Soil and pine foliage nutrient responses 15 years after competing-vegetation control and their correlation with growth for 13 loblolly pine plantations in the southern United States[1]

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Abstract: Influences of competition-control treatments on long-term soil and foliar nutrition were examined using a regional data set (the Competition Omission Monitoring Project) that documents loblolly pine (*Pinus taeda* L.) plantation development for 15 years after early intensive woody and (or) herbaceous control. Examined were trends for macronutrients in soils sampled at years 0 and 15 and in pine foliage at years 2, 6, and 15 and their correlations with one another and with pine growth. Early control treatments resulted in distinct plantation successional patterns with contrasting herbaceous and woody components, all under pine-dominated canopies. There was an overall decrease in soil nutrient concentrations after 15 years of pine-plantation management, while C, N, and Ca decreased most after vegetation control. Early herbaceous treatments resulted in significantly less foliar N and K at year 15 as well. Foliar nutrient contents and fascicle mass at year 2 tended to be better correlated with year-15 pine volume than values at year 6 or year 15. Year-15 P concentrations had the strongest correlations between soil and foliar nutrient levels (r = 0.71–0.77). By year 15, intensive pine culture and vegetation control had placed demands on soil nutrient supplies to support enhanced growth that have not yet been replaced.

Résumé : Les effets des traitements de maîtrise de la végétation compétitrice sur l'équilibre nutritif à long terme entre le sol et le feuillage ont été étudiés à l'aide d'un ensemble de données régionales (« Competition Omission Monitoring Project ») qui portent sur le développement de plantations de pin à encens (*Pinus taeda* L.) pendant les 15 années qui ont suivi des traitements intensifs de maîtrise de la végétation herbacée ou ligneuse. Nous avons examiné les tendances pour les macronutriments dans les sols échantillonnés à l'année 0 et après 15 ans, dans le feuillage du pin après 2, 6 et 15 ans ainsi que les corrélations entre ces groupes d'échantillons et les corrélations entre ces échantillons et la croissance du pin. Les premiers traitements de maîtrise de la végétation ont engendré des patrons de succession distincts dans les plantations caractérisés par des différences dans les composantes herbacée et ligneuse, mais tous dominés par un couvert de pin. Il y a eu une diminution globale des concentrations de nutriments dans le sol après 15 ans d'aménagement des plantations de pin alors que C, N et Ca ont diminué le plus après les traitements de maîtrise de la végétation. Les premiers traitements de maîtrise de la végétation herbacée ont aussi causé une diminution significative de N et K après 15 ans. Après 2 ans, la teneur en nutriments foliaires et la masse de fascicules avaient tendance à être plus étroitement corrélées avec le volume des pins après 15 ans qu'avec les mêmes valeurs après 6 ou 15 ans. Les plus fortes corrélations entre les niveaux de nutriments dans le sol et le feuillage (r = 0,71–0,77) étaient celles des concentrations de P après 15 ans. Après 15 ans, la maîtrise de la végétation et la culture intensive du pin ont provoqué une diminution des stocks de nutriments dans le sol pour supporter la croissance et ces nutriments n'ont pas encore été remplacés.

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Introduction

Most pine forests in the southern USA grow in soils that have been used, and at times exploited, by extractive agriculture and forestry for up to 250 years and are assumed to be in a stage of recovery (Henderson 1995; Richter et al. 1995). Soil factors and their management control forest productivity because much of the soils have reduced organic matter (resulting in low N and P availability), low base saturation (resulting in low K, Ca, and Mg availability), and relatively few weatherable primary minerals (Allen et al. 1990; Richter and Markewitz 1996). Nutrients of pine forests and plantations of the region reside mainly in the soil, including 60%–85% of a site's N, P, and K and 75%–95% of its Ca and Mg, while organic C is scarcer, at less than 1% (Jorgensen and Wells 1986; Tew et al. 1986; Trettin et al. 1999). Thus, management and maintenance of these residual nutrient pools, especially organic C, during this era of intensifying management will determine sustainable productivity (Powers 1999).

Sustainable management of forests requires conservation of soil organic matter and site nutrition (The Montreal Process, Criteria and Indicators, http://www.mpci.org/criteria_e.html; Powers 1999). Pine plantations with increasing intensities of management occupy 15% of the southern region and may occupy 26% by as early as 2040 (Wear and Greis 2002). The southern USA produces approximately 60% of the US timber supply, and more industrial timber than any other single region in the world (World Resources Institute 1996; Prestemon and Abt 2002). Loblolly pine (*Pinus taeda* L.) is presently the leading timber species in the USA, predominating on more than 13 million ha of southern forest lands (Schultz 1997). The intensive management of loblolly pine plantations using mechanical site preparation, competition-control treatments, fertilization, and improved genotypes can increase productivity up to threefold in the short term (Borders and Bailey 2001; Miller et al. 2003*b*; Wagner et al. 2004; Allen et al. 2005); however, whether these enhanced growth rates can be sustained in the long term remains in question (Tew et al. 1986; Johnston and Crossley 2002).

Presently, half a million hectares in the region are treated annually with herbicides for site preparation and herbaceous-plant control (McCullough et al. 2005). In addition, site preparation may involve the displacement of nutrients into windrows and bedded mounds or accelerate nutrient release from residual biomass through crushing, disking, or burning, often followed by one or two applications of herbicides to retard competition and plant associates (Morris et al. 1983; Vitousek and Matson 1985; Tew et al. 1986). With shortened rotations, nutrients are harvested and removed from sites in biomass at more frequent intervals (Johnston and Crossley 2002). The consequences of these intensifying practices on long-term soil nutrient conservation in the region remain unclear (Power et al. 2005); especially under-reported are data on long-term nutritional changes after intensified forest-vegetation management (Carter et al. 2006).

The Competition Omission Management Project (COMP) was initiated in 1984 to address a range of questions regarding the productivity potential of loblolly pine plantations managed with intensive competition control. This project employs a uniform treatment protocol at 13 locations (Miller et al. 1991, 1995*a*, 1995*b*; Zutter and Miller 1998; Miller et al. 2003*a*,2003*b*). The objective of this report is to examine nutrient changes in soils and pine foliage and their correlations with one another and with pine growth over the subsequent 15-year period. Pine foliar nutrient levels at years 2 and 6 were previously reported by the COMP team (Zutter et al. 1999) and are further examined in this report relative to year-15 sampling. The use of a standard experimental protocol and the wide range of soils, physiographic provinces, geographic distribution, and levels of woody vegetation among study locations allow for a comprehensive look at nutrient responses and relationships not afforded by data from a single location or examination of several independent experiments.

