>
</tr>
<tr>
<td>Yield</td>
<td>Wickham</td>
<td>3080a A</td>
</tr>
<tr>
<td>-------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td>Bojac 1</td>
<td>2980a A</td>
</tr>
<tr>
<td></td>
<td>Bojac 2</td>
<td>1780b A</td>
</tr>
</tbody>
</table>

† Denotes mean differences between soil types for measurement date within crop rotation. Means with the same lower case letter are not significantly different at the 0.05% level as determined by Fisher's protected LSD.

‡ Denotes mean differences between rotations for each soil type. Means with the same upper case letter are not significantly different at the 0.05% level as determined by Fisher's protected LSD.
Table 3.6. Plant population, seed yield, and LAI differences between soil types for five sites during two study years.

<table>
<thead>
<tr>
<th>Year</th>
<th>Site</th>
<th>Soil</th>
<th>Population</th>
<th>Yield</th>
<th>LAI 1§</th>
<th>LAI 2</th>
<th>LAI 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>plants ha⁻¹ x1000</td>
<td>kg ha⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>Hanover</td>
<td>Caroline</td>
<td>450a†</td>
<td>2890a†</td>
<td>5.16a†A‡</td>
<td>4.86a A</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Duplin</td>
<td>430a</td>
<td>3130a</td>
<td>4.73b A</td>
<td>4.80a A</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Norfolk</td>
<td>410a</td>
<td>2850a</td>
<td>5.06ab A</td>
<td>4.83a A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Washington</td>
<td>Augusta</td>
<td>440a</td>
<td>2390a</td>
<td>4.64a A</td>
<td>3.23a B</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roanoke</td>
<td>400a</td>
<td>2440a</td>
<td>4.92a A</td>
<td>3.60a B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prince George</td>
<td>Pamunkey</td>
<td>290</td>
<td>2350</td>
<td>5.13</td>
<td></td>
<td>§§</td>
</tr>
<tr>
<td>2001</td>
<td>Port Royal</td>
<td>Tarboro</td>
<td>280a†</td>
<td>2140b†</td>
<td>1.57c†B‡</td>
<td>2.52b A</td>
<td>3.92b A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bojac</td>
<td>261a</td>
<td>3580a</td>
<td>3.23b B</td>
<td>5.38a A</td>
<td>5.67a A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wickham</td>
<td>290a</td>
<td>3840a</td>
<td>4.55a C</td>
<td>5.65a B</td>
<td>5.81a A</td>
</tr>
<tr>
<td>Soil Type</td>
<td>LAI 1</td>
<td>LAI 2</td>
<td>LAI 3</td>
<td>LAI 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinston</td>
<td>450a</td>
<td>2440a</td>
<td>2.90a B</td>
<td>4.60a A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goldsboro</td>
<td>430a</td>
<td>2340a</td>
<td>3.04a B</td>
<td>5.05a A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lynchburg</td>
<td>390a</td>
<td>2360a</td>
<td>2.66a B</td>
<td>4.46a A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Denotes mean differences between soil types within the study year.

Means with the same letter are not significantly different at the 0.05% level as determined by Fisher's protected LSD.

‡ Denotes mean differences between LAI measurement times within the study year.

Means with the same letter are not significantly different at the 0.05% level as determined by Fisher's protected LSD.

§ LAI 1: Denotes development stage R3 (Hanover, Washington, Prince George), R2 (Port Royal), and V6 (Kinston)

LAI 2: Denotes development stage R5 (Hanover, Washington, Prince George), R4 (Port Royal), and R1 (Kinston)

LAI 3: Denotes development stage R6 (Port Royal)

§§ LAI was not taken due to lodging throughout the field.
Fig. 3.1. Maps showing measurement locations in 2000 (above) and 2001 (below) for the cropping systems study in Port Royal, VA.
Fig. 3.2. Daily rainfall, cumulative rainfall, and cumulative evapotranspiration rates over time for Port Royal, VA in 2000 and 2001. LAI measurement dates and development stages for each cultivar are indicated by arrows.
Fig. 3.3 a and b. Relationship of yield to LAI at two development stages for two soybean cultivars in three soil types at the cropping systems study at Port Royal, VA in 2000.
Fig. 3.4 a, b, and c. Relationship of yield to LAI at three development stages for two soybean cultivars in three soil types at the cropping systems study at Port Royal, VA in 2001.
Fig. 3.5 a and b. Relationship of yield to LAI at two development stages in three soil types at Hanover, VA in 2000.
Fig. 3.6 a and b. Relationship of yield to LAI at two development stages in two soil types at Washington, NC in 2000.
Fig. 3.7 a and b. Relationship of yield to LAI at two development stages in three soil types at Kinston, NC in 2001.
Fig. 3.8 a, b, and c. Relationship of yield to LAI at three development stages in three soil types at Port Royal, VA in 2001.
Chapter 4 -- Prediction of Double-Crop Soybean Leaf Area Index and Yield Utilizing the Normalized Difference Vegetation Index

ABSTRACT:
In order to facilitate site-specific management decisions to obtain and maintain adequate soybean \textit{Glycine Max} (L.) Merr leaf area, there is a need to quickly and accurately estimate leaf area index (LAI) variability between and within fields. The use of vegetation indices acquired from remotely sensed data may be a means of accurately estimating both soybean LAI and yield during the early reproductive soybean stages by which the critical LAI levels must be obtained. The objective of this experiment was to determine if the normalized difference vegetation index (NDVI), obtained from color-infrared aerial images, might be used to estimate LAI and yield of double-crop soybean. Significant correlations ranging from 0.46 to 0.90 were found between NDVI and LAI, and from 0.36 to 0.83 between NDVI and yield. Instances where all LAI measurements were below 3.0 typically resulted in a linear relationship of LAI to NDVI. Where LAI exceeded 3.0 and no soil type or cultivar interactions were observed, LAI increased exponentially with increases in NDVI. LAI levels above 4.0 had no significant relationship with NDVI. At early development stages, cultivar and soil type affected the relationship between LAI and NDVI. Yield was observed to respond in a similar fashion as LAI, indicating a relationship between soybean LAI and yield. Images acquired between the beginning pod and beginning seed development stages resulted in the strongest correlations between LAI and yield and NDVI.
Leaf area index (LAI) is the ratio of unit leaf area of a crop to unit soil surface area and is a reliable indicator of crop biomass (Shibles and Weber, 1966). In soybean, it has been reported that LAI levels between 3.5 and 4.0 are needed by flowering in order to maximize yield potential (Egli, 1988; Westgate, 1999). Because soils in the Mid-Atlantic U.S.A. can vary greatly within a field, soil-specific management techniques that manipulate leaf area development to achieve critical LAI levels may increase final average yields. Such techniques may include variable-rate seeding, row spacing alterations, and/or cultivar selection. In addition, knowledge of leaf area variation between or within fields could allow more accurate and site-specific insect pest management (Malone, 2001).

