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Growth and nutrition response of young sweetgum plantations to repeated nitrogen fertilization on two site types

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Abstract

Short-rotation intensive tree culture is being investigated in the southern United States as a method of producing hardwood fiber, but little is known about the early productivity and nutritional needs of these systems, especially on different site types. We studied the growth and foliar nutrition response of two sweetgum (*Liquidambar styraciflua* L.) plantations on a converted agricultural field and a pine cutover site to biannual applications of three nitrogen (N) fertilizer rates: 0, 56, and 112 kg N ha^{-1}. The trees did not respond to treatment at any age on the agricultural field site, but the fertilized trees on the cutover site had about 60% greater biomass at ages 5 and 6. Fertilization doubled foliar biomass on the cutover site in the years fertilizer was applied. Stem biomass was directly related to foliar biomass, but the relationship was age-specific at both sites. Stem biomass was also related to the foliar N concentration. Foliar critical values of N were about 18 g N kg^{-1}. Foliage phosphorus (P) and potassium (K) contents were diluted by the N fertilization-induced growth responses at both sites. Fertilization of young intensive-culture sweetgum plantations is necessary for optimum foliar N concentrations and foliar and stem biomass production, but is site-specific.

Keywords: Short-rotation; Woody crops; Nitrogen fertilization; Sweetgum; Bioenergy

1. Introduction

Hardwood plantations will be needed as a source of fiber and biomass in the US and across the world, but their success depends heavily on management intensity [1]. Hardwood fiber is required in certain pulping mixtures, especially those used for producing high-quality writing and packaging papers, and hardwood plantations show promise for bioenergy crops [2]. Until recently, hardwood fiber has generally been available from natural stands, but the availability and reliability of this source is becoming more and more uncertain due to economic and environmental factors. As an alternative to fiber production from naturally regenerated hardwood stands, the feasibility of producing hardwood fiber in short-rotation (3–20 yr), intensively cultured plantations is being explored throughout the US and other countries [3]. Relative

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to most plantation systems, short-rotation hardwood plantations require more intensive site selection and preparation, herbaceous and woody competition control, and nutrient management for success. Nutrient management is especially important in managing hardwood plantations because they generally require more nutrients per unit biomass than conifers, but we have only cursory knowledge of the nutritional control on growth of most hardwood species.

Foliage nutrient concentrations taken from a specific portion of the tree crown are used operationally to diagnose nutrient status in plantations [4]. Nutrient concentrations of a standardized foliar sample are commonly used to diagnose nutrient status in slash (*Pinus Elliottii* Engelm.) and loblolly (*P. taeda* L.) pines in the southeastern US [5,6], a variety of conifers in western North America [7–9], eucalyptus in Australia [10], and other species throughout the world with a critical level-approach [11]. This diagnosis is based on the well-established yield and nutrient sufficiency relationship. Although foliar nutrient concentrations have been reported for some hardwood species in natural stands and plantations, critical levels have not been established for all important woody biomass crops.

Furthermore, low nutrient concentrations in a diagnostic foliage sample do not necessarily indicate a nutrient deficiency, nor do high foliar concentrations necessarily indicate sufficiency [12]. Increases in foliage nutrient concentrations without a concomitant increase in foliage biomass and nutrient content may be due to luxury consumption, and increases in foliage biomass and nutrient content with a decrease in foliage nutrient concentration indicate nutrient dilution. Trees may also appear to have "sufficient" foliage nutrient concentrations when foliage production is limited by available soil nutrients and foliage nutrient concentrations do not decrease [13]. Because of these limitations of using foliage nutrient concentrations taken from a diagnostic sample, other techniques such as whole-crown nutrient analysis are better at interpreting treatment effects.

Rapid early growth is essential for bioenergy plantations, and nutrients may limit growth prior to crown closure. Most nutrients, e.g., P and K, can be relatively easily managed with mineral or organic fertilizers, but N is much more difficult to manage due to its biogeochemical cycle. Inherent soil fertility and resulting tree nutrition is site-specific; in the southern US, two distinct site types are being explored for hardwood fiber and bioenergy plantations: converted agricultural fields and cutover forest lands. Therefore, the objectives of our study were to determine stem and foliar biomass responses of young sweetgum plantations to repeated N fertilization on an converted agricultural field and a cutover pine site, to measure tree response as a function of foliar nutrition, and to determine the effect of repeated N fertilization on foliar P and K nutrition.

2. Materials and methods

2.1. Site descriptions

Two sites of contrasting land use history were selected for this study to illustrate the potential differences in growth and nutrition response to N fertilization. One was an agricultural field, while the other was a loblolly pine plantation site, hereafter referred to as the "ag field" and "cutover" sites, respectively.