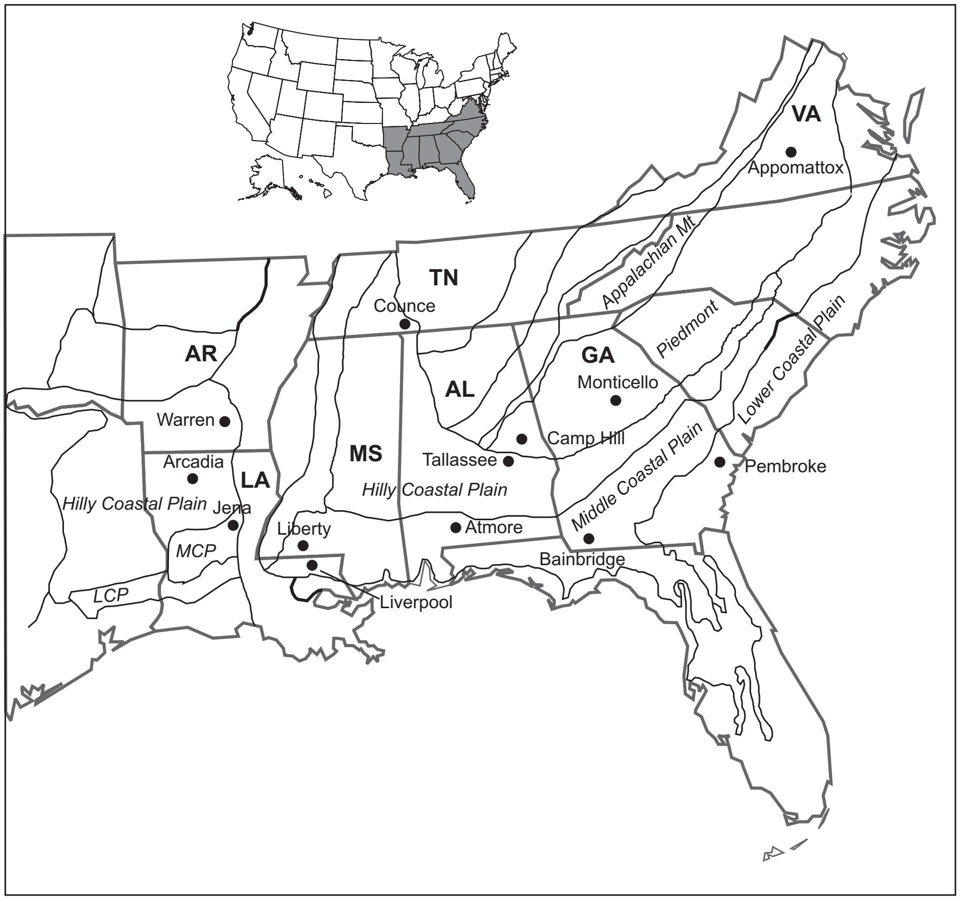
Methods

COMP study locations are distributed across the southern USA in four physiographic provinces from Louisiana to Georgia and northward to Tennessee and Virginia (Fig. 1). The climate encompassed by these scattered locations (30°48′–37°28′N, 78°47′–92°57′W) is humid temperate to subtropical with 200–300 days above 0 °C. Average growing-season rainfall (March to October) ranged from 600 to 1250 mm over the 15-year study period and mean January and July temperatures were 5–12 and 27–28 °C, respectively. Study sites were located on commonly occurring soil series for each province that had mostly sandy to sandy loam surface textures and increasing clay with depth, while the two most northerly locations (Counce, Tennessee, and Appomattox, Virginia) had more loamy surface soils (for more details see Miller et al. 1995*a*). Approximate site indices for loblolly pine calculated for plots without vegetation treatment ranged from 15 to 27 m at base age 25 years. Most sites were upland in topography except for an upper river-terrace site (Liberty, Mississipi), a bottomland site (Bainbridge, Georgia), and a poorly drained Lower Coastal Plain site that experienced winter flooding (Pembroke, Georgia). Elevations ranged from 10 m at the Lower Coastal Plain to 140 m in the Piedmont. The past history of most sites undoubtedly included an extended period of extractive row-crop farming on the more level blocks, evident from remnant terraces, followed by old-field succession with animal grazing and several timber harvests of pine–hardwood stands over a 100- to 250-year period (Sampson 2004).

Prior to establishment of the study, pine plantations or mixed pine–hardwood stands were stem-only harvested. At 10 locations, site preparation was by roller-drum chopping and prescribed burning. A shear-pile method was used at Counce that displaced topsoil into windrows, while at Atmore Alabama, a complete aboveground harvest removed most standing woody biomass from the site that did not require chopping. The seasonally wet forest on the Lower Coastal Plain site near Pembroke was rebedded (strip-mounded) after a wildfire destroyed a 6-year-old pine plantation, concentrating topsoil and debris along the planting rows. Additional details on each site, along with soil textures, can be found in Miller et al. (1995*a*, 2003*a*).

A factorial combination of two woody control treatments (no control of woody plants versus elimination of woody plants) and two herbaceous control treatments (no control of

Fig. 1. Competition Omission Management Project (COMP) study locations relative to physiographic provinces.



herbaceous plants versus elimination of herbaceous plants) were established in a randomized complete block design with four blocks at 12 of the 13 locations. The four treatments are designed as follows: no control (NC); woody control only (including hardwoods and shrubs) (WC); herbaceous control only (including semi-woody plants) (HC); and total control (TC). A completely randomized design was used at the uniform bottomland location. Treatment plots were 0.1 ha in size (32 m × 32 m) and interior measurement plots were 0.04 ha. Herbicide treatments were applied to appropriate treatment plots two or more times each year during the first 3–5 years to achieve control conditions (Miller et al. 1991).

Precisely measured planting spots on a 2.7 m × 2.7 m spacing were used at all but two operationally planted locations. The spacing resulted in an average of 1329 trees·ha^{1}, with 49 pines in the measurement plots with two border rows surrounding measurement plots. Height and diameter of pines in the interior plots were measured during the dormant season in years 1–11 and 15. Merchantable volume was calculated from these diameter and height data using the volume equations provided by Tasissa et al. (1997). In September of years 1–11 and 15 on three 2.7 m × 5.4 m sample plots per measurement plot, vegetative-cover estimates were recorded according to growth-form class (pine trees, nonpine trees, shrubs, and herbaceous components), as well as the dominant genera of herbaceous plants, woody vines, and semi-woody plants (for detailed procedures see Miller et al. 2003*a*).

Soils were initially sampled in April after site preparation was completed and pine seedlings had been planted (referred to as year 0). Uniformly spaced across each interior measurement plot, 20 soil-tube samples (2.5 cm diameter) were extracted from three depths: 0–15, 15–30, and 30–60 cm. Forest-floor and humus-layer materials were not included in soil samples, and soil bulk densities were not sampled. For each plot, samples were composited by depth, thoroughly mixed, cleared of large stones and roots, and stored in freezer bags in a cool room at 4 °C (often after rush shipping or cooler transportation) until further processing. At year 15, soils were sampled again in April in like manner, except that four soil-tube samples were extracted from around five predesignated numbered pines to yield the 20 samples. Samples were taken at a central position within a four-pine quadrant, equidistant from pines, according to Ruark and Zarnock (1992), and adjusted away from the base of large hardwood trees, shrub clumps, down wood, or old stumps. This meant that only interbed areas were sampled at Pembroke and interwindrow areas at Counce.

Cold-stored soil samples were further prepared by discarding rocks, roots, and charcoal bits immediately before air-drying for 3 days. In year 0, samples were crushed with a mill-grinder to pass a 2 mm mesh sieve, while year-15 samples were sieved (2 mm mesh) and ball-milled to a fine flour, as were year-0 samples for C and N analysis. All were placed again in cold storage until analysis. Two 5-g subsamples in year 0 and four 5-g subsamples in year 15 were each extracted with 20 mL Mehlich 1 (double weak acid) solution (0.05 mol/L HCl + 0.025 mol/L H_2SO_4). P was analyzed using the antimonylmolybdate – ascorbic acid colorimetric method of Watanabe and Olsen (1965). Determination of K, Ca, and Mg was by atomic absorption spectrometry. Three 0.5-g subsamples were analyzed with a C and N analyzer. The pH was determined on duplicate year-0 samples and quadruplicate year-15 samples with a 1:1 soil–water mixture and pH meter. All soil analyses were performed by the Auburn University Soil Testing Laboratory using the same procedures for year-0 and year-15 samples.

Composite samples of pine foliage were collected from each measurement plot in January following the 15th growing season, using the same procedures as in previous samplings after the second and sixth growing seasons (Zutter et al. 1999). Foliage was collected from the first growth flush of the previous growing season in the upper one-third of the crown according to the methods of Colbert and Allen (1996). Previous research has shown that maximum N and P concentrations in loblolly pine foliage occur in late winter (Zhang and Allen 1996). Twenty fascicles were collected from each of five trees that were also the designated center pines for soil sampling. Twelve sites were sampled consistently in this manner for the three sampling periods (year-2 and year-6 samplings were previously reported by Zutter et al. 1999), while the Liberty site was sampled for foliar analysis only in years 6 and 15.