In order to implement site-specific LAI management techniques, LAI variation must first be determined for the site in question. Destructive measurement techniques are tedious, time consuming and unfeasible for large-scale production usage (Daughtry and Hollinger, 1984). Methods that estimate LAI with plant canopy analyzers or light bars are more efficient, but are limited to certain light conditions (Welles and Norman, 1991), and the expense of this equipment may prevent widespread use. Newer methods to determine LAI variation in large fields are needed.

Remote sensing is the process of acquiring information about objects from remote platforms. Remote sensing provides both spatial and temporal information (National Research Council, 1997), and can contribute towards making site-specific management
decisions a reality (Schepers and Francis, 1998). Remotely sensed data has been captured using digital cameras (Adamsen et al., 1999), video images (Beverly, 1996), and digital multispectral scanning sensors (Shanahan et al., 2001) from platforms as varied as conventional fixed-wing aircraft (Flowers et al., 2001) to satellite imagery (Thenkabail et al., 1992).

The principles underlying remote sensing of crops require an understanding of radiant energy and its interaction with the plant. Radiant energy interacts with leaf structures by absorption and scattering (Gates et al., 1965). The energy absorbed selectively at certain wavelengths by chlorophyll is converted first into heat or fluorescence, and then converted photo-chemically into stored energy in the form of organic compounds through photosynthesis. Chlorophyll and other pigments will absorb incident radiation in the visible wavelengths from 400-nm to 700-nm. In the near infrared (NIR) wavelengths (700 to 1300-nm), leaf pigments and cellulose are transparent so leaf absorbance is very low and radiation is either strongly reflected or scattered. As cell layers increase, the proportion of radiation in the NIR that is reflected increases (Monteith, 1972, 1977; Guyot, 1990).

A number of factors can influence reflectance data. Modeling has suggested that leaf reflectance and transmittance, leaf orientation, plant structure reflectance, background reflectance, zenith, look, and azimuth angles can all influence crop reflectance (Colwell, 1974). Near infrared reflectance was found to be sensitive to changes in percent vegetation cover beyond those values at which reflectance in the red region became insensitive. This sensitivity can be attributed to multiple scattering between layers of vegetation that contributes to an enhanced NIR reflectance potentially greater than that of
any individual component. Near infrared reflectance by itself is poorly correlated to low levels of biomass because of the brightness of the soil background (Elliott and Regan, 1993).

Remotely sensed data has been used for a number of agricultural applications, including determination of yield and dry matter in durum wheat (*Triticum aestivum* L.) (Aparicio et al., 2000), measuring the rate of durum wheat senescence (Adamsen et al., 1999), and estimation of grain yield for corn (*Zea mays* L.) (Shanahan et al., 2001). Satellite images from Landsat-5 Thematic Mapper observations proved valuable in evaluating management and growth characteristics of soybean and corn (Thenkabail et al., 1992). Aerial photography was useful for measuring the variability of nitrogen deficiency in corn (Blackmer et al., 1996), and for making tiller count estimates and nitrogen application timing and rate recommendations for winter wheat (Flowers et al., 2001). Data from remote sensing applications have been successfully used as inputs in crop simulation models to model wheat yield and crop evapotranspiration rates (Wiegand et al., 1979; Maas, 1993). Remote sensing has been suggested to be useful for making field maps in conjunction with global positioning systems (GPS), and for gathering large and small-scale spatial soil information (Schnug et al., 1998).

It may be possible to utilize remote sensing techniques to provide relatively fast and accurate measurements of soybean LAI and yield over large field settings. Much success has been reported in the literature pertaining to accurate measurements of LAI and yield for a variety of crops. Remotely sensed LAI of wheat obtained from Landsat images was strongly correlated with ground-truth measurements of LAI (Wiegand et al., 1979), and actually provided more accurate estimates of wheat yields in crop models than
corresponding ground-truth measurements (Maas, 1993). Wanjura and Hatfield (1986) reported strong correlations between remotely sensed data and measurements of leaf area and biomass for cotton (*Gossypium hirsutum* L.), soybeans, sunflower (*Helianthus annus* L.), and grain sorghum ([*Sorghum bicolor* (L.)]. Researchers in Arkansas determined the proportion of ground area covered by a soybean canopy from digital images taken above the canopy, and reported a one to one relationship when they compared canopy coverage values with LI measurements taken near solar noon (Purcell, 2000).

For agricultural applications, analysis of remotely sensed data generally involves the usage of some form of vegetation index. Vegetation indices were developed to combine the response of radiation in the visible and near infrared (NIR) wavelengths to a single value that relates to the amount of green actively photosynthesizing vegetation. These indices attempt to maximize the relationship between reflectance and crop characteristics by minimizing the effects of soil background and variation in illumination (Tucker, 1979; Curran, 1985).

There are numerous vegetation indices that have been used in agricultural research. The simple ratio vegetation index (SR) was an early procedure that divided the reflectance in the NIR wavelengths by the reflectance in the red wavelengths (Jordan, 1969). This vegetation index is based on the relationship between red and NIR light. In green leaves, light in the red region is strongly absorbed by chlorophyll, whereas light in the NIR region is reflected or transmitted (Avery and Berlin, 1992). On bare soil however, light in the red region is less strongly absorbed due to the lack of chlorophyll, and light in the NIR region is reflected less. The resulting reflectance ratio reveals a contrast between soil and vegetation that can be quantified. Simple ratio has been closely
identified with both LAI and yield of wheat (Aparicio et al., 2000; Serrano et al., 2000). Researchers working with wheat related LAI measurements to three vegetation indices found in the literature; the transformed vegetation index, green vegetation index, and perpendicular vegetation index (Wiegand et al., 1979). They found these three indices to be significantly correlated with measured LAI from the time LAI was approximately 0.3 until senescence.