The ag field study site was located on International Paper's Trice Research Forest in Sumter County, South Carolina, USA (33°58′N 80°12′W) on the middle Atlantic coastal plain. The soil is a well-drained Norfolk sandy loam (loamy, kaolinitic, thermic Typic Kandiudult). Nine 0.2-ha treatment plots with 0.04-ha measurement plots were established in February 1996 with 280 1-0 bare-root sweetgum seedlings ($\sim$ 1400 ha^{-1}). The site had been regularly managed for dry land crops, e.g., corn (*Zea mays* L.) and soybeans (*Glycine max.* (L.) Merr), for more than 20 years, and soybean, a N_2 fixing legume, was the primary crop for the 5 years previous to plantation establishment. The site index for naturally grown sweetgum was 32 m at age 50 yr, and the pasture productivity was 10 Animal Unit Months (AUM) [14]. All plots were treated with an initial fertilizer application of 280 kg ha^{-1} diammonium phosphate (DAP), which supplied 50 kg N ha^{-1} and 56 kg P ha^{-1} in November 1995 and 100 kg ha^{-1}urea, which supplied 46 kg N ha^{-1}, in August 1996. Non-crop vegetation was restricted to herbaceous vegetation, mostly broomsedge (*Andropogon virginicus* L.), due to the agricultural legacy and early-rotation (3 yr) chemical weed control (pre-emergent and directed spray herbicides).

The cutover pine site was on MeadWestvaco Corporation land, located in Colleton County, South Carolina (32°8′N 80°7′W) on the lower Atlantic coastal plain, and was established in February 1995. The soil is a somewhat poorly to poorly drained Argent sandy loam (clayey, mixed, active, Typic Endoaqualf) developed from marine deposits. The site undergoes wide fluctuations in soil water contents, from saturated soils with standing water in the dormant season to dry soils during the growing season. The heavy clay subsoil restricts water percolation through the solum, and the low elevational gradient ($< 2\%$) restricts lateral flow. These mechanisms induce short-term saturation after heavy rain events throughout the growing season. The site index for naturally grown sweetgum was 29 m at age 50 yr and the pasture productivity was 9 AUM [15]. Nine 0.2-ha treatment plots with 0.04-ha measurement plots were established with 280 1-0 bare-root sweetgum seedlings ($\sim$ 1400 ha^{-1}) of the same genetic source as the ag field site following loblolly pine harvest and site preparation. Site preparation consisted of bedding, fertilization, and non-crop vegetation control. All plots received 50 kg N ha^{-1} and 56 kg P ha^{-1} as DAP in March 1995. The plots also received 3.9 Mg ha^{-1} dolomitic lime in March 1995. The lime application raised pH at 0–20 cm from approximately 4.8 to 5.5. Non-crop vegetation control consisted of pre-emergent herbicide applications in February and March of 1995, 1996, and 1997. Herbicides were also applied by directed spray in 1995 and 1996 during the growing season. Although this aggressive chemical weed control program was used for the first 3 yr, woody and herbaceous plants were present when competition control measures ceased.

2.2. Experimental design

At each site, three biannual N fertilizer rates were initiated at age 2 and replicated three times. At ages 2, 4, and 6, ammonium nitrate (NH_4NO_3) was applied at the following rates: 0 kg ha^{-1} (Control), 168 and 336 kg ha^{-1}, which provided 0, 56, and 112 kg ha^{-1} N, respectively. At the cutover site, 56 kg P ha^{-1} was added as triple superphosphate at age 6 on all plots because we were concerned that P limitations might develop as a result of the N fertilization on this site and the experiment was designed to test N response. The error control design at the cutover site was a Completely Randomized Design, while the design at the ag field site was a Randomized Complete Block Design [16], where the blocking factor was the depth to redoximorphic features. The wide separation of the sites in space, the different establishment years (1996 at the ag field site and 1995 at the cutover site), and different cultural management approaches between the two sites precluded a quantitative comparison of the two sites. However, the similarity in fertilizer application rates and data collection procedures allowed qualitative comparisons of site-to-site differences in plant responses.

2.3. Soil characterization

Soil samples were collected from each treatment plot in 1999 and 2000. Nine 2-cm diameter subsamples were collected per treatment plot in April and November of each year from two soil depths: 0–20 cm (A horizon) and 20–40 cm (E horizon). The subsamples were air-dried, sieved to pass a 2-mm sieve and bulked by treatment plot, depth, and year. The samples were analyzed for total carbon (C), total N, available P, exchangeable potassium (K), calcium (Ca), magnesium (Mg), and pH. Total C and N were determined with a vario MAX CNS analyzer (Elementar, Hanau, Germany). Available P was determined by extracting the soils with Mehlich I extractant [17] and analyzing the extract via Inductively Coupled Plasma—Atomic Emission Spectroscopy (SpectroFlame Modula Tabletop ICP, Spectro Analytical Instruments, Fitchburg, MA) [18]. Exchangeable K, Ca, and Mg were determined by ammonium acetate (pH 7) extractant [19] and analyzed via ICP. Soil pH was determined for the samples in a 1:2 soil:water mixture with a combination pH probe [20].

2.4. Diagnostic foliage sampling

In September 1998, 1999, and 2000, which corresponded to ages 3, 4, and 5 at the ag field site and ages 4, 5, and 6 at the cutover site, a diagnostic foliage sample was taken from the crowns of the five center trees on a diagonal line in each treatment plot. The diagnostic sample consisted of six fully developed leaves from the upper crown position on the southern side of each of the five trees.

2.5. Whole-crown foliage sampling

Three separate foliage samples were taken from the southern portion of the crowns from the same five trees in each treatment plot for the whole-crown sample. The samples consisted of six leaves of all stages of development from single branches, and were collected within the upper, middle, and lower crown positions [21].