Foliage samples were stored at 4 °C until they were oven-dried at 65 °C, weighed to determine fascicle mass, and ground in an electric Wiley Mill to pass through a 0.84 mm mesh screen. A 200-mg subsample of dried foliage was wet-digested using a combination of sulfuric acid and hydrogen peroxide (Parkinson and Allen 1975). These samples were then analyzed for total N and P using a Lachat QuickChem System IV colorimeter and for K, Ca, and Mg using atomic absorption spectrometry. Fascicle nutrient content was calculated by multiplying nutrient concentration, expressed as a proportion of dry mass, by mean fascicle mass. All foliar analyses were performed by the North Carolina State University Forest Nutrition Cooperative.

Data analysis

Four of the 208 total plots were deleted from the data set before analysis, owing to past land-use practices that led to exceptionally poor productivity, bark beetle infestations, or excessive ice damage. Also deleted were two blocks affected by severe wildfire at Tallassee, Alabama, and all foliar-nutrient data at Liberty because of incomplete sampling.

Pine and competition data were analyzed separately by location using the analysis of variance GLM procedure of SAS® 8.2 software (SAS Institute Inc. 1989), with percentages transformed by arcsine square root. For each soil nutrient and pH, a mixed-model analysis (PROC MIXED, SAS® version 9.1) was performed using plot-level data averaged across sampling depths to examine treatment effects at year 0 and year 15, the change represented by year 15 minus year 0, and the change attributable to main effects. Replications were nested in locations and the model was as follows: MODEL nutrient = location block treatment location × treatment; lsmeans location × treatment / slice = location. The main effects were defined as *woody treatment* (average of WC and TC vs. average of NC and HC), *herbaceous treatment* (average of HC and TC vs. average of NC and WC), and *woody treatment* × *herbaceous treatment interaction* (average of TC and NC vs. average of WC and HC). References in the text and tables to effects of "woody treatment" or "herbaceous treatment" apply to tests of main effects, whereas references to NC, WC, HC, or TC apply to the four treatments within the study design. Both actual changes and arcsine square root transformed percentage changes (year 15 minus year 0 divided by year 0) were analyzed. Foliar fascicle mass, nutrient content, and concentrations at year 15 were also analyzed using the same mixed-model analysis. With all analyses, an additional contrast was used to examine vegetation treatment versus no treatment. To further examine overall treatment influences, soil nutrient concentrations and pH values were averaged across depths and blocks to obtain location means, which were analyzed separately for each treatment using a SAS® test for homogeneity of the change represented by year 15 minus year 0, i.e, whether it differed from zero. Analyses for linear correlation were calculated among year-15 pine merchantable volume and soil nutrients using block means by location (*n* = 52). Linear correlation analysis was also performed for each location for foliar nutrients at the three sampling years and for year-15 pine merchantable volume. Finally, correlation analyses were performed using block means by location for soil nutrient concentrations at years 0 and 15 averaged across depths versus pine foliar nutrients at years 2, 6, and 15. A 0.05 level of probability for a Type I error was considered significant with all tests.

Results

Stand dynamics and components

Patterns of stand development were significantly altered by early vegetation-control treatments during the 15-year study period (Fig. 2) (Miller et al. 1991, 2003*a*). The participating species and successional dynamics of associated vegetation varied by location relative to hardwood and shrub abundance but progression showed similar trends (Miller et al. 1995*b*, 2003*a*). WC initially increased herbaceous cover to greater than 80%, on average, by year 2, while HC increased hardwood cover and decreased shrub cover, which varied widely by site according to initial hardwood rootstock densities (Miller et al. 2003*a*). Herbaceous cover, including leguminous forbs, remained significantly less with herbaceous treatments during the 15 years on HC and TC plots, and began to decline on NC and WC plots beginning in years 6–8. Low levels of hardwood and shrub reestablishment occurred at some locations on WC and TC plots starting about year 8, but averaged less than 30% cover at year 15. Thus, four different plantation stand types were created by the early intensive control treatments that varied in the amounts of woody and herbaceous components, while pine dominance characterized all plots. The rate of pine canopy development was most rapid on TC plots and varied somewhat by treatment until it reached similar levels, 80%–98% cover, by year 15. Pine litter dominated forest floors for all

Fig. 2. Overall mean cover of loblolly pine, non-pine woody plants (hardwoods and shrubs), and herbaceous plants on four vegetation-control treatments for 13 loblolly pine plantations through 15 years.

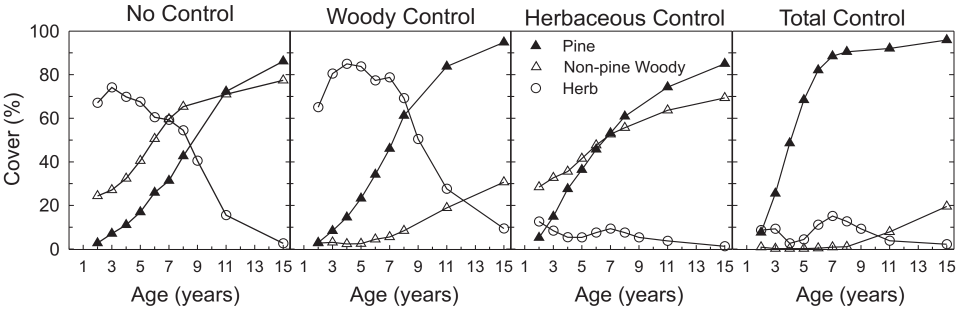
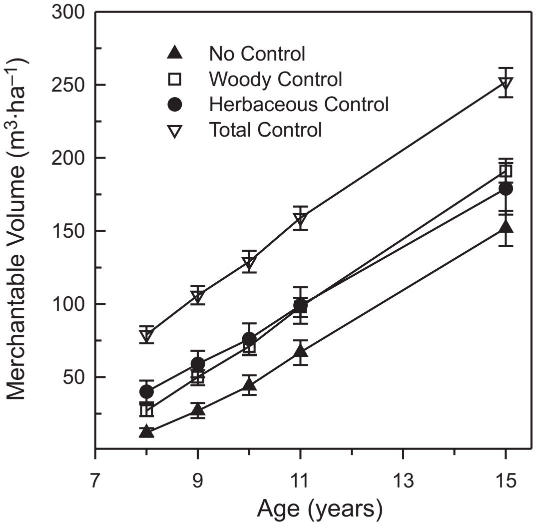


Fig. 3. Overall mean merchantable volume on four vegetation-control treatments for 13 loblolly pine plantations through 15 years. Bars indicate 1 SE above and below the mean.



treatments and sites, which contained varying amounts of hardwood, shrub, and herb litter according to treatment (observational information, since the forest floor was not sampled).

Merchantable pine volume increased, on average, by 23%–121% depending on location (average 66%) after TC relative to NC and the gains were greatest on sites where the most hardwoods and shrubs occurred and were controlled (Fig. 3). Overall gains with WC and HC became similar by year 8, with volume increases by year 15 averaging 20% with WC and 18% with HC. Early woody treatments increased year-15 merchantable pine volume on 11 sites by 14%–118%, while herbaceous treatment yielded somewhat less, on average: a 17%–50% increase on 10 sites (Miller et al. 2003*b*).