One of the most commonly used and accepted vegetation indices for measuring biomass and leaf area is the normalized difference vegetation index (NDVI). Normalized difference vegetation index was introduced as a method of estimating green biomass (Tucker, 1979), and is related to green biomass by the amount of photosynthetically active radiation (PAR) absorbed by the crop canopy (Sellers, 1985; 1987). Near infrared reflectance alone is sensitive to changes in percent vegetation beyond the values at which red radiation becomes insensitive. However, when combined with reflectance in the red region, a useful ratio was created that enhanced the measurement of crop biomass (Colwell, 1974). The resulting ratio was the NDVI, calculated by dividing the difference of the reflectance in the NIR and red wavelengths by the sum of the reflectance in these wavelengths (NDVI = [NIR (900 nm) – R (680 nm)] / [NIR (900 nm) + R (680 nm)]) (Tucker, 1979; Aparicio et al., 2000).

Normalized difference vegetation index values have been observed to change depending on the type and tillage condition of soil that makes up the background of the image (Bellairs et al., 1996). These authors observed NDVI to be higher above bare soil that was disturbed after sowing, and then as the soil settled, NDVI values fell slightly. Other researchers have indicated that NDVI may not be an adequate tool for measuring
biomass due to confounding soil background effects, and have suggested the use of alternate indices such as transformed soil adjusted (TSAVI) (Baret et al., 1989); optimized soil adjusted (OSAVI) (Rondeaux et al., 1996); or green normalized difference (GNDVI) (Gitelson et al., 1996; Shanahan et al., 2001). However, Bellairs et al (1996) found that within a particular soil type, stronger correlations of NDVI than TSAVI to LAI existed.

Other authors have noted strong relationships between NDVI and biomass and LAI (Tucker, 1979; Sellers, 1985). Research with durum wheat indicated that NDVI appeared limited to LAI values less than 3.0 (Aparicio et al., 2000). Wanjura and Hatfield (1986) tended to concur. Work with cotton, soybeans, sunflower, and grain sorghum seemed to indicate that when LAI does not exceed 3.0, NDVI is highly sensitive to LAI and ground cover.

It has been suggested that a LAI level of 3.5 to 4.0 be reached by flowering to maximize potential yield (Christy and Williamson, 1985; Westgate, 1999). A quick and accurate method to estimate LAI variability between and within fields would allow implementation of site-specific management tactics to attain and maintain adequate LAI levels. There is need to determine if NDVI can accurately estimate soybean LAI during the reproductive soybean stages by which the critical LAI levels must be obtained. Furthermore, information on whether vegetation indices can be used to measure soybean yield variability in large fields is lacking. The objective of this experiment was to determine if NDVI values obtained from aerial infrared images could be used to estimate double-crop reproductive stage soybean LAI and soybean yield variability.
MATERIALS AND METHODS

Research was conducted at six sites in 2000 and 2001. In 2000, one site of the experiment (Camden site 1) was located at Camden farms near Port Royal, VA, another site was located at Engel farms in Hanover Co., VA, and the final study site was at Brandon Plantation in Prince George Co., VA. Camden site 1 from 2000 was utilized again in 2001. New sites in 2001 included another from Camden farms (Camden site 2), and one located on the Tidewater Agricultural Research and Extension Center (TAREC) near Suffolk, VA. Locations, field size, and soil types from each site are listed in Table 4.1.

Experimental design, planting methods, and plant populations for Camden site 1, the Engel farm, and Brandon farm in 2000 and Camden sites 1 and 2 in 2001 are described thoroughly in Chapter 3. Likewise, descriptions of experimental design and planting information for the TAREC site in 2001 are described in detail in Chapter 2.

In 2000, LAI measurements were obtained at 53 and 73 DAP at Camden site 1; at 66 and 87 DAP at the Engel farm; and at 61 DAP at Brandon farm. Leaf area index was not measured at a proposed later measurement date at Brandon due to lodging, which would result in poor LAI estimates. In 2001, LAI was measured at 41, 54, and 69 DAP for Camden site 1; at 56, 71, and 105 DAP for Camden site 2; and at 41, 55, 70, and 86 DAP for the TAREC site. Leaf area index was measured with a LAI-2000 plant canopy analyzer following sampling methods described by Welles and Norman (1991), and described in detail in Chapter 2. Latitude and longitude were determined for each sample location using a differential global positioning system (DGPS) receiver with 1-m accuracy (Trimble AG 132, Trimble Navigation, Sunnyvale, CA).
At all study sites, aerial targets were placed at each field corner and geo-referenced using the DGPS receiver. In 2000, aerial photographs from each site were taken from the belly of a small fixed-wing aircraft on 17 August and 11 September. Soybean was in the R3 to R4 and R5 to R6 stages on 17 August and 11 September, respectively. In 2001 aerial photographs were obtained on 7 August, 17 August, and 7 September, when soybean were in the late vegetative to R2, R3 to R4, and R5 to R6 stages, respectively. These dates coincided to within three days of the time when LAI was measured at each site. Digital color and color infrared images were acquired at each site. Digital images were captured onto 3.5” diskettes using a Sony Digital Mavica camera (model MVC-FD91, Sony Corporation, Japan). Color infrared images were obtained with a 35-mm Minolta camera model SRT-101 in 2000 or a 35-mm Minolta camera model Maxxum STsi (Minolta Corporation U.S.A., Ramsey NJ) in 2001. The cameras were equipped with a Tiffen brand yellow number 12 filter (The Tiffen Company, Happauge, NY) to facilitate the color infrared development process. Kodak Ektachrome EIR 135-36 film (Eastman Kodak Co., Rochester, NY) was used to capture the color infrared images. Images were taken on cloudless days, from an altitude that would enable the entire field to be captured in one image. This resulted in a range of altitudes from approximately 900-m at the Camden sites to 300-m at the TAREC site. All images were acquired between 1000 and 1500 h eastern standard daylight savings time.

Color infrared images were processed using Process AR-5 for infrared accuracy (Eastman Kodak Company, 1999) and mounted onto slides. Slides were digitally scanned using a Nikon model Coolscan III (LS-30) slide scanner (Nikon Company, Japan) at a resolution of 2700 dpi. Color infrared images respond to three specific
regions of the light spectrum, the near infrared band (Band 1, NIR, 700-900-nm), the red band (Band 2, R, 550-700-nm), and the green band (Band 3, G, 490-550-nm) (Flowers et al., 2001). Each pixel of a color infrared image consists of three color bands, in values ranging from 0 to 255. It is these values in combination with one another that make the intensity and hue of the color unique.

