



## Influence of CO<sub>2</sub> enrichment and nitrogen fertilization on tissue chemistry and carbon allocation in longleaf pine seedlings

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### Abstract

One-year old, nursery-grown longleaf pine (*Pinus palustris* Mill.) seedlings were grown in 45-L pots containing a coarse sandy medium and were exposed to two concentrations of atmospheric CO<sub>2</sub> (365 or 720 μmol<sup>-1</sup>) and two levels of nitrogen (N) fertility (40 or 400 kg N ha<sup>-1</sup> yr<sup>-1</sup>) within open top chambers for 20 months. At harvest, needles, stems, coarse roots, and fine roots were separated and weighed. Subsamples of each tissue were frozen in liquid N, lyophilized at -50 °C, and ground to pass a 0.2 mm sieve. Tissue samples were analyzed for carbon (C), N, nonpolar extractives (fats, waxes, and oils = FWO), nonstructural carbohydrates (total sugars and starch), and structural carbohydrates (cellulose, lignin, and tannins). Increased dry weights of each tissue were observed under elevated CO<sub>2</sub> and with high N; however, main effects of CO<sub>2</sub> were significant only on belowground tissues. The high N fertility tended to result in increased partitioning of biomass aboveground, resulting in significantly lower root to shoot ratios. Elevated CO<sub>2</sub> did not affect biomass allocation among tissues. Both atmospheric CO<sub>2</sub> and N fertility tended to affect concentration of C compounds in belowground, more than aboveground, tissues. Elevated CO<sub>2</sub> resulted in lower concentrations of starch, cellulose, and lignin, but increased concentrations of FWO in root tissues. High N fertility increased the concentration of starch, cellulose, and tannins, but resulted in lower concentrations of lignin and FWO in roots. Differences between CO<sub>2</sub> concentrations tended to occur only with high N fertility. Atmospheric CO<sub>2</sub> did not affect allocation patterns for any compound; however the high N treatment tended to result in a lower percentage of sugars, cellulose, and lignin belowground.

**Abbreviations:** FWO – fats, waxes, and oils, Cel – cellulose, SC – structural carbohydrates, Lig – Lignin, Tan – tannins, NSC – nonstructural carbohydrates, TC – total carbon.

### Introduction

Substantial research has demonstrated positive effects of increasing CO<sub>2</sub> in the atmosphere on plants, including increased growth and yield (Rogers and Dahlman, 1993; Wittwer, 1990), increased photosynthesis (Long and Drake, 1992; Radin et al., 1987), and decreased respiration (Amthor et al., 1992; Bunce, 1990; Wullschleger et al., 1994) for many plant species. It is this increased C uptake and assimilation which re-

sults in increased phytomass production; and, in many cases, the largest proportion of this extra phytomass is found belowground (Prior et al., 1994; Rogers et al., 1994; Wittwer, 1978). Increased C from elevated atmospheric CO<sub>2</sub> can also enter the rhizosphere via root growth, turnover, and exudation (Lekkerkerk et al., 1990; Norby et al., 1987; Pregitzer et al., 1995; Zak et al., 1993). There is increasing recognition that belowground responses to the CO<sub>2</sub> environment aboveground may be the critical missing link in our analysis of ecosystem responses to a changing atmosphere.

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The primary effect of elevated CO<sub>2</sub> is to increase the rate of photosynthesis, and enhanced photosynthesis is likely to increase the amount of C allocated to sinks, especially to root systems. In yellow-poplar (*Liriodendron tulipifera* L.) saplings grown in open top field chambers with elevated CO<sub>2</sub>, photosynthesis was enhanced and remained so throughout three growing seasons (Norby et al., 1992). This did not result in a significant increase in plant mass, but rather a change in allocation from leaf production to fine root production and an apparent increase in C flux through the root system.

An increased supply of photosynthate to roots could alter root chemistry. Elevated CO<sub>2</sub> increased carbohydrate concentrations in loblolly pine (*Pinus taeda* L.) seedlings by 68% and compensated for the decline in carbohydrates caused by water stress (Tschaplinski et al., 1993). The concentration of non-structural carbohydrates in roots of cotton (*Gossypium hirsutum* L.) plants was 2 to 4 fold higher in elevated CO<sub>2</sub> (Wong, 1990). Carbon to nitrogen ratio (C:N) of roots of the marsh plant, American bulrush (*Scirpus americanus* Pers.), was 22% higher under CO<sub>2</sub>-enriched conditions (Curtis et al., 1990). Nitrogen concentration in roots also tended to be lower under elevated CO<sub>2</sub> in white oak (*Quercus alba* L.) and yellow-poplar fine roots from field-grown saplings (Norby et al., 1995) and in fine roots from potted *Quercus* spp. and *Liriodendron* spp. seedlings (Norby and O'Neill, 1989; Norby et al., 1986). Despite the increasing attention forest species are receiving in CO<sub>2</sub> effects research, there remain a paucity of data describing the effects of atmospheric CO<sub>2</sub> on the concentration of secondary metabolites, such as lignin and tannins, in plant tissues. The objective of this study was to examine the effects of elevated atmospheric CO<sub>2</sub>, combined with soil N fertilization, on tissue chemistry of longleaf pine (*P. palustris* Mill.).