Soil nutrients

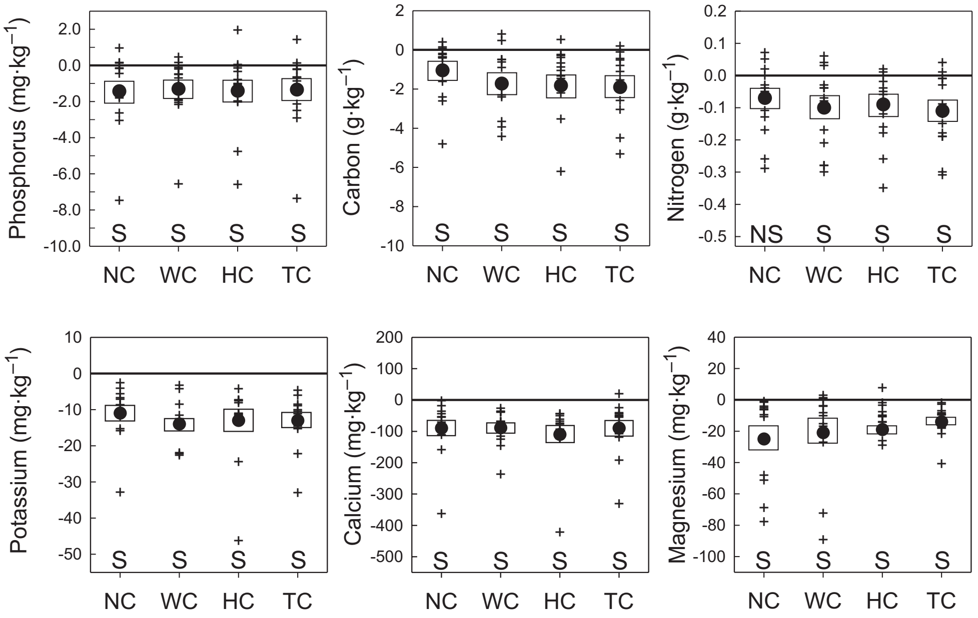
There were significant decreases in soil concentrations of P, C, N, K, Ca, and Mg during the 15-year period when averaged across the three depths and determined by analysis of homogeneity; the concentrations were fairly consistent regardless of treatment, except for N and C (Fig. 4). Averaged across depths, soil pH remained generally constant from year 0 to year 15, ranging from 4.4 to 5.9 depending on location (Table 1). It is recognized that pH can influence P concentration in soils, and thus there were also no treatment differences in soil P concentration (Table 1). However, there were consistent decreases in P concentration across all treatments (Fig. 4), ranging from –48% to –56% of initial levels. Only the periodically flooded site at Pembroke and the site with the lowest soil P concentration at Atmore, both near the coast, had increases in P concentration on all treatments. Generally, decreases in P concentration were greater in the upper soil depths, though decreases were evident at all three depths (Fig. 5).

The soil organic C concentrations decreased significantly with all treatments over the 15-year period, from –10% to –20% (Fig. 4, Table 1). Decreases in soil C concentration were significantly greater with vegetation-control treatments, particularly after herbaceous treatment (Table 1). Unlike P, decreases in C concentration were similar at all three depths (Fig. 5). The largest losses (2 to 4 times more than at other sites) occurred in soils at two locations having the lowest amount of hardwoods (Pembroke and Warren, Arkansas). Three central locations with the greatest amount of hardwoods were stable or had slight gains of 1 $g \cdot kg^{-1}$ in soil C (Tallassee, Camp Hill, Alabama, and Bainbridge).

Decreases in N concentration were significant after competition-control treatments, though not the NC treatment as determined by the analysis of homogeneity (Fig. 4). Overall year-15 N losses were –7% on NC and ranged from –9% to –13% after control treatments, which were not significant with the mixed-model analysis (although they were significant from the NC with an exploratory SAS® GLM analysis) (Table 1). Approximately half of the plots across locations had no N loss and stable N levels. Consistent N losses for all treatments occurred at those locations having the highest N levels at year 0 (Warren, Jena, Louisiana, Monticello, Georgia, and Pembroke). Trends in average N decreases by soil depth varied with treatment, while the loss was most notable at the 15–30 cm depth after HC and the 0–15 cm depth after TC (Fig. 5).

Consistent and significant decreases were documented for soil K, Ca, and Mg concentrations across most locations and treatments (Fig. 4). Soil losses averaged by nutrient ranged from –22% to –41% from year-0 levels (Table 1). As far as main effects are concerned, only the percent change in Ca concentration after herbaceous treatment was significant, while the actual change in Ca concentration was not. Both K and Mg concentrations decreased comparably by treatment. The K concentration decreased at all locations, while Ca and Mg concentrations decreased at all but one or two locations

Fig. 4. Actual change (year 15 minus year 0) for soil P, C, N, K, Ca, and Mg on four vegetation-control treatments (no control (NC), woody control (WC), herbaceous control (HC), and total control (TC)) averaged across three depths. Location means are indicated by a plus sign. The solid circle is the overall mean and the box denotes the SE; a test for homogeneity of the change is denoted (“S” denotes a value significantly different from zero ($P < 0.05$) and “NS” denotes a value that is not significantly different from zero).



where initial concentrations were high. K and Ca concentrations were highest, on average, in surface soils and the decrease diminished with depth (Fig. 5). Unlike the other nutrients, Mg concentrations increased with depth, while the decrease was similar for depths (Fig. 5).

Foliar nutrients

The general trends, as well as the site trends for the 13 locations, for fascicle mass and nutrient concentrations over the 15 years are evident in Figs. 6 and 7. In the absence of comparable data sets, it is debatable whether the trends from years 6 to 15 are repeatable or the result of environmental conditions in years 14 and 15 that influenced mass and nutrient concentrations of foliage sampled at year 15. Recognizing that retranslocation of nutrients is a long-term mechanism for conserving nutrients within trees, together with the uniqueness of this data set, Figs. 6 and 7 reveal only proposed trends that will require validation by other data sets. These figures show location means for years 2 and 6 not previously reported.

Most striking in the case of these four significantly different pine stand communities are the similarities, not the differences, in trends, especially from year 6 to year 15. The year-15 data extend the period of observation reported for years 2 and 6 by the COMP team (Zutter et al. 1999). By year 2, control treatments had resulted in significant differences in fascicle mass; the main effects of herbaceous treatment (increased mass at 11 sites) and woody treatment (increased mass at 7 sites) are evident in Fig. 2. Generally, fascicle mass increased in the order TC > WC > HC > NC (Fig. 6). In year 2, fascicle mass was less variable on NC and WC, with coefficients of variation (CV) of 13–14, while CV for year-2 HC was 22 and for TC was 23. As pines grew in volume and foliar fascicle mass severalfold from year 2 to year 6, fascicle mass varied substantially by location (treatment CVs = 19–25), while significant main-effect treatment differences were found at only two or three sites for each nutrient (Zutter et al. 1999). During years 2–6 there were consistent overall increases in fascicle mass, with increases in the order NC > WC > HC, to reach similar overall means, while TC plots decreased or increased depending on site to yield an overall constant mean. From year 6 to year 15, individual sites decreased, increased, or remained constant, to become less variable, with CVs ranging from 11 to 15 by year 15. From year 6 to year 15, overall mean fascicle mass declined only slightly by similar amounts for all treatments, indicating that maximum fascicle mass was generally attained by year 6. Fascicle mass did not vary by treatment in year 15 (Table 2).

The significant differences in year-2 fascicle mass were not evident in P concentration (Fig. 6): there was a generally consistent and level trend in P concentrations from year 2 to year 15, with the notable exceptions of the annually flooded stands at Pembroke (Zutter et al. 1999). Pembroke and Arcadia, Louisiana, had the lowest P levels in year 2 and Pembroke had the highest P concentrations in years 15. Overall mean P concentration varied by only 10% from year 2 to year 15, mainly because of increases from year 2 to year 6 on WC, HC, and TC, with two to six sites below critical P levels at any one year within a treatment. The overall and site means were almost identical for the four different treatments by year 15, with no differences indicated by the mixed-model analysis (Table 2).