Once scanned, the digital images were orthorectified, using the Image Analysis extension of the ArcView geographic information system (ERDAS, 1998). Orthorectification is the process of aligning images to their ‘true’ geographic location. The geo-referenced aerial targets placed at the corners of each field site provided ground control points for aerial alignment. These targets are observed in the aerial image of the site. Using ArcView, it is possible to align the visual representation of the aerial targets with the corresponding ground control points. When alignment is achieved, all geo-referenced data locations (e.g. LAI and yield data) can be meaningfully interpreted through analysis of the image.

Using the Enhanced Farm Research Analyst extension of ArcView (EFRA, 2002), the geo-referenced LAI and yield measurement locations were buffered to a circular area of approximately 13 m². Within this buffer zone, the digital counts of bands 1, 2, and 3 (from 0 – 255) were extracted, and the average digital count for each color band at that location determined. Once the pixel value for each of the color bands was determined, the NDVI could be calculated using the digital counts from the NIR and R spectrums (Tucker, 1979), such that:

\[ \text{NDVI} = \frac{(\text{NIR} - R)}{(\text{NIR} + R)} \]
The green normalized difference vegetation index (GNDVI) and the simple ratio (SR) were also calculated using the digital counts acquired from the images, however, due to the complexity and number of resulting relationships, these data are not discussed in this chapter. However, regressions of LAI and yield to these indices are presented in Appendix B.

Soybean at the TAREC site were harvested with a small plot combine equipped with moisture tester and data logger at maturity. All other sites were harvested at maturity with production scale combines equipped with yield monitoring and DGPS technology.

The effect of soil type or cultivar on the relationship between NDVI and LAI or yield was determined using the PROC MIXED procedures in SAS (SAS Institute, 1997). If soil type or cultivar interactions were present, relationships between NDVI and LAI or yield were performed within soil type and/or cultivar treatments. At sites where no interactions were observed, soil type and cultivar were combined for analysis. Significant relationships between NDVI and LAI or yield for each image within each site year were determined using Pearson correlation coefficients in PROC CORR of SAS (SAS Institute, 1999). If correlation analysis indicated significance, LAI and yield were then regressed on the vegetation indices using PROC REG of SAS (SAS Institute, 1999) to further examine that relationship.

**RESULTS AND DISCUSSION**

Table 4.2 lists the Pearson correlation coefficients between soybean LAI and NDVI for sites in 2000 and 2001. In 2000, both cultivar and soil affected the relationship for the 17 August measurement date at Camden 1. At this site and measurement date,
significant correlations of 0.90 and 0.56 were observed for the AG3701 cultivar on the Bojac2 soil type, and the 9492 cultivar respectively (Table 4.3). Correlations of the Bojac1 and the Wickham soils were not significant. Leaf area index was above 4.0 (data not shown) at all measurement locations for both soils. This agrees with past research indicating that the NDVI-LAI relationship is poor once LAI exceeds 3.0 (Aparicio et al., 2000; Wanjura and Hatfield, 1986). No significant correlations were observed for the 11 September measurement at Camden 1 (Table 4.2). The poor correlations at this site were likely due to an image alignment problem. Upon examination of the image, two of the aerial targets were unable to be seen. Due to this problem, extra ground control points were collected from prominent features in the image, such as building corners. Unfortunately, these points were not at adequate locations to achieve proper orthorectification, and the image remained skewed.

Significant, but weak correlations of 0.49 and 0.51 were observed on 17 August and 11 September respectively at the Engel farm (Table 4.2). At this location, LAI ranged from 2.40 to 6.34 on 17 August and from 3.62 to 5.24 on 11 September, and the amount of leaf area acquired depended on soil type for the first measurement date (Table 4.4). Although LAI differences between soil types within this field became non-significant, the range in LAI still provided for significant correlation between LAI and NDVI (Table 4.4). No significant correlations were found between LAI and NDVI at the Brandon farm due to the uniformity of the soil and LAI values, which ranged from 3.94 to 5.74. Both the Engel and Brandon sites were very uniform in plant population and soil type, and all LAI values were above 3.5 to 4.0 by the R3 development stage. A number of authors have shown that NDVI was less appropriate when chlorophyll content or LAI reached
moderate to high values (Buschman and Nagel, 1993; Gitelson and Merzlyak, 1994; Aparicio et al., 2000). The Engel and Brandon sites satisfy these requirements and may be the reason for the low correlation coefficients at Engel and lack of correlation at the Brandon site.

In 2001, soil type affected the relationship of LAI and NDVI for the 7 August measurement at Camden 1, but unlike 2000, cultivar had no effect. Significant correlations of 0.77 and 0.5 were observed between LAI and NDVI for soybean growing on the Bojac1 and Bojac2 soil types at Camden 1 on 7 August (Table 4.3). Soil type had no effect on the LAI:NDVI relationship at later image acquisition-LAI measurement dates. Significant correlation coefficients of 0.75 and 0.67 were observed for 17 August and 7 September measurements at Camden 1 (Table 4.2). At both the Camden 2 and TAREC sites, significant correlations occurred between LAI and NDVI measurements at all measurement dates whether cultivar differences existed or not (Table 4.2 and 4.3).

Cultivar affected the relationship of LAI and NDVI for the 7 August and 17 August LAI measurements at the TAREC site in 2001. Coefficients for these sites are shown in Table 4.3.

Figure 4.1 shows the relationship of LAI and NDVI for AG3701 soybean on the Bojac2 soil (Fig. 4.1a) and for 9492 over all soil types (Fig. 4.1b) at Camden site 1 in 2000. The image was acquired on 17 August when the earlier maturing AG3701 cultivar was at the R3 development stage and the later maturing 9492 cultivar was at the R2 development stage. Soybean LAI increased in a linear fashion with increasing NDVI for the AG3701 cultivar on the Bojac2 soil. The relationship of LAI and NDVI for AG3701 on the Bojac1 and Wickham soils, and 9492 over all soil types, was not significant.
according to regression analysis. Except for the AG3701 cultivar on the Bojac2 soil, LAI for all measurements were above 3.0 (data not shown), where the relationship of LAI and NDVI has been shown to be weaker (Buschman and Nagel, 1993; Gitelson and Merzlyak, 1994; Aparicio et al., 2000).