2.6. Foliage analyses

The diagnostic and whole-crown foliage samples were chilled on-site, transported to the laboratory in a cooler, and processed within 24 h. The leaves were oven-dried at 65°C to a constant weight and ground to pass a 40-mesh screen. Foliage litterfall was collected three to five times from October to December from five randomly located litter traps (approximately 1 m^2 per trap) per plot. We determined the foliage mass for each crown position by multiplying the total foliage litterfall by relative weighting factors [21], which account for disproportionate increases in foliage mass among crown positions due to fertilization. Foliage N concentrations were determined on each foliage and litter sample with a N analyzer (LECO FP-528, St. Joseph, MI). Nutrient cation (P, K) concentrations were determined by dry ashing 0.03 g of tissue at 420°C for 4 h, digesting the ash with 2 ml concentrated HCl, diluting the digest with 20 ml of 5% HNO_3 and 2.5% HCl, and measuring the concentrations via ICP (Perkin Elmer Optima 3000, Wellesley, MA). Total foliage nutrient content on an area basis was determined for the whole-crown samples by multiplying the whole-crown foliage nutrient concentration by the foliage mass for each crown position.

2.7. Tree growth

Total height was measured with a height pole and diameter at breast height (dbh) was measured using a diameter tape on all surviving planted trees within the measurement plot ($\sim$ 53 trees $plot^{-1}$). Stem biomass (outside bark) was determined on each tree using a biomass equation [22]; it was summed by treatment plot for area-based estimates of stem biomass.

2.8. Statistical analysis

Treatment effects within a site and age class were determined using analysis of variance at $p = 0.10$. If the model was significant, Duncan's Multiple Range test was used to separate the means [23].

In order to relate foliage biomass production to stand biomass growth, we used linear regression to test the relationship between stem biomass and foliage biomass across both sites and ages. Because the relationship appeared to be site and age-specific, we performed separate regressions on each site and used categorical (dummy) variables to test the age-specific relationship within each site [24]. First, the regression was performed using the full model (Eq. (1)); all intercept and slope adjustment terms were included as well as foliage biomass, the main regressor:

$$Y = b_0 + b_1A_1 + b_2A_2 + b_3X + b_4XA_1 + b_5XA_2,$$

where Y is the stem biomass (kg ha^{-1}), A_n the age variable (dummy), and X the foliage biomass (kg ha^{-1}).

The regression was tested iteratively; each combination of categorical variables was tested for significance at $p = 0.10$.

Regression analysis was also used to determine if a relationship existed between the diagnostic foliage N concentrations and tree biomass. If so, we hypothesized that a first approximation foliage N critical level could be established. Because stem biomass was highly site-dependent, the biomass data were first standardized using PROC STDIZE [23], by site, to the mean biomass across both sites for ages 4 and 5 without specifying a standard deviation. Because data were not available from both sites at ages 3 and 6, the non-standardized original data were used for those two ages. The square-root model (Stem Biomass = foliar N + foliar $N^{0.5}$) [25] was then fit to the data from each age. Because this model may predict a N-induced toxicity at potentially normal foliar N concentrations, we verified the model's estimates graphically [26].

A vector analysis [27] was performed to elucidate the relative response of foliar biomass, multiple nutrient concentrations, and content to N fertilization. Vectors were computer-generated using SigmaPlot software (SPSS, Chicago, IL).

Table 1
Soil chemical characteristics at 0–20 cm (A horizon) and 20–40 cm (E horizon) in two young sweetgum plantations in South Carolina

Site/horizon	C ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	C:N	P ($mg\ kg^{-1}$)	K ($mg\ kg^{-1}$)	Ca ($mg\ kg^{-1}$)	Mg ($mg\ kg^{-1}$)	pH
Ag field A	5.2	0.34	15.2	29.3	112	47.5	15.7	5.0
Ag field E	3.1	0.22	14.6	20.3	176	54.2	17.2	5.1
Cutover A	2.3	1.1	29.6	9.07	342	54.7	134	5.1
Cutover E	9.9	0.46	21.6	2.69	79.5	54.3	81.3	5.2

Table 2
Mean tree response of two young sweetgum plantations to N fertilizer applications in South Carolina

Site/treatment	Height (m)				Diameter (cm)			
	Age 3	4[a]	5	6[a]	Age 3	4[a]	5	6[a]
Ag field								
Control	3.53a[b]	5.01a	5.87a	—	4.42a	5.84a	6.56a	—
56 kg ha^{-1}	3.57a	4.95a	5.96a	—	4.18a	5.54a	6.55a	—
112 kg ha^{-1}	3.63a	5.05a	5.99a	—	4.39a	5.92a	6.78a	—
Cutover								
Control	—	4.54a	5.50b	6.31b	—	5.34a	5.71b	6.99b
56 kg ha^{-1}	—	4.84a	6.04ab	6.98a	—	6.46a	6.85a	8.63a
11 kg ha^{-1}	—	4.84a	6.28a	7.02a	—	6.49a	7.23a	8.50a

[a]Fertilizer was applied to the 56 and 112 kg N ha^{-1} treatment plots at ages 4 and 6.
[b]Treatment means within a site and column followed by the same letter are not significantly different at $p = 0.10$.