The mixed-model analysis detected significant treatment differences in year-15 N levels, herbaceous treatment plots having the lowest content and concentration (Table 2). However, overall trends in foliar N concentration were very similar for the four treatments, with a general slight decrease from year 2 to year 6, often to below critical values, followed by an increase at most sites by year 15 to levels simi-

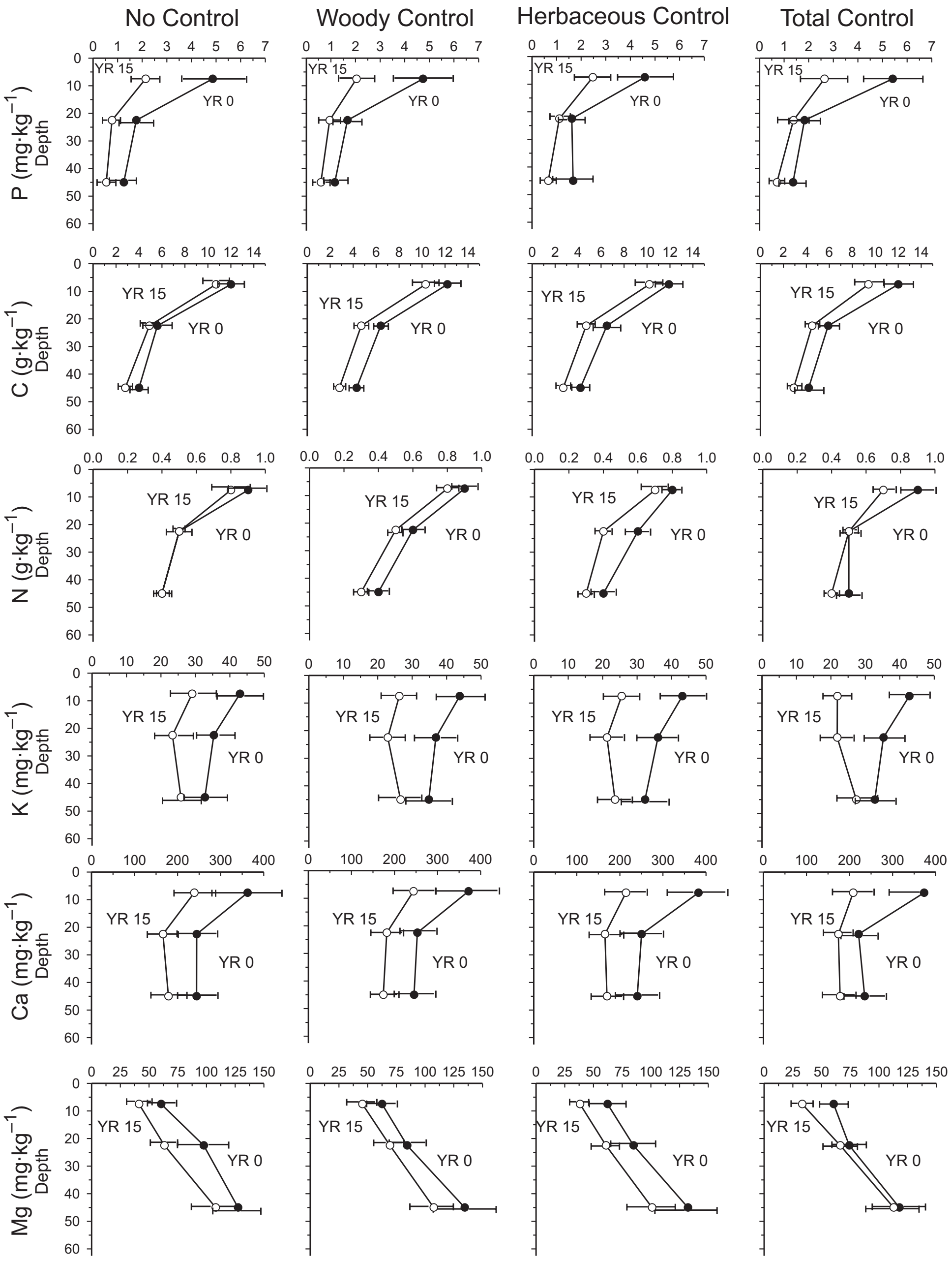
Table 1. Overall mean soil pH values and nutrient concentrations for 13 loblolly pine plantations averaged across three depths for year 0 and year 15, with actual and percent changes.

Type of control	Year 0	Year 15	Actual change	Percent change
pH				
None	5.21	5.17	–0.04	–0.6
Woody	5.21	5.22	+0.01	+0.3
Herbaceous	5.25	5.19	–0.06	–1.0
Total	5.22	5.17	–0.05	–0.8
Woody treatment			+0.03	+0.6
Herbaceous treatment			–0.04	–0.8
P concentration ($mg\cdot kg^{-1}$)				
None	2.55	1.12	–1.43	–56
Woody	2.41	1.11	–1.30	–54
Herbaceous	2.53	1.25	–1.28	–51
Total	2.78	1.44	–1.34	–48
Woody treatment			+0.03	+5.0
Herbaceous treatment			+0.05	+5.0
C concentration ($g\cdot kg^{-1}$)				
None	7.31	6.26	–1.05a	–10a
Woody	7.80	6.08	–1.72b	–15b
Herbaceous	7.60	5.78	–1.82b	–19b
Total	7.58	5.68	–1.90b	–20b
Woody treatment			–0.38	–3.0
Herbaceous treatment			–0.48*	–7.0*
N contentration ($g\cdot kg^{-1}$)				
None	0.63	0.56	–0.07	–7
Woody	0.65	0.54	–0.10	–9
Herbaceous	0.61	0.52	–0.09	–12
Total	0.63	0.53	–0.10	–13
Woody treatment			–0.03	–1.0
Herbaceous treatment			–0.01	–4.0
K concentration ($mg\cdot kg^{-1}$)				
None	38	27	–11	–35
Woody	39	25	–14	–38
Herbaceous	36	23	–13	–38
Total	37	24	–13	–40
Woody treatment			–1.5	–2.5
Herbaceous treatment			–0.5	–2.5
Ca concentration ($mg\cdot kg^{-1}$)				
None	291	201	–90	–33
Woody	289	200	–89	–32
Herbaceous	287	177	–110	–41
Total	273	183	–90	–35
Woody treatment			+10.5	+3.5
Herbaceous treatment			–10.5	–5.5*
Mg concentration ($mg\cdot kg^{-1}$)				
None	98	73	–25	–25
Woody	97	76	–21	–22
Herbaceous	86	67	–19	–22
Total	85	71	–14	–22
Woody treatment			+4.5	+1.5
Herbaceous treatment			+6.5	+1.5

Note: Values in a column followed by a different letter are significantly different at the 0.05 level as determined by the contrast of no control versus treated plots; values without letters are not significantly different.

*Main-effect values significantly different at the 0.05 level. The woody treatment × herbaceous treatment interaction is not significant.