The relationship of LAI and NDVI for Camden 1 in 2001 is shown in Fig. 4.2. Leaf area index measurements took place at the V7, R2, and R4 development stages for the 9492 cultivar, and at the R1, R3, and R5 development stages for the AG3701 cultivar, for the 7 August, 17 August, and 7 September images, respectively. At the 7 August date, a significant, but poor relationship existed between LAI and NDVI ($r^2 = 0.53$) for the Bojac1 soil, (Fig. 4.2a). No significant relationship was observed for the Bojac2 or Wickham soils (data not shown). All LAI measurements at this date were less than 3.0. By 17 August leaf area of the Wickham and some Bojac1 measurements were above 3.0 and leaf area increased linearly with increasing NDVI (Fig. 4.2b). By the third measurement, the LAI:NDVI relationship was exponential, and became more asymptotic near an LAI of 4.0 (Fig. 4.2c).

Figure 4.3 shows the relationship of LAI and NDVI for Camden 2 in 2001. At this site, LAI was measured at the R2, R4, and R6 development stages for the 7 August, 17 August, and 7 September images respectively. A strong relationship, as indicated by the coefficients of determination, existed between LAI and NDVI. Leaf area index increased exponentially with increases in NDVI for every image date. However, there were differences between these three images. The NDVI of the soybean growing on the Wickham and Bojac soil types during the R2 development stage (Fig. 4.3a) was higher than the NDVI of soybean growing on these soils at both the R4 and R6 stages (Fig. 4.3b.
The NDVI of the Wickham soil type decreased as the crop matured from R2 to R4, where it became more stable and did not change with increases in LAI. In contrast, NDVI values for all measurements in the Tarboro soil remained relative constant.

This phenomenon may be due in part to the amount of background soil or crop residue reflectance observed in the image. Soil reflectance values vary depending on soil type, water content, and tillage condition (Richardson and Wiegand, 1977; Bellairs et al., 1996). The influence of soil background on reflectance above cereal plots was investigated (Bellairs et al., 1996). The authors observed that NDVI values over sandy soils were much lower than those measured over soils with more clay content. Consequently, the authors observed that the differentiation in NDVI between bare soil and vegetation was more pronounced for the more clayey soils.

In this experiment, the Wickham soil type of Camden 1 and 2 is more clayey than the sandier Bojac2 and Tarboro soils of Camden 1 and 2 (Table 4.1). At the early reproductive stages there was more soil background reflectance observed on the Wickham and Bojac soils than later in the development stages, when soil was completely covered. This would have resulted in a similar scenario to that observed by Bellairs et al. (1996), with the more clayey soil having a higher NDVI value. As the crop canopy developed, the NDVI values became more a function of the crop reflectance and less a function of the soil background. This resulted in a decrease in NDVI values to a more stable level. On the Tarboro soil, the canopy failed to completely close by the early reproductive stages. Therefore, on these soils the sandy background, as well as the lower amount of crop growth, was likely a factor in keeping NDVI consistent throughout the growing season.
In all of these experiments, however, soybean were no-till planted into small grain residue and little soil was visible, especially for the more productive Wickham soil type. Discussion in the literature regarding reflectance of small grain stubble is virtually nonexistent. It is possible however that reflectance from the small grain residue may have affected the intensity of the NDVI values measured. A large amount of residue was left from a high-yielding barley crop on the Wickham soil. Therefore it is more likely that residue, and not soil, background reflectance caused the decrease in NDVI from R2 to R4. However, residue from the barley crop left over on the Bojac2 and Tarboro soils was observed to be very sparse; and it is likely that soil reflectance was still an important factor on these soils.

The relationship of LAI and NDVI at the TAREC site in 2001 is shown in Fig. 4.4. Two cultivars were used at this site, and measurements were obtained when the RT-3975 cultivar was at the R2, R4, and R5 and the RT-557N cultivar at the V7, R2, and R4 development stages for 7 August, 17 August, and 7 September, respectively. Cultivar was observed to affect the LAI:NDVI relationship on 7 August (Fig. 4.4a) and 17 August (Fig. 4.4b). An exponential relationship was observed for the first two measurement dates and the relationship became asymptotic at LAI levels above 3.0 to 4.0 (Fig. 4.4a and b). Furthermore, NDVI levels were typically greater for the earlier maturing RT-3975 cultivar. By 7 September, no relationship existed between LAI and NDVI according to regression analysis although correlation analysis (Table 4.2) indicated a very weak relationship ($r^2 = 0.46$).

There are some important differences in the images from TAREC in 2001 that were not observed in previously shown relationships. First, NDVI values were generally
higher. Second, no matter what cultivar or measurement date, the NDVI values remained high for the majority of the plots measured until the last evaluation date. This field has been in continuous no-till corn/wheat/double-crop soybean rotation for over 3 years, and a substantial amount of crop residue has been acquired. As previously discussed, residue reflectance may have caused a higher NDVI value to occur. Only after most of the plots reached full canopy coverage (LAI > 4) did the NDVI values decrease to levels more consistent with data from other sites.

Table 4.4 shows the Pearson correlation coefficients between yield and NDVI at study sites in both 2000 and 2001. In 2000, cultivar or soil type did not affect the yield:NDVI relationship. The only site and date in 2000 to show significant correlations to yield, was Camden 1 on 17 August. At this site, the image from 11 September was very poorly correlated, primarily due to the image alignment problem discussed earlier. No significant correlations were observed at either the Engel or Brandon farms in 2000. These fields were very uniform in plant population and soil type, LAI was high, and no yield differences were observed between measurement locations or soil type within these fields in 2000 (Table 4.5). Mean yields for the Engel and Brandon sites were 2950 (± 109 SE) and 2350 (± 49 SE) kg ha\(^{-1}\). The lack of correlation between yield and NDVI at these sites is likely due to the small range in yields across the fields.

In 2001, cultivar did not affect the yield:NDVI relationship for any site (Table 4.4). Soil type was observed to affect the relationship of yield and NDVI for the 7 August date at Camden 1. At this site, correlations for the measurements from the Bojac2 and Wickham soil types were significant, but poor (Table 4.6) and no significant correlation
was observed for measurements from the Bojac1 soil type. Correlations at all other sites at all image acquisition dates in 2001 were significant, and are shown in Table 4.4.

Figure 4.5 shows the relationship of seed yield and NDVI at Camden 1 in 2000. Although yield was correlated with NDVI, the relationship was poor as indicated by the low $r^2$ value of 0.35 (Fig. 4.5).

Figure 4.6 shows the relationships of yield and NDVI at Camden 1 in 2001. On 7 August, there was no significant relationship between yield and LAI due to high data variability. Background soil and/or residue interference may have contributed to this variability. As the crop matured, no differences in the relationship between yield and NDVI were noted between soil types or cultivars (Fig. 4.6b and c) and the relationship of yield and NDVI was exponential.