## Materials and methods

### *Plant growth and exposure system*

Longleaf pine seedlings, from a wild seed source, were lifted from a Florida nursery in February 1993. Seedlings were stored (2 °C) for less than one week, graded (mean root collar diameter = 13 mm; standard deviation = 2), and planted on February 25, 1993 into 45-L plastic containers containing a coarse sandy medium (pH 5.1) which was low in mineral elements

(P, K, mg, and Ca = 0.9, 5.6, 6.9, and 26.6 mg kg<sup>-1</sup>, respectively).

Treatments were arranged in a split-plot design with five replications. Carbon dioxide treatments (main plots) were randomly assigned to chambers. Nitrogen treatments (subplots) were randomly assigned within each chamber. To avoid within chamber location effects, pot locations were re-randomized monthly.

Seedlings were exposed to ambient ( $\approx 365 \mu\text{mol CO}_2 \text{ mol}^{-1}$ ) or elevated ( $\approx 720 \mu\text{mol CO}_2 \text{ mol}^{-1}$ ) CO<sub>2</sub> within an open top chamber system similar to that described by Rogers et al. (1983). The chambers, CO<sub>2</sub> supply, and CO<sub>2</sub> monitoring systems have been previously described for this study site (Mitchell et al., 1995). Carbon dioxide exposures were initiated on March 30, 1993 and continued until November 28, 1994 (20 months). Average daytime CO<sub>2</sub> concentrations ( $\pm$  standard deviation) through the duration of the experiment were  $372.3 \mu\text{mol}^{-1}$  ( $\pm 19.0$ ) in the ambient chambers and  $739.5 \mu\text{mol}^{-1}$  ( $\pm 39.7$ ) in the elevated CO<sub>2</sub> chambers.

Nitrogen treatments were similar to those described by Bazzaz and Miao (1993) with slight modification. Nitrogen treatments consisted of applying either 400 or 40 kg N ha<sup>-1</sup> yr<sup>-1</sup> at three-month intervals (as sulfur coated urea; 38-0-0) which correspond to high and low N treatments. Fertility of other nutrients was maintained in non-limiting levels in all pots by application of sulfur coated potassium (0-0-47 = 80 kg K ha<sup>-1</sup> yr<sup>-1</sup>) and MicroMax<sup>TM</sup> Plus<sup>1</sup> (0-4-0; P = 280, Ca = 1140, Mg = 560, and S = 100 kg ha<sup>-1</sup> yr<sup>-1</sup>, plus a complete compliment of micronutrients) mixed into sand at the time containers were filled, with a second application at the end of the first year. Iron chelate (0.007 mg Fe g<sup>-1</sup> soil) was applied once in April 1993. Nitrogen treatments were initiated at the time of planting and CO<sub>2</sub> treatments were initiated March 30, 1993.

Longleaf pine xylem pressure potential was measured periodically using a pressure chamber apparatus (Scholander et al., 1965). Gravimetric measurements of each container were made two times each week using a scale (Model LP-C4, 101 kg; Tri-Coastal Industries, Mukilteo, Washington, USA.). Gravimetric measurements were correlated with pre-dawn xylem pressure potentials, measured on excised needles at each weighing for one month. Trees received water

<sup>1</sup> Trade names and products are mentioned solely for information. No endorsement by the USDA is implied.

Table 1. Concentration of N and C fractions in *Pinus palustris* tissue after 20 months of growth at ambient and elevated CO<sub>2</sub> with high and low N soil fertility in open top chambers