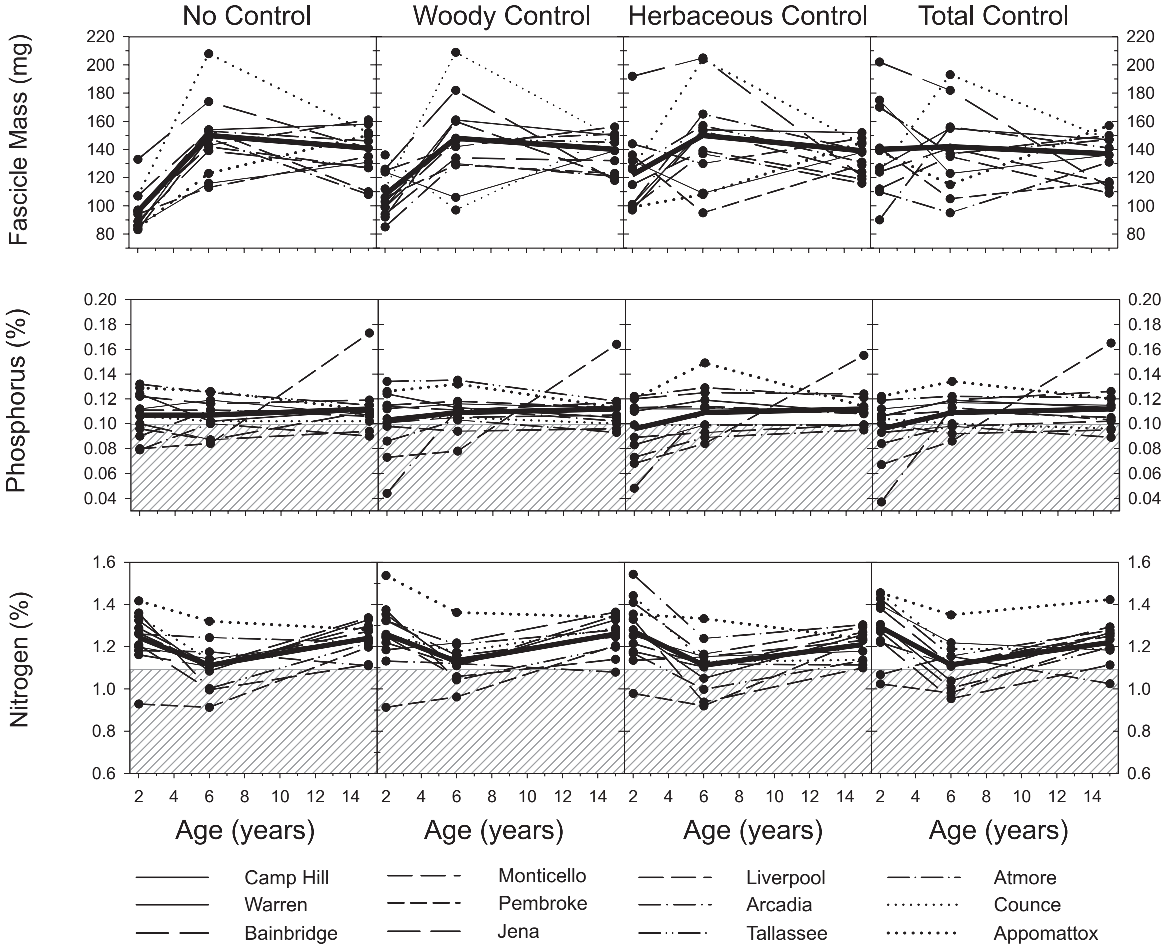
Fig. 5. Mean soil concentrations of P, C, N, K, Ca, and Mg at years 0 (●) and 15 (○) by vegetation-control treatment and depth. Bars indicate 1 SE above and below the mean.



lar to those at year 2 (Fig. 6). The variation among sites decreased from year 2 to year 15, with CVs at year 2 ranging from 10 to 12 by treatment and at year 15 ranging from 6 to 8. Four or five sites were below critical N levels at year 6 on all treatments, while by year 15, only two locations, Arcadia and Monticello, were at or below critical levels, regardless of treatment, and had also experienced decreases in soil N concentrations of –7% and –25%, respectively.

K concentrations had elevated levels on vegetation-control treatments at two to four sites at year 2 (Zutter et al. 1999), followed by generally level or slightly declining concentrations of similar amount for all treatments from year 6 to year 15 (Fig. 7). Only Pembroke had K concentrations below critical values. Foliar K concentrations were significantly different at year 15, levels being highest with NC, and herbaceous treatment resulting in lowered K contents and concentrations (Table 2). Ca followed a trend of the highest values at year 2, which were significantly decreased on 10 sites by herbaceous treatment and on 2 sites by woody treatment (Zutter et al. 1999), followed by similar trends across treatments in years 6–15. Warren had by far the highest Ca values at year 6, recognizing that it had the highest soil Ca values of all sites at year 0 (550–660 mg·kg^{-1}), then foliar Ca returned to concentrations similar to those at other sites by year 15. Pembroke had the lowest soil Ca concentrations (45–55 mg·kg^{-1}) and was the only site below critical

Fig. 6. Individual fascicle mass and foliar P and N concentrations at years 2, 6, and 15 by location and vegetation-control treatment. The hatched area of each graph shows the critical concentration (Allen 1987). The thick lines track the overall means.



values, regardless of treatment, by year 15. By year 15, Ca did not vary by treatment (Table 2).

Mg concentrations were the most influenced by vegetation-control treatments by year 2, as is evident in Fig. 7 (Zutter et al. 1999). Herbaceous treatment had significantly decreased concentrations on 12 sites and woody treatments had significantly decreased concentrations on 6 sites; these are evident in Fig. 7 as declining overall means from WC to HC to TC. HC at two sites and TC at six sites resulted in concentrations below critical values in year 2, the lowest levels occurring at Jena and Arcadia. These two locations had higher than average Mg levels in year-0 soils: 160 and 110 mg·kg^{-1}, respectively. As with Ca, Monticello and Appomattox had the lowest foliar Mg values at year 6, which were near or below critical levels, and both recovered to higher than average foliar levels by year 15. From year 6 to year 15, general increases in foliar Mg levels occurred at 12 locations, with the exception of Warren (Fig. 7). As with Ca, Warren had the highest Mg levels in year-0 soils (on average, 193 mg·kg^{-1}) and displayed a similar trend of exceptionally high foliar Mg levels at year 6, with a return to concentrations similar to those at other sites by year 15. Treatment differences were not evident in year-15 Mg content or concentration (Table 2).

Nutrient correlations

The combined data sets afforded a unique opportunity to examine the relationships between nutrient levels in soil and foliage using year-15 pine merchantable volume as a possible predictor. With regard to year-0 and year-15 soil nutrient concentrations, only moderately strong, positive correlation coefficients (r = 0.34–0.47) were significant for pH and K, Ca, and Mg levels (Table 3). Similar significant correlations existed between pine merchantable volume and year-15 soil levels for the same nutrients, except that K concentration was not significant. Soil C level and pine volume had a slight significant correlation at year 15, but was notably negative (r = –0.31). Soil levels of neither P nor N exhibited any distinct relationship with year-15 pine merchantable volume across all locations for either soil-collection year, even though these are considered the region's most limiting nutrients for pine growth.

Significant correlations with year-15 pine merchantable volume were only consistently evident with year-2 foliar fascicle mass and nutrient content and not year-6 or year-15 values when plot means at individual locations were analyzed. When the erratic, most westerly site, Jena, was excluded (Liberty was previously excluded because of incomplete sampling), significant fascicle-mass r values for

Fig. 7. Pine foliar K, Ca, and Mg concentrations at years 2, 6, and 15 by location and vegetation-control treatment. The hatched area of each graph shows the critical concentration (Allen 1987). The thick lines track the overall means.