A similar relationship between yield and NDVI occurred at Camden 2 in 2001. Initially, NDVI values exhibited a greater range of values than at later stages of development (Fig. 4.7a). However, as the crop matured, NDVI was observed to decrease and changed very little at later development stages (Fig. 4.7b and c). This relationship follows closely with that of LAI and NDVI, as shown in Fig. 4.3, and the explanation appears to hold true for the relationship of yield and NDVI as well. Once again, soil and/or residue interference was suspected to result in higher NDVI values at earlier development stages.

Although correlation analysis indicated some correlation between yield and NDVI, regression analysis revealed no significant relationships between yield and NDVI at the TAREC site in 2001 for any measurement date (Fig. 4.8). As observed with the LAI:NDVI relationships (Fig. 4.4), NDVI values from this site were generally higher
then NDVI values observed from other sites. It is possible that the large amount of crop residue levels at this site resulted in erroneous NDVI values.

**CONCLUSIONS**

Vegetation indices have potential for accurate, non-destructive, and early prediction of soybean yield and leaf area index from analysis of remotely sensed images. This study determined that the normalized difference vegetation index, or NDVI, was correlated with LAI and yield for soybean. Accurate use of NDVI as a predicting variable, however, did seem limited to a certain soybean development stages. Images acquired from soybean still in mid to late vegetative or early reproductive stages typically resulted in apparent confounding soil or residue background effects. Likewise, images acquired later in the reproductive stages, when LAI was greater than 5.0 were not related to LAI or yield. When acquired at an appropriate time, NDVI values were correlated to both yield and LAI, regardless of soil type or cultivar. NDVI was observed to be effective as a predictor of LAI, until LAI reached approximately 3.5 to 4.0.

Future studies investigating the impacts and ramifications of altitude on the quality of images should be conducted. Sites of different land area require adjustments in altitude to encompass the area in one image, and information on how reflectance measurements change depending on altitude should be considered. Background interference factors, including soil and residue, need to be examined more closely in order to adjust and normalize images over a variety of sites and environments.
More frequent data acquisition, combined with calibrations for background interference will likely improve relationships between NDVI and LAI and yield, and heighten the power of remote sensing for predicting crop growth characteristics.
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Sellers, P.J. 1987. Canopy reflectance, photosynthesis, and transpiration: II. The role of

winter wheat under different nitrogen supplies. Crop Sci. 40:723-731.

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production by various soybean planting patterns. Crop Sci. 6:55-69.


Table 4.1. Location, field size, and soil types for study sites in 2000 and 2001.

<table>
<thead>
<tr>
<th>Season</th>
<th>Site</th>
<th>Field Size</th>
<th>Soil Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Camden 1</td>
<td>24 ha</td>
<td>Bojac loamy sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Coarse loamy, mixed, thermic Typic Hapludults</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bojac sandy loam</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Coarse loamy, mixed, thermic Typic Hapludults</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wickham fine sandy loam</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Fine-loamy, mixed, thermic Ultic Hapludalfs</em></td>
</tr>
<tr>
<td></td>
<td>Engel</td>
<td>11 ha</td>
<td>Ashlar sandy loam</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Coarse-loamy, kaolinitic, thermic Typic Kandiudults</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Caroline fine sandy loam</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Fine, mixed, subactive, thermic Typic Paleudults</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Duplin fine sandy loam</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Fine, kaolinitic, thermic Aquic Paleudults</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Norfolk fine sandy loam</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Fine-loamy, kaolinitic, thermic Typic Kandiudults</em></td>
</tr>
<tr>
<td>Location</td>
<td>Area</td>
<td>Soil Type</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------</td>
<td>---------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------</td>
</tr>
<tr>
<td>Brandon</td>
<td>9 ha</td>
<td>Pamunkey loam</td>
<td>Fine loamy, mixed, thermic Ultic Hapludalfs</td>
</tr>
<tr>
<td>(37°15' N, 77°00' W)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Camden 2</td>
<td>12 ha</td>
<td>Bojac loamy sand</td>
<td>Coarse loamy, mixed, thermic Typic Hapludults</td>
</tr>
<tr>
<td>(38°09' N, 77°08' W)</td>
<td></td>
<td></td>
<td>Tarboro sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mixed, thermic Typic Udipsamments</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wickham fine sandy loam</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fine-loamy, mixed, thermic Ultic Hapludalfs</td>
</tr>
<tr>
<td>TAREC</td>
<td>0.4 ha</td>
<td>Eunola sandy loam</td>
<td>Fine-loamy, siliceous, thermic Aquic Hapludults</td>
</tr>
<tr>
<td>(36°39' N, 76°44' W)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.2. Pearson correlation coefficients for LAI and NDVI at study sites in 2000 and 2001.

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camden 1</td>
<td>17-Aug-00</td>
<td>†</td>
</tr>
<tr>
<td></td>
<td>11-Sep-00</td>
<td>n.s.</td>
</tr>
<tr>
<td>Engel</td>
<td>17-Aug-00</td>
<td>0.49 *</td>
</tr>
<tr>
<td></td>
<td>11-Sep-00</td>
<td>0.51 *</td>
</tr>
<tr>
<td>Price</td>
<td>17-Aug-00</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td>11-Sep-00</td>
<td>n.s.</td>
</tr>
<tr>
<td>Camden 1</td>
<td>7-Aug-01</td>
<td>†</td>
</tr>
<tr>
<td></td>
<td>17-Aug-01</td>
<td>0.75 *</td>
</tr>
<tr>
<td></td>
<td>7-Sep-01</td>
<td>0.67 *</td>
</tr>
<tr>
<td>Camden 2</td>
<td>7-Aug-01</td>
<td>0.87 *</td>
</tr>
<tr>
<td></td>
<td>17-Aug-01</td>
<td>0.80 *</td>
</tr>
<tr>
<td></td>
<td>7-Sep-01</td>
<td>0.90 *</td>
</tr>
<tr>
<td>TAREC</td>
<td>7-Aug-01</td>
<td>†</td>
</tr>
<tr>
<td></td>
<td>17-Aug-01</td>
<td>†</td>
</tr>
<tr>
<td></td>
<td>7-Sep-01</td>
<td>0.46 *</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 level
† Indicates that soil type, cultivar, or both affected the LAI-NDVI relationship.

Correlations for these dates are shown in Table 4.3.
n.s. = non-significant
Table 4.3. Pearson correlation coefficients for LAI and NDVI by soil type and/or cultivar at sites in 2000 and 2001.