3. Results and discussion

3.1. Soil characterization

The cutover site surface horizons had about 5 times the soil C and 3.5 times the soil N concentrations of the ag field (Table 1). The organic substrate quality, as measured by C:N ratio of these two sites was also different due to the recent vegetation. The other soil nutrients were also directly related to past land use history. Available P was about 5 times greater throughout the surface soil at the ag field site than at the cutover site due to past P fertilization, because P fertilization at tree establishment was similar. However, exchangeable K, Ca, and Mg were 228%, 28%, and 900% greater, respectively, in the A horizon at the cutover site compared to the ag field site, due to inherent differences in soil properties and historic crop removals. Although the cutover site was expected to have lower soil pH than the ag field, the cutover site's soil pH was similar to the ag field's because the cutover site was limed at establishment.

3.2. Stem growth responses

Stem growth responses to fertilization varied by site (Tables 2 and 3). The trees on the ag field site did not respond to N fertilizer applications by age 5, the last year measured. Since the stand biomass had not yet shown any fertilizer response, the trees on the ag field site will not likely respond in the next year or two. The trees at the cutover site did not respond to fertilization until age 5, even though they had received fertilizer at ages 2 and 4. At age 5, the fertilized trees were about 12% taller, 23% greater in diameter (Table 2), and had 58% more stem biomass (Table 3) than the unfertilized control treatment. These growth responses were maintained at age 6, but were not increased by the fertilizer application in the spring of that year. Apparently, the tree growth responses lag 1 yr behind

Table 3
Stem and foliage biomass responses of two young sweetgum plantations to nitrogen fertilizer applications in South Carolina

Site/treatment	Stem biomass (kg ha^{-1})				Foliage biomass (kg ha^{-1})			
	Age 3	4[a]	5	6[a]	Age 3	4[a]	5	6[a]
Ag field								
Control	1960a	4550a	6570a		476a[b]	2260a	1540b	—
56 kg ha^{-1}	1800a	4180a	6850a		475a	2470a	2780a	—
112 kg ha^{-1}	1930a	4630a	7080a		586a	3100a	2220ab	—
Cutover								
Control		3840a	5130b	8400b	—	1340b	2110a	1750b
56 kg ha^{-1}		5520a	7800a	13600a	—	1950ab	2640a	2670ab
112 kg ha^{-1}		5780a	8800a	13700a	—	2820a	3220a	3480a

[a]Fertilizer was applied to the 56 and 112 kg N ha^{-1} treatment plots at ages 4, 5, and 6.
[b]Treatment means within a site and column followed by the same letter are not significantly different at $p = 0.10$.

fertilizer applications at the cutover site. In general, when foliage N concentrations increase due to increased soil N availability, photosynthetic efficiency is increased due to the ability to produce chlorophyll [28]. This increase in photosynthetic efficiency then allows greater leaf area production, which in turn, allows total photosynthesis (and stem growth) to increase.

In general, trees at the ag field site, regardless of treatment, were larger than unfertilized trees on the cutover site, but were smaller than the fertilized trees on the cutover site (Table 2). Tree heights were similar between the sites regardless of treatment, but the fertilized trees at the cutover site had 9% greater diameters and had 21% more total stem biomass than the ag field trees. Although fertilization increased tree heights at the cutover site, diameter was the more responsive variable. The biomass responses were a direct result of the diameter responses, because plantation density was similar at both sites.

Tree growth on both sites was comparably good for sweetgum plantations because of the intensive-culture management. These plantations were managed as short-rotation woody crop systems, which entailed rigorous site selection, mechanical and chemical site preparation, 3 years of complete weed control, and improved genetic stock. While several studies have reported on planted sweetgum growth and nutrition [21,29,30], few have studied both growth and nutrition on sites managed this intensively. Age 4 and 5 total biomass (bole, branch, and leaf) estimates of three treatments: control, irrigated, and fertigated (fertilizer applied in irrigation water), were reported in a study designed to determine maximum sweetgum biomass growth, i.e., fiber farming [31,32]. The authors found 7.5, 15, and 31 Mg ha^{-1} for the three treatments, respectively, at age 4, and 10.4, 22.5, and 49.9 Mg ha^{-1} for the three treatments at age 5. Using their total biomass equation (as opposed to the bole-only biomass equation used in this study), the estimated total biomass in this study ranged from 7.3 to 10.6 Mg ha^{-1} at age 4 and 9.5 to 16.1 Mg ha^{-1} at age 5, respectively. Overall, biomass production on the two sites in this study was similar or greater than the control treatment of the maximum-production study [31,32]. The irrigation and fertigation treatments in the maximum-production study caused a greater growth response than found in our study, which was designed to determine N fertilizer response without supplemental water.

The two N rates affected biomass growth similarly. Neither the 56 nor the 112 kg N ha^{-1} fertilization rate improved growth at the ag field site, and the 56 kg N treatment performed almost as well as the 112 kg N treatment at the cutover site, and appears to be sufficient for early growth (Table 2). These fertilization rates were, however, applied at frequent intervals, i.e., biannually. It is likely that optimum fertilization rates will vary with changes in the frequency of application and more biologically and economically efficient fertilization regimes may be possible.