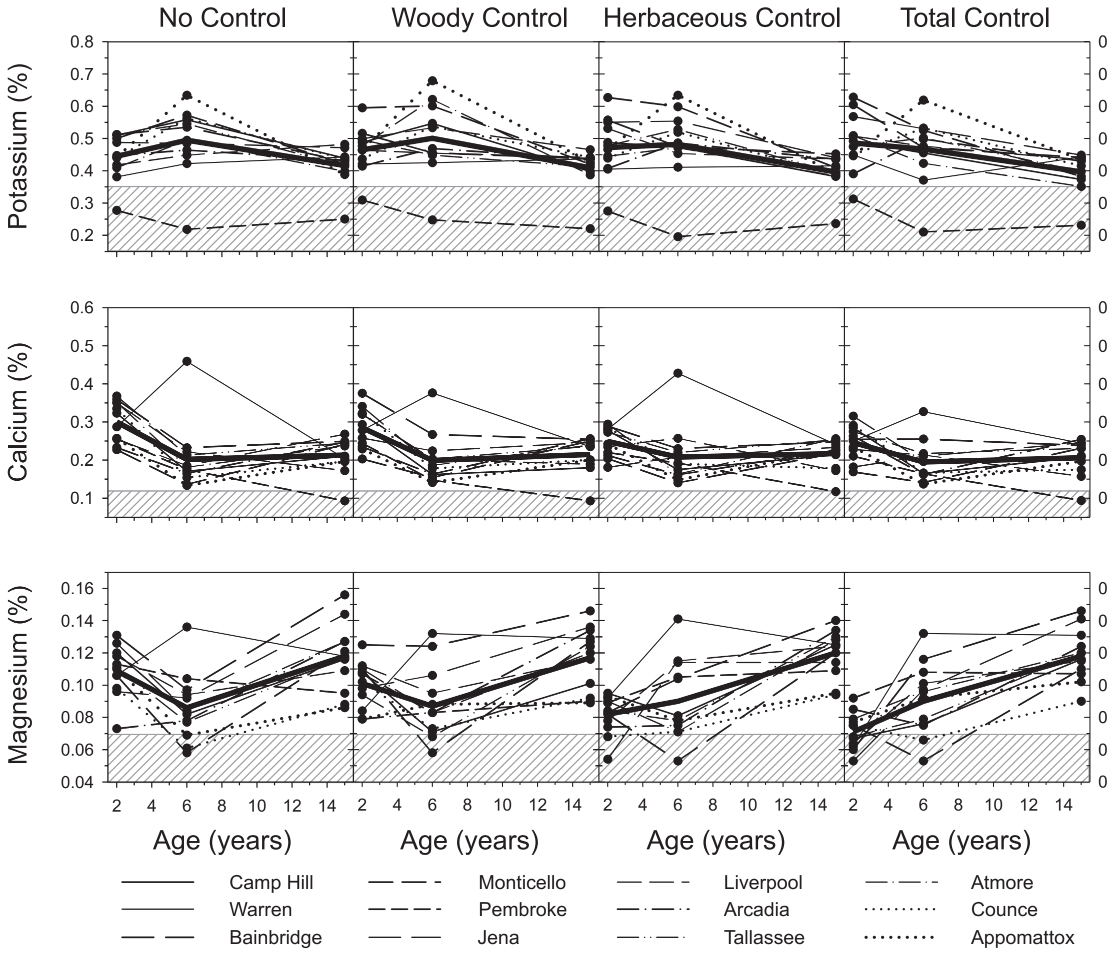


Table 2. Year 15 foliar fascicle mass, nutrient content, concentration, and responses to treatment and main effects.

Treatment	Fascicle mass (mg)	Content (mg·fascicle^{-1}) P	N	K	Ca	Mg	Concentration (%) P	N	K	Ca	Mg
No control	136.3	15.3	169.4	57.1	28.8	15.8	0.112	1.24	0.417a	0.213	0.117
Woody control	136.6	15.2	172.5	56.4	29.1	15.7	0.111	1.26	0.410b	0.214	0.116
Herbaceous control	133.1	14.8	160.8	52.9	28.5	15.9	0.111	1.21	0.396b	0.214	0.120
Total control	131.7	14.7	162.3	53.1	26.8	15.4	0.112	1.23	0.400b	0.205	0.118
Woody treatment	–0.5	–0.1	2.3	–0.2	–0.7	–0.3	0.000	0.023	–0.001	–0.004	–0.002
Herbaceous treatment	–4.1	–0.5	–9.4*	–3.8*	–1.3	–0.1	0.000	–0.029*	–0.016*	–0.004	0.002

Note: Values in a column followed by a different letter are significantly different at the 0.05 level as determined by the contrast of no control versus treatment; values without letters are not significantly different.

*Main-effect values significantly different at the 0.05 level. The woody treatment × herbaceous treatment interaction is not significantly different.

11 sites ranged from 0.59 to 0.85, with a median of 0.67. Because foliar nutrient concentrations showed few significant correlations regardless of year of collection, and year-2 fascicle mass was consistently and positively correlated with volume, then, as might be expected, specific nutrient contents were also consistently and positively correlated for year-2 foliage with year-15 pine merchantable volume. The most consistent were N and P contents. Correlation coefficients for year-2 foliar N content and pine merchantable volume were significant and positive at all 11 sites and ranged from 0.52 to 0.88, with a median of 0.64. Correlations of P level with volume were significant at nine sites and ranged from 0.57 to 0.90, with a median of 0.68. Only the two sites nearest the coast showed no significant correlations for foliar N and P contents, while both had significantly negative *r* values for P concentration with pine merchantable volumes of –0.50 (Pembroke) and –0.66 (Bainbridge).

The strongest correlations between soil and foliar nutrients occurred with P between year-15 soil concentrations and both year-15 concentrations and year-15 contents in fo-

Table 3. Correlation coefficients and probabilities between pine merchantable volume at year 15 and soil nutrient concentrations averaged across three depths at years 0 and 15 (n = 52).

	Year 0	Year 15
pH	**0.47**	**0.44**
	<0.01	**<0.01**
P concentration	0.16	–0.02
	0.27	0.88
C concentration	–0.11	**–0.31**
	0.44	**0.02**
N concentration	0.01	–0.17
	0.92	0.24
K concentration	**0.34**	0.23
	0.01	0.09
Ca concentration	**0.45**	**0.47**
	<0.01	**<0.01**
Mg concentration	**0.34**	**0.38**
	<0.01	**<0.01**

Note: Values in boldface type are significant at <0.05 probability.

liage (R = 0.72 and 0.63, respectively; Table 4). Foliar P concentrations in year 6 also showed a significant positive correlation with soil levels in year 0. Of all the nutrients, K concentrations for all samplings were most consistently and significantly correlated between foliage and soils, associations being moderate to weak (r = 0.39–0.66). For Ca the strongest correlations were between foliar concentrations in year 15 and soils in years 0 and 15 (r = 0.52 and 0.62, respectively).

Discussion

Distinct plant associations were created and maintained in pine plantations through 15 years by early control treatments, while general trends in soil and foliar nutrients due to treatment were few and confined principally to C and N. The general decrease in soil nutrient concentrations in the soil coarse fraction across all treatments was most noteworthy.

There are few documented long-term studies of forest soil nutrients for this region or anywhere in the USA; especially critical is the absence of soil C balances. These data presented from 13 locations, although just concentrations, significantly augment the few scattered reports. Organic C recognizably accumulates in merchantable and non-merchantable biomass, while little long-term net change has been observed in soils under forest cover (Richter et al. 1999). Maier et al. (2004) studied respiratory C use and storage in fertilized and non-fertilized loblolly pine stands at 12 years and concluded that non-fertilized stands at that age were neither a source nor a sink for atmospheric C. Any stored C was derived mainly from an increase in foliage and perennial woody biomass. In fact, decreases in soil C are expected during early stand development, as soil respiration rates are higher than C inputs (Henderson 1995; Powers 1999).

In one of the longest studied forest soils in the region, an initial period of C loss to year 15 of the same magnitude as those reported here, followed by a period of soil C accumulation, was documented during 36 years' monitoring of a loblolly pine plantation in the Piedmont of South Carolina (Richter et al. 1999). Decreases similar to those reported for COMP locations were also reported for K, Ca, and Mg at the South Carolina site during the 15-year period (Richter and Markewitz 1996). In general, Johnsen et al. (2001) surmised that C in southern forest soils may be relatively static, with inputs nearly equivalent to decomposition losses and only a small residual fraction potentially accumulating. Thus, it could be speculated from current reports and our findings that shortened rotations for conifers in the range of 15–20 years could be accompanied by low C concentrations in the soil. A succession of shortened rotations, then, could result in yield declines similar to those in agriculture (Mitchell et al. 1991). It should be noted that Powers et al. (2005) reported coarse-fraction C losses in two loblolly pine plantation sites in the southern USA, while fine-fraction C increased slightly or was unchanged in harvest-compacted soils. Therefore, a study of fractional classes and types of C in forest soils is warranted before firm conclusions can be reached.