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>Soil</th>
<th>Cultivar</th>
<th>NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camden 1</td>
<td>17-Aug-00</td>
<td>Bojac1</td>
<td>AG3701</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bojac2</td>
<td>AG3701</td>
<td>0.90*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wickham</td>
<td>AG3701</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>†</td>
<td>9492</td>
<td>0.56*</td>
</tr>
<tr>
<td>Camden 1</td>
<td>7-Aug-01</td>
<td>Bojac1</td>
<td>†</td>
<td>0.77*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bojac2</td>
<td>†</td>
<td>0.50*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wickham</td>
<td>†</td>
<td>n.s.</td>
</tr>
<tr>
<td>TAREC</td>
<td>7-Aug-01</td>
<td>Eunola</td>
<td>RT-3975</td>
<td>0.83*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eunola</td>
<td>RT-557N</td>
<td>0.65*</td>
</tr>
<tr>
<td></td>
<td>17-Aug-01</td>
<td>Eunola</td>
<td>RT-3975</td>
<td>0.75*</td>
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<tr>
<td></td>
<td></td>
<td>Eunola</td>
<td>RT-557N</td>
<td>0.72*</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 level.
† Indicates no soil type effects on the LAI-NDVI relationship.
‡ Indicates no cultivar effects on the LAI-NDVI relationship.
n.s. = non-significant
Table 4.4. Pearson correlation coefficients for yield and NDVI at study sites in 2000 and 2001.

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camden 1</td>
<td>17-Aug-00</td>
<td>0.60*</td>
</tr>
<tr>
<td></td>
<td>11-Sep-00</td>
<td>n.s.</td>
</tr>
<tr>
<td>Engel</td>
<td>17-Aug-00</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td>11-Sep-00</td>
<td>n.s.</td>
</tr>
<tr>
<td>Price</td>
<td>17-Aug-00</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td>11-Sep-00</td>
<td>n.s.</td>
</tr>
<tr>
<td>Camden 1</td>
<td>7-Aug-01</td>
<td>†</td>
</tr>
<tr>
<td></td>
<td>17-Aug-01</td>
<td>0.78*</td>
</tr>
<tr>
<td></td>
<td>7-Sep-01</td>
<td>0.70*</td>
</tr>
<tr>
<td>Camden 2</td>
<td>7-Aug-01</td>
<td>0.83*</td>
</tr>
<tr>
<td></td>
<td>17-Aug-01</td>
<td>0.81*</td>
</tr>
<tr>
<td></td>
<td>7-Sep-01</td>
<td>0.78*</td>
</tr>
<tr>
<td>TAREC</td>
<td>7-Aug-01</td>
<td>0.59*</td>
</tr>
<tr>
<td></td>
<td>17-Aug-01</td>
<td>0.63*</td>
</tr>
<tr>
<td></td>
<td>7-Sep-01</td>
<td>0.52*</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 level
† Indicates that soil type, cultivar, or both affected the yield:NDVI relationship.

Correlations for these dates are shown in Table 4.6.
n.s. = non-significant
Table 4.5. Yield and LAI measurements with standard error at Engel and Brandon farms in 2000.

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil</th>
<th>Yield</th>
<th>LAI</th>
<th>17-Aug-01†</th>
<th>11-Sep-01‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engel</td>
<td>Caroline</td>
<td>2880 ± 80 a*</td>
<td>5.47 ± 0.15 a</td>
<td>4.86 ± 0.15 a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Duplin</td>
<td>3130 ± 116 a</td>
<td>4.73 ± 0.19 b</td>
<td>4.80 ± 0.19 a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Norfolk</td>
<td>2850 ± 130 a</td>
<td>5.23 ± 0.24 ab</td>
<td>4.83 ± 0.24 a</td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td>Pamunkey</td>
<td>2350 ± 49</td>
<td>5.13 ± 0.15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Corresponds to LAI measurements taken at the R3 development stage.
‡ Corresponds to LAI measurements taken at the R5 development stage.
* Indicates significant differences between yield and LAI measurements between soil types at the Engel farm. Values with the same letter are not significantly different at the 0.05 level.
Table 4.6. Pearson correlation coefficients for yield and NDVI by soil type and/or cultivar at sites in 2000 and 2001.

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>Soil</th>
<th>Cultivar</th>
<th>NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camden  1</td>
<td>7-Aug-01</td>
<td>Bojac1†</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bojac2†</td>
<td>0.54 *</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wickham†</td>
<td>0.36 *</td>
<td></td>
</tr>
</tbody>
</table>

* Significant at the 0.05 level.
† Indicates that cultivar did not affect the yield:NDVI relationship.

n.s. = non-significant
Fig. 4.1 a and b. Relationship of LAI and NDVI of a) AG3701 soybean cultivar on a Bojac2 LS and b) 9492 cultivar averaged over three soil types. Images and LAI measurements were acquired on 17 August 2000 at Camden site 1.
Fig. 4.2 a, b, and c. Relationship of LAI and NDVI on three soil types at Camden site 1 in 2001. Images and LAI measurements were acquired on a) 7 August, b) 17 August, and c) 7 September.
Fig. 4.3 a, b, and c. Relationship of LAI and NDVI on three soil types at Camden site 2 in 2001. Images and LAI measurements were acquired on a) 7 August, b) 17 August, and c) 7 September.
Fig. 4.4 a, b, and c. Relationship of LAI and NDVI of RT-3975 and RT-557N cultivars on a Eunola SL at TAREC in 2001. Images and LAI measurements were acquired on a) 7 August, b) 17 August, and c) 7 September.
Fig. 4.5. Relationship of yield and NDVI of AG3701 and 9492 soybean cultivars on three soil types at Camden site 1 in 2000. Images were acquired on 17 August.
Fig. 4.6 a, b, and c. Relationship of yield and NDVI of AG3701 and 9492 soybean cultivars on three soil types at Camden site 1 in 2001. Images were acquired on a) 7 August, b) 17 August, and c) 7 September.
Fig. 4.7 a, b, and c. Relationship of yield and NDVI of AG3701 soybean cultivar on three soil types at Camden site 2 in 2001. Images were acquired on a) 7 August, b) 17 August, and c) 7 September.
Fig. 4.8 a, b, and c. Relationship of yield and NDVI of RT-3975 and RT-557N cultivars on a Eunola SL at TAREC in 2001. Images were acquired on a) 7 August, b) 17 August, and c) 7 September.
Three experiments over two years measured the relationships between soybean leaf area index, plant population, and yield. In Suffolk, increasing plant population increased LAI for both an early and later maturing cultivar in 2000 and 2001. Higher populations were able to reach proposed critical LAI levels of 3.5 to 4.0 earlier. Seed yield increased with increasing plant population quadratically in 2000. In 2001, no relationship between plant population and seed yield was observed. The relationship of seed yield and LAI was dependent on whether a critical LAI of 3.5 to 4.0 was reached by the R2 development stage. If this level was reached, no further increases in yield were observed. At later development stages, this relationship became linear, because leaf area continued to increase after the R2 stage at a greater rate for lower populations than for higher populations. In 2001, an early frost may have prevented any linear-plateau relationship from occurring with either cultivar.