Fertilization responses were dependent upon the stage of plantation development. The fertilized trees did not respond at either site until age 5. Although some residual fertilizer may have remained from the initial urea fertilization at the ag field site and the fertilization treatment at age 2 on both sites, it is more likely that this fertilization was unwarranted at either site, and fertilization may not be necessary at the ag field site until age 6 or beyond.

Because the expected rotation length of these plantations is short, i.e, 20 years or less, the time required to reach a given biomass production may be a more meaningful measure of plantation success than relative biomass response. The fertilized trees at the cutover site were, in effect, 1 year advanced in biomass growth compared to the unfertilized trees. The biomass of the fertilized trees on the cutover site at age 5 was greater than the biomass of the unfertilized trees at age 6 (Table 3). Therefore, the fertilized trees at the cutover site may be 2–3 years advanced in biomass growth at age 6.

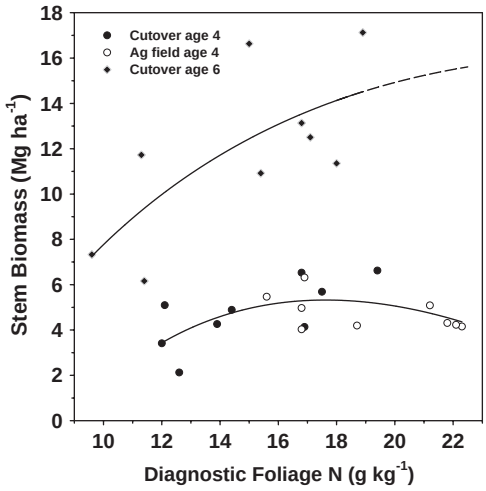

Fig. 1. Sweetgum stand biomass as a function of N concentration taken from a diagnostic foliage sample at an old agricultural field and a pine cutover. The age 4 data were standardized to the mean biomass value.

3.3. Stem biomass and foliage N concentrations

Stem biomass growth was related to foliar diagnostic nutrition, but the relationship varied between sites and among ages. A significant relationship ($p < 0.06$, $R^2 = 0.31$) was found for the standardized data of both sites at age 4 (Fig. 1). No significant relationship was found for the ag field data at age 3 ($p < 0.14$, $R^2 = 0.48$) or for the standardized data from both sites at age 5 ($p < 0.33$, $R^2 = 0.14$). The cutover data at age 6 ($p < 0.12$, $R^2 = 0.50$), while not significant at $p = 0.1$, had the best fit of any of the ages and followed a similar relationship to the age 4 data. Therefore, it was included in the analysis.

Foliage critical levels, defined as the concentration sufficient for 90% of maximum growth, were determined for age 4 and age 6 data (Fig. 1) using these regression analyses. The least-squares regression lines were solved algebraically for the biomass maxima, which were multiplied by 0.90 to determine the 90% maximum biomass level. The foliage nutrient concentrations were then determined arithmetically from the 90% maximum biomass levels and the least-squares regression lines. The foliage critical levels at age 4 and 6 were 15 and 19 g N kg^{-1}, respectively, for an average critical level of 17 g N kg^{-1}. At age 4, the stem biomass to foliage N concentration relationship was not as steep as at age 6, possibly due to the inclusion of the relatively high foliage N ag field plots which had relatively low biomass due to water limitations and the lack of trees with high N concentrations at age 6. The foliage N concentration associated with 90% of maximum biomass at age 4 (15 g N kg^{-1}) was lower than the level associated with 100% of maximum biomass (18 g N kg^{-1}).

Therefore, we suggest using the level associated with maximum biomass at age 4 and 90% biomass at age 6, which results in an average critical level of about 18 g N kg^{-1} for young, intensively managed sweetgum plantations. While this value was obtained from a limited sample size, we propose this be used for N critical levels in young intensive-culture sweetgum plantations and evaluated in future research. Given the relationship between stem biomass growth and foliage N concentration in a diagnostic foliage sample, we examined the treatment effect on foliage N concentrations. Foliage N concentrations were not affected by N fertilization on the ag field site (Table 4). The foliage N concentrations decreased by about 2 g kg^{-1} N per year as the trees matured, but there were no differences among treatments in any year. Except for the unfertilized trees at age 5, the ag field trees all had foliage

Table 4
Diagnostic foliage nutrient concentrations for two N-fertilized sweetgum sites

Site/treatment	Diagnostic foliage N concentration (g kg^{-1})			
	Age 3	4[a]	5	6[a]
Ag field				
Control	20.0a	17.5a	13.7a	—
56 kg ha^{-1}	21.0a	20.3a	18.5a	—
112 kg ha^{-1}	21.6a	19.6a	17.3a	—
Cutover				
Control	—	12.2c	13.3a	10.8c
56 kg ha^{-1}	—	15.0b	13.9a	15.7b
112 kg ha^{-1}	—	17.9a	15.8a	18.0a

Treatment means within a site and column followed by the same letter are not significantly different at $p = 0.10$.
[a]Fertilizer was applied to the 56 and 112 kg N ha^{-1} treatment plots at ages 4 and 6.