Because only nutrient concentrations were measured, it could be argued that if soil bulk density increased from year 0 to year 15, then overall concentration decreases could have been offset. Also, treatment effects on bulk density might have compensated for concentration changes to result in no change in the rooting-zone outcomes. First, it should be recognized that sampling of concentrations was to 60 cm depth. This should have encompassed much of the herbaceous and shrub rooting zone and the zone of lateral roots and some taproots of tree species. Thus, most of the nutritional environment encountered by roots of both pines and associated vegetation would have been sampled regardless of density differences. Second, no treatment effects on bulk density were found in the 0–15 cm deep topsoil at three Piedmont and three Coastal Plain COMP locations sampled in year 7 (Lin 1994). Other reports of bulk densities are few, while a report from 26 locations of the Long-term Soil Productivity Experiment in North America showed a general decrease in bulk density for compacted forest soils after 10 years (Powers et al. 2005). In another report, Stransky (1981) studied mechanical site-preparation treatments of chopping and windrowing in east Texas and reported that recovery from compaction occurred in only 3 years. Further, it is not logical that bulk densities would have increased sufficiently over 15 years to offset the one-quarter to one-half decrease in these macronutrients.

The decreases in soil nutrients found during the 15-year period on COMP sites occurred during the period of high nutrient uptake by the stands, while N- and P-mineralization rates were low and N and P were being immobilized in the forest floor. Decreases in soil organic N similar to ours have been reported over a 20-year period for the Piedmont pine plantation on the Calhoun forest in South Carolina (Jorgensen and Wells 1986). We found that organic N decreases were lowest on plots where no vegetation control occurred, and this was most likely due to continued occupation by non-leguminous and leguminous N fixers like the com-

Table 4. Correlation coefficients and probabilities between soil nutrient concentrations at years 0 and 15 and pine foliar nutrients measured as concentration and content at years 2, 6, and 15 ($n = 48$).

		Concentration			Content		
Nutrient	Year	2 years	6 years	15 years	2 years	6 years	15 years
P	0	0.24	**0.53**	0.21	0.23	0.00	0.23
		0.11	**<0.01**	0.14	0.11	0.98	0.12
	15	–0.07	0.01	**0.72**	0.01	–0.20	**0.63**
		0.65	0.95	**<0.01**	0.95	0.15	**<0.01**
N	0	**–0.29**	–0.03	0.15	0.11	**–0.39**	0.09
		0.04	0.83	0.30	0.44	**0.01**	0.53
	15	0.22	**0.37**	**0.29**	0.13	–0.26	**0.38**
		0.14	**0.01**	**0.04**	0.37	0.08	**0.01**
K	0	**0.39**	**0.52**	**0.47**	0.20	**0.30**	**0.37**
		<0.01	**<0.01**	**<0.01**	0.17	**0.04**	**0.01**
	15	**0.47**	**0.66**	**0.42**	0.18	**0.47**	**0.31**
		0.01	**<0.01**	**0.01**	0.22	**<0.01**	**0.03**
Ca	0	**–0.35**	**0.47**	**0.52**	–0.24	**0.36**	**0.33**
		0.01	**<0.01**	**<0.01**	0.10	**0.01**	**0.02**
	15	**–0.40**	0.11	**0.62**	**–0.41**	0.12	**0.40**
		0.01	0.45	**<0.01**	**0.01**	0.38	**0.01**
Mg	0	–0.10	0.11	**0.33**	–0.03	**0.36**	0.23
		0.49	0.44	**0.02**	0.82	**0.01**	0.12
	15	–0.23	0.05	0.28	–0.12	**0.31**	0.25
		0.12	0.75	0.06	0.41	**0.03**	0.09

Note: Values in boldface type are significant at <0.05 probability.

mon shrub *Morella cerifera* and frequent herbaceous legumes in the genera *Chamaecrista*, *Desmodium, Lespedeza*, and *Mimosa* (Miller et al. 1995*b*, 2003*a*; Johnson and Curtis 2001). Earlier investigations at the Tallassee Hilly Coastal Plain location compared organic C and N levels at years 0 and 7 (Wood et al. 1992). During this period, net N gains on NC, HC, and WC treatments were attributed to N-fixing plants that were controlled on TC treatments. By as early as year 7, a net C loss was evident on all treatments. Evidence needed to understand the eventual equalization of treatments noted here at year 15 comes from another examination of litterfall and decomposition rates at the Tallassee location for C, N, and P at years 7–10 (Lockaby et al. 1995). During the 3-year examination, Lockaby et al. (1995) found that N and P litterfall content did not vary significantly by treatment, while greater litterfall on TC plots transferred more N and P. These greater transfers were offset by decreased decomposition rates for C and P on TC and WC treatments as well as greater rates of immobilization of N. Litter decomposition released C and P but immobilized N on all treatments during a 20-month period. Likewise, in a North Carolina loblolly plantation by year 17, the forest floor had net N and P immobilization over a 26 month period, while K, Ca, and Mg were released (Piatek and Allen 2001).

Both woody and herbaceous treatments had significant positive or negative effects on fascicle mass and foliar nutrient concentration and content at year 2 that were not evident at year 6 (Zutter et al. 1999). By year 15, vegetation-control treatments, especially herbaceous treatment, had reduced N and K concentrations in foliage. The early elimination of N-fixers, suspected in the lower N levels in soils, would have produced similar results with lower N concentrations in foliage. The foliar N concentrations are tightly linked with foliar K concentrations (Zhang and Allen 1996). Zhang and Allen (1996) concluded that, in general, stand growth will slow during midrotation to match soil N supplies in order to maintain foliar N levels in the 1.0%–1.2% range. With the majority of COMP treatments, concentrations were in this range at year 15.

Comparable long-term data for pine foliar nutrients are few for this region. Foliar N and P levels at year 15 reported here are similar to those reported for a 15-year study at a North Carolina site by Piatek and Allen (2000), while fertilization only elevated levels to the same range reported here for non-fertilized sites. Piatek and Allen (2000) found no differences in N and P concentrations relative to varying intensities of mechanical site preparation and vegetation control, although hardwood levels comparable to on COMP treatments were found to decrease pine foliar production by 56%, but did not reduce re-translocation rates. Rates of re-translocation from senescing foliage of 56%–69% for N and 58%–78% for P indicate the retention capabilities of loblolly pine after maximum nutrient acquisition that occurs in regional soils from years 0–8 (Wells and Jorgensen 1975). Thus, the increased growth exhibited on vegetation-control treatments at the COMP sites could enhance re-translocation retention in these stands compared with those receiving no vegetation control. Further, the enhanced growth could lead to a dilution of available nutrients in foliage, resulting in the equalizing effect documented in these stands.

Conclusions

Fifteen years after establishment of 13 loblolly pine plantations on previously forested sites, soil concentrations were about one-half of the initial available P, one-third of K and Ca, and one-quarter of C, N, and Mg. These percentages of decrease in the upper 60 cm were of a magnitude that could not be offset or explained by potential increases in bulk densities, which were not measured in this research. The magnitude of the consistent decreases in concentrations of essential nutrients represents a possible cause for concern with regard to sustaining intensive plantation culture on this region's historically degraded soils following 100–200 years of extractive agriculture and forestry, especially if final harvest rotations approach 15 years and thinning removal of nutrients increases. Clearly, most forest-soil systems of the South will not be able to provide enough nutrients to meet the increased demands of wood production unless management systems and treatments improve nutrient supplies through fertilization or increase the availability of existing nutrients at times when they are required for vigorous stand development. In another approach, alternative silvicultural systems (i.e., not even-aged) could be used to avoid these losses, rather than having to redress the losses through nutrient inputs.

Intensive herbaceous plant control treatments were associated with more pronounced decreases in soil C and N, which were reflected in reduced pine foliage N and K levels at year 15. The early abundant herbaceous flora that characterizes these plantations appears to be critical for conserving C in soils and maintaining N-fixation inputs. Further research is needed to identify the competitive and beneficial attributes of specific herbaceous genera so that wiser control programs can be formulated. Current forest vegetation control strategies should consider treatments that selectively leave legumes and minimize herbaceous control relative to pine growth gains.

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