Similar responses were observed in 2001 at Port Royal. Leaf area index increased with increasing plant population for soybean planted on Bojac and Tarboro soils. Soybean planted on the Wickham soil failed to show any relationship to LAI at either the late vegetative or early reproductive stages. Greatest seed yield was observed on the Wickham soil, regardless of plant population, which was a function of PAWHC. No relationship was observed between yield and LAI at Port Royal in 2001.

There was no significant effect of crop rotation on either LAI or seed yield at the cropping systems study in 2000. Soil type was observed to impact both LAI and yield, with the soybean grown on the Wickham soil (high PAWHC) having a greater LAI for all crop rotations than the soybean grown on the Bojac2 soil (lower PAWHC). Soybean on
the Wickham soil also produced significantly more yield than the soybean on the Bojac2 soil. Crop rotation did affect LAI and yield in 2001. Soybean on the Wickham soil had greater LAI and seed yield than the soybean on the Bojac2 for all crop rotations. Leaf area index was observed to be less for the less intensive rotations, but this could possibly have been related to soil compaction differences in the top 15 cm or to an unknown effect caused by successive soybean crops in that rotation. Neither soil type nor rotation affected the relationship between LAI and yield in 2000, and yield increased linearly with increasing LAI for all LAI measurements. In 2001, yield also increased linearly with increasing LAI, and unlike 2000, soil type was observed to significantly affect the relationship of yield and LAI. Yield increased quickly with increasing LAI for soybean on the Bojac2 soils, whereas the yield of soybean on the Bojac1 and Wickham soils increased at a lower rate. As the crop matured, no interaction was observed between these factors. The linear-plateau response discussed in the literature was not observed for these sites. Studies on grower fields to validate relationship observed in previous work revealed similar results. Where yield differences were observed between soil types, the relationship of yield and LAI was observed to be linear.

The normalized difference vegetation index (NDVI) correlated well with LAI and yield across most soils and sites in 2000 and 2001. Accurate use of NDVI as a predicting variable, however, did appear to be limited to measurements taken from a narrow development stage window. Soil and/or residue background effects may have confounded images acquired in mid- to late-vegetative stages. Images acquired in later reproductive stages resulted in non-significant relationships. When acquired at an appropriate time, NDVI correlated with both yield and LAI, regardless of soil type or
cultivar. NDVI was observed to be effective as a predictor of LAI, until LAI reached approximately 3.5 to 4.0.
APPENDIX A

Cumulative and daily rainfall over time for year 2000 and 2001 in Suffolk, VA.

Year 2000 - Suffolk, VA

Year 2001 - Suffolk, VA
Appendix B1. Relationship of LAI to GNDVI for three soil types at Camden site 1 in 2000. Images were acquired at a) 17 August, and b) 11 September.
Appendix B2. Relationship of LAI to GNDVI for two cultivars and three soil types at Camden site 1 in 2001. Images were acquired at a) 7 August, b) 17 August, and c) 7 September.
Appendix B3. Relationship of LAI to GNDVI for three soil types at Camden site 2 in 2001. Images were acquired on a) 7 August, b) 17 August, and c) 7 September.
Appendix B4. Relationship of LAI to GNDVI for two cultivars at TAREC in 2001. Images were acquired on a) 7 August, b) 17 August, and c) 7 September.
Appendix B5. Relationship of LAI to SR for Camden site 1 in 2000. Images were acquired on a) 17 August, and b) 11 September.
Appendix B6. Relationship of LAI to SR for Camden site 1 in 2001. Images were acquired on a) 17 August, and b) 11 September.
Appendix B7. Relationship of LAI to SR for Camden site 2 in 2001. Images were acquired on a) 17 August, and b) 11 September.
Appendix B8. Relationship of LAI to SR for TAREC in 2001. Images were acquired on a) 17 August, and b) 11 September.
Appendix B9. Relationship of yield to GNDVI for Camden site 1 in 2000. Images were acquired at a) 17 August, and b) 11 September.
Appendix B10. Relationship of yield to GNDVI for Camden site 1 in 2001. Images were acquired at a) 7 August, b) 17 August, and c) 7 September.
Appendix B11. Relationship of yield to GNDVI for Camden site 2 in 2001. Images were acquired on a) 7 August, b) 17 August, and c) 7 September.
Appendix B12. Relationship of yield to GNDVI for TAREC in 2001. Images were acquired on a) 7 August, b) 17 August, and c) 7 September.
Appendix B13. Relationship of yield to SR for Camden site 1 in 2000. Images were acquired on a) 17 August, and b) 11 September.
Appendix B14. Relationship of yield to SR for Camden site 1 in 2001. Images were acquired on a) 7 August, b) 17 August, and c) 7 September.
Appendix B15. Relationship of yield to SR for Camden site 2 in 2001. Images were acquired on a) 7 August, b) 17 August, and c) 7 September.
Appendix B16. Relationship of yield to SR for TAREC in 2001. Images were acquired on a) 7 August, b) 17 August, and c) 7 September.
Brian P. Jones

Brian Jones grew up in rural Augusta County in the beautiful Shenandoah Valley of Virginia. He is the son of Roger and Sue Jones of Weyers Cave, VA, and has one sister, Sheri. Brian graduated with an Associates in Arts and Sciences degree from Blue Ridge Community College in May of 1996, and went on to Virginia Polytechnic Institute and State University, where he received a B.S. in Crop and Soil-Environmental Sciences. Brian married Coleen Mowrey Jones in 2001, and has been pursuing his M.S. degree under the guidance of Dr. David Holshouser in Suffolk, VA. Future plans include pursuing a Ph.D. degree in weed science at Penn State University, and continuing with a career in agricultural research.

“Whoever could make two blades of grass to grow upon a spot of ground where only one grew before, would deserve better of mankind, and do more essential service to his country, than the whole race of politicians put together.”

- Jonathan Swift (1667-1765)