N concentrations in excess of 18 g kg^{-1} , indicating that, in general, N was sufficient even for the unfertilized trees and fertilization was not necessary. At the cutover site, the foliage N concentrations were higher in the fertilized plots at ages 4 and 6, which were the years in which N was applied. No differences existed at age 5, when no N was applied. At age 4, the foliage N concentration of the trees in the 56 kg treatment was about 23% greater than the control, and the foliage concentration of the trees treated with 112 kg was about 19% greater than the 56 kg treatment. At age 6, the foliage concentrations of the 56 and 112 kg were about the same as at age 4, and showed the same response. At age 5, when no N was applied, the foliage concentrations of the 56 and 112 kg treated trees were about 10% lower than the average of the same treatments across ages 4 and 6. In general, the foliage N concentrations of the unfertilized trees and the trees treated with 56 kg N were below the critical level, indicating that the trees were likely N deficient.

3.4. Whole-crown foliar nutrition

Vector analyses were performed with the total crown nutrient concentrations, contents, and associated foliage biomass to interpret relative responses among sites, tree ages, and fertilization rates. The nutrient concentration, content, and foliage biomass of each N fertilizer treatment was set relative to the control, and expressed as a percent [27]. Interpretations of this analysis are used to illustrate qualitative responses of several nutrients to all three variables and their interactions. One assumption of this approach is that the third axis, in this case foliage biomass, is correlated with the desired tree response variable, e.g., stem biomass.

The relationship between stem and foliar biomass varied between sites and among ages within a site. In the ag field site, the coefficients for the categorical variables that represented ages 3 and 4 (b_1, b_4) were not significant between ages 3 and 4, while both parameters [slope (b_5) and intercept (b_2)] were different for age 5. In other words, the relationship between foliage and stem biomass was significantly different at age 5 than the relationship at ages 3 and 4. Overall, the model for the ag field site was significant ($p < 0.0001$) and explained 90% of the variation. At the cutover site, the age-specific intercept parameters were not significant, but the slope of age 6 regression line was greater than the slope of ages 4 and 5 regression line. Overall, the model for the cutover site was significant ($p < 0.0001$) and explained 84% of the variation.

This analysis indicates two patterns. First, except for the ag site at age 5, stem biomass is highly related to foliage biomass, as expected. Secondly, because the canopy closed in the fertilized plots at the cutover site at age 6, the greater stem:leaf biomass response at age 6 implies that the fertilization treatments not only increased leaf biomass and area, but also increased growth efficiency, defined as the stem biomass growth per unit leaf biomass. Regardless,

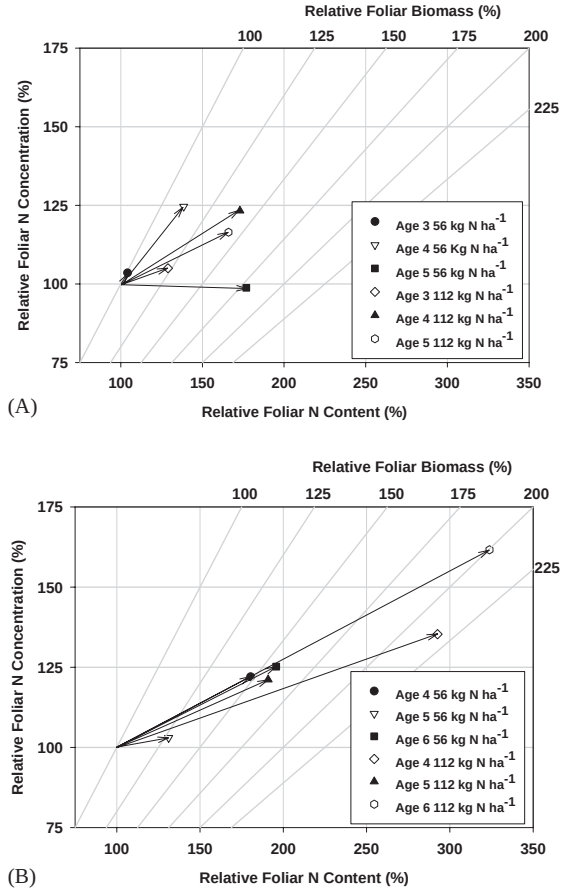

Fig. 2. (A–B) Vector analyses of the whole-crown foliage N dynamics of two young sweetgum plantations in South Carolina in response to N fertilization.

this analysis indicates that, although the relationship between foliage and stem biomass is not constant, it is significant and positive. Therefore, using vector analysis of whole-crown nutrition is a valid method for assessing treatment effects on potential stem responses.

3.4.1. Nitrogen

At both sites and at all ages, except for the 56 kg treatment at the ag field site at age 5, the vectors were positive, i.e., when N was added, N concentration, content, and foliage biomass all increased, which indicates that the Control plots were deficient with respect to N (Figs. 2 A and B). The magnitude of the responses, shown by the length and horizontal angular deviation of the vector lines, varied widely due to site and age. At the ag field site, foliage concentrations of the 112 kg treated trees were 8% and 20% greater than the Control trees at ages 3 and 5, respectively, but were otherwise similar among treatments (Fig. 2A). Foliage biomass of the 56 kg treatment was 81% greater than the control at age 5, but was otherwise similar among treatments. Foliage N content in the trees treated with 112 kg at age 4 was 73% higher than the Control trees, but was otherwise similar among treatments. At the cutover site, sweetgum responded to all fertilizer treatments, but the magnitudes varied due to age (Fig. 2B). The trees of the 112 kg treatment had about 110% and 100% greater foliage biomass than the Control treatment at ages 4 and 6, respectively, which were ages in which N was applied. The greater foliage biomass of the 112 kg treatment trees was associated with 35% and 62% greater foliage N concentrations and 193% and 223% greater contents at ages 4 and 6, respectively. Foliage biomass did not respond to 56 kg N, but N concentrations were 22% and 25% greater in the treated trees than in the Control trees at ages 4 and 6, respectively.

In general, N applications greatly increased N concentrations, contents and foliage biomass, showing that sweetgum was N deficient at this early age. The greatest foliage responses occurred in the same years that N was applied. In years in which no N was applied to any plot, the foliage N concentrations were similar to years in which N was applied, but foliage biomass and N contents were less. These results suggest that (1) sweetgum was clearly N deficient on the cutover site at this early age, (2) foliage N response is short-lived and the applied N is not increasing the available soil N and (3) the stands were not able to produce as much leaf biomass during years when no N was applied compared to years in which it was applied due to N limitations.

3.4.2. Phosphorus

Phosphorus response to the N fertilizer applications varied with site and age (Figs. 3 A and B). Foliage P concentrations of the fertilized trees at the ag field site were generally lower than the unfertilized trees, but foliage P contents and biomass were greater in the fertilized trees than in the unfertilized trees, indicating that foliage P was diluted due to the greater amount of

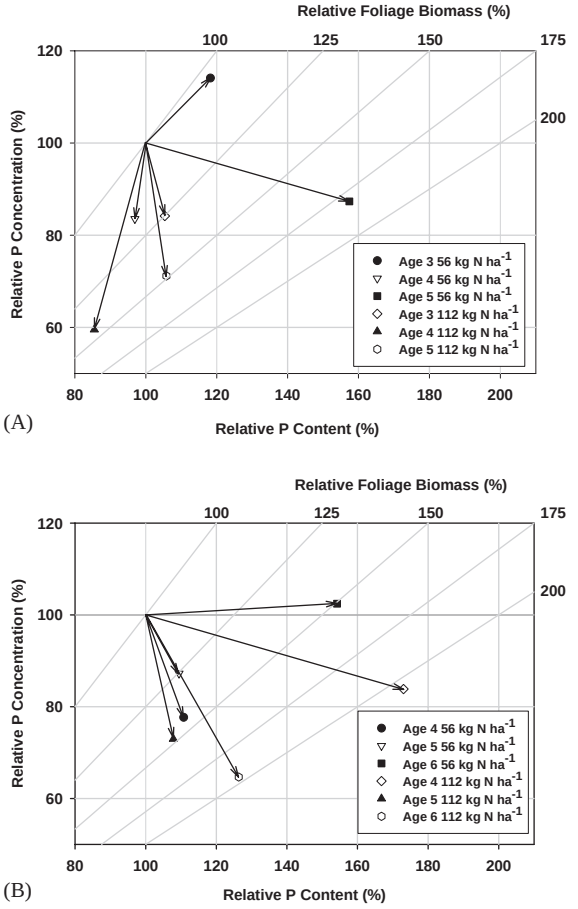

Fig. 3. (A–B) Vector analyses of the whole-crown foliage P dynamics of two young sweetgum plantations in South Carolina in response to N fertilization.

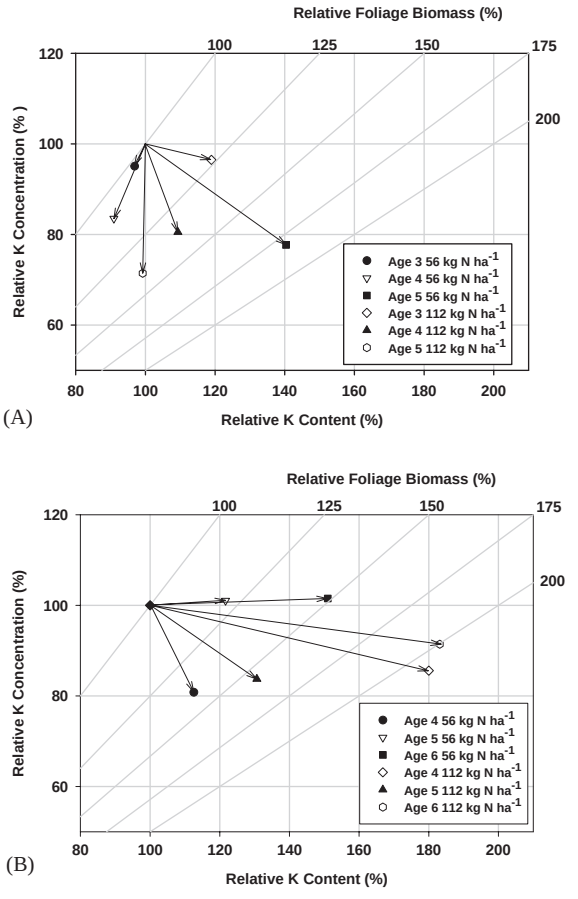

Fig. 4. (A–B) Vector analyses of the whole-crown foliage K dynamics of two young sweetgum plantations in South Carolina in response to N fertilization.

biomass induced by the N treatments. At the cutover site, all P shifts but the 56 kg treatment at age 6 were toward lower P concentrations with higher P contents and biomass, indicating that foliage P was diluted by the N fertilizer applications.

The low levels of available soil P at the cutover site may be insufficient for future growth responses to added N. The additional P application at age 6 on the cutover site was probably necessary for a full response to the added N, and it is likely that both N and P should be added together when soil P levels are low to ensure a full response to added N. Because P fertilizer largely remains in the soil, the P fertilization at age 6 may have remedied future P deficiencies, but further P fertilization may be necessary if P uptake had not yet reached a maximum by age 6.

3.4.3. Potassium

Potassium response at the ag field site ranged from dilution to antagonism, with no apparent consistency (Figs. 4A and B). The 56 kg treatment at ages 3 and 4 and the 112 kg treatment at age 5 was antagonistic to K nutrition, but the 56 kg treatment at age 5 and the 112 kg treatment at ages 3 and 4 all indicated dilution rather than antagonism. Although the K concentrations of the trees treated with 56 kg N on the ag field site were 17% lower than those of the Control trees, there were no content differences. Because the

foliage K concentrations of the ag field site trees were almost twice that of the cutover site trees, the high dilution and slight antagonistic response of K seen at the ag field site indicates that much of the K uptake in the unfertilized trees was luxury consumption. At the cutover site, K response to N additions varied from slightly synergistic for the 56 kg treatment at ages 5 and 6 to moderately diluted for the other treatment-age combinations, indicating that little to no luxury consumption occurred. Although some slight antagonistic responses of K to N additions occurred, these data indicate that on soils with similar K contents, N fertilization does not induce K deficiency at these ages.

Whether an N-induced deficiency of P, K, or other nutrients will occur at either site in the future is uncertain, but the strong dilution of both P and K in these stands warrant soil and foliage P and K testing along with N in these fast-growing stands to avoid N fertilization-induced deficiencies.

4. Conclusions

Characterizing the soil chemistry and monitoring the nutrition of young sweetgum stands is necessary to avoid over-fertilization on unresponsive sites and to avoid losing potential growth responses to nutrient deficiencies. One rationale for using marginal ag fields for hardwood plantations is that they may be more fertile, except for N, as a result of past fertilization. However, the results of this study indicated that our assumption was false. We initially hypothesized that the ag field site would be more responsive to added N due to its 3-fold lower total soil N content. Instead, the ag field site was not as responsive to N fertilization as the cutover site with respect to biomass production or foliar nutrition. The lack of response to N at the ag field site is probably due to greater N mineralization, also unexpected, and possibly limited soil water availability. The ag field site, in comparison to the poorly drained cutover site, was well-drained and averaged 11% volumetric soil water content in the surface 20 cm in 1998 and 1999 (data not shown), while the cutover site averaged 17% volumetric soil water content through the same time period. Height, diameter, stem biomass, foliage biomass, leaf area, and foliage N concentrations and content all increased in response to N fertilization treatments at the cutover site due to inadequate soil N supply, while only foliage biomass and foliage N concentrations and contents responded at the ag field site. The lack of response at the ag field site can also be seen in the foliage N concentrations. Foliage N concentrations were below 18 g kg^{-1}, our proposed critical level, only at the cutover site. Foliage P and K were generally diluted when N fertilization caused growth responses. Although we did not observe a P or K deficiency, they may occur on some sites when biomass growth rates (and nutrient uptake) reach their maximum levels. Furthermore, we may have observed a P deficiency on the cutover site at age 6 had we not fertilized the plots with 56 kg P ha^{-1}.

This study showed that early, repeated N fertilization of short-rotation sweetgum plantations can greatly increase foliage and stem biomass production, but the responses are site-specific. Although sites with greater organic matter are assumed to have more available N and exhibit less response to N fertilizer, the results of this study indicated that this assumption can be erroneous. Soil N availability is governed by a host of factors, of which total soil N is only one.

While early fertilization can reduce the time required to achieve merchantable size by 1–3 ys, fertilization is probably not needed until age 4 or 5 on sites similar to our cutover site, and is probably not needed until canopy closure on sites similar to our ag field site if sustained competition control is maintained. Furthermore, the 112 kg N treatment was necessary to increase the foliage N concentrations to 18 g kg^{-1} at the cutover site, but with biannual fertilization frequencies, stem biomass growth was not improved by the higher N rate at either site, and was not needed for optimum early growth.

Based on these limited data, our recommendations for fertilizing young sweetgum plantations are:

(1) Post-establishment N fertilization is not needed in sweetgum plantations that are managed with sustained competition control until age 4 or beyond. N fertilization may be needed at establishment.
(2) If diagnostic foliage N concentrations are below 18 g kg^{-1} N, 4, 5, or 6-year-old plantations will respond to N applications of 56 kg N ha^{-1} or greater.

(3) Intensive N fertilization may induce P or K deficiencies in sweetgum plantations on some soils; monitoring should be performed to avoid N fertilization-induced deficiencies.
(4) A greater understanding of soil nutrient supplying capacities with particular focus on N dynamics is needed.

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