Tissue	Treatment		Biomass (g)	Nitrogen mg N g <sup>-1</sup> tissue	Carbon Fractions					
	CO <sub>2</sub> (μmol mol <sup>-1</sup> )	Nitrogen (kg ha <sup>-1</sup> yr <sup>-1</sup> )			FWO <sup>a</sup>	Sugar	Starch	Cellulose	Lignin	Tannin
Needles	365	40	22.9 b <sup>b</sup>	6.1 c	166.7 a	7.0 a	239.0 a	412.2 a	152.0 a	23.0 ab
	720	40	19.4 b	5.8 c	161.6 a	6.9 a	248.0 a	408.5 a	148.2 a	26.7 a
	365	400	153.6 a	14.5 a	175.7 a	6.6 a	264.4 a	383.6 a	155.6 a	14.1 b
	720	400	181.5 a	10.9 b	145.2 a	7.2 a	281.0 a	394.0 a	155.0 a	17.7 ab
Stems	365	40	12.8 c	2.6 c	279.6 a	6.1 a	164.5 a	370.2 a	158.5 a	21.0 a
	720	40	17.1 bc	3.5 c	355.4 a	5.4 a	146.2 a	322.4 a	151.8 a	18.9 a
	365	400	60.4 ab	13.5 a	233.7 a	6.4 a	234.6 a	327.1 a	166.8 a	31.4 a
	720	400	97.7 a	8.7 b	347.3 a	5.5 a	173.8 a	313.6 a	141.4 a	18.5 a
Taproots	365	40	16.8 c	3.1 c	226.5 a	6.2 a	311.8 ab	268.8 a	157.2 ab	29.6 b
	720	40	15.8 c	3.8 c	364.9 a	5.2 a	119.2 c	302.3 a	194.7 a	13.6 c
	365	400	44.7 b	8.8 a	278.9 a	5.8 a	241.1 b	276.7 a	162.5 ab	34.7 b
	720	400	74.1 a	6.0 b	249.4 a	6.0 a	405.1 a	195.4 a	94.1 b	49.9 a
Laterals	365	40	15.9 c	4.0 c	353.2 a	5.0 a	194.6 a	267.5 a	166.0 a	13.6 ab
	720	40	16.2 c	4.1 c	356.9 a	5.3 a	179.4 a	270.1 a	176.3 a	12.0 b
	365	400	87.8 b	9.4 a	315.4 a	5.5 a	250.2 a	240.3 a	167.2 a	21.4 a
	720	400	140.9 a	6.3 b	387.0 a	5.2 a	220.9 a	231.0 a	140.8 a	15.1 ab
Fine Roots	365	40	9.5 b	6.1 b	333.4 b	8.1 a	114.7 b	278.5 ab	251.7 a	13.4 a
	720	40	11.0 b	5.4 b	502.8 a	6.4 a	74.0 b	225.9 b	180.4 b	10.4 a
	365	400	32.6 a	13.4 a	197.6 b	7.5 a	191.8 a	334.9 a	252.8 a	15.3 a
	720	400	46.0 a	7.9 b	339.6 b	7.9 a	134.7 ab	269.2 b	232.7 ab	16.1 a

<sup>a</sup>FWO = fats, waxes and oils.

<sup>b</sup>For each tissue, in each column within each tissue type, values followed by the same letter are not significantly different as determined by the Least Square Means Test ( $p \leq 0.05$ ),  $n = 5$ .

sufficient to return them to field capacity weight when gravimetric measurements indicated a xylem pressure potential of  $-0.5$  MPa had been reached. Pre-dawn xylem pressure potential continued to be taken a minimum of once each month as a check on gravimetric readings. Gravimetric measurements were again correlated with pre-dawn xylem pressure potentials to establish new field capacity values after November, 1993 (8 months) and July 1994 (16 months) to compensate for changes in plant mass; xylem pressure potential was measured on each container for one month following determination of new field capacity weights. Deionized water was used in order to ensure that fertility treatments remained unaffected by watering.

#### Plant harvests

One container from each N treatment in each chamber was destructively harvested in November 1994, corresponding to 20 months of CO<sub>2</sub> exposure. Plants were separated into tissue component parts (needles, stems, taproots, lateral roots, and fine roots), oven dried at 55 °C to a constant weight, and dry weight recorded. A detailed description of treatment effects on biomass production and morphological variables has been previously reported (Prior et al., 1997).

#### Tissue analysis

A 0.2 g subsample from each plant tissue was analyzed for C fractions. Soluble fats, waxes and oils were removed using a series of dichloromethane washes (TAPPI, 1975). Sugars and starches were removed

and measured using methods described by Hanson and Moller (1975). Cellulose and lignin were determined gravimetrically (Effland, 1977). Hot water extractable tannins were extracted and measured by methods described by Allen et al. (1974). Proximate C fractions were corrected for ash and presented as ash-free dry weight (Ryan et al., 1990). Tissue N content was determined with a LECO CHN-600 analyzer (LECO Corp., St. Joseph, MI).

#### *Data analysis*

Data were totaled for each seedling and averaged for each container prior to analysis. Data were tested for homogeneity of variance and transformations to achieve normality were not necessary. Data analysis was conducted using the General Linear Models (GLM) procedure of the Statistical Analysis System (SAS, 1990). Error terms appropriate to the split-plot design were used to test the significance of main effects variables and their interactions. Residuals were equally distributed with constant variances. Significance was determined at  $p \leq 0.05$  with the Least Square Means test.

## **Results**

#### *Concentration (mg g<sup>-1</sup>)*

Biomass of all tissues (needles, stems, taproots, lateral roots, and fine roots) was usually greater when plants received the high N treatment regardless of CO<sub>2</sub> concentration (Table 1). In general, biomass of all tissues was greater when plants received both elevated CO<sub>2</sub> and N. The effects of elevated CO<sub>2</sub> and N on concentration of C fractions were observed for belowground, but not aboveground, tissues. Elevated CO<sub>2</sub> resulted in lower concentrations of starch, cellulose, and lignin, but increased the concentration of FWO in root tissues. High N fertility increased the concentration of starch, cellulose, and tannins, but resulted in lower concentrations of lignin and FWO in roots. Interactions between CO<sub>2</sub> and N often occurred with differences between CO<sub>2</sub> concentrations only with high N fertility. Nitrogen concentration (mg g<sup>-1</sup>) was significantly greater in all tissues for plants grown in the high N treatment. Elevated CO<sub>2</sub> resulted in lower N concentrations for all tissues when grown with the high N treatment.

In fine roots, FWO were significantly higher when plants received elevated CO<sub>2</sub> with low N. Starches in

fine roots were higher for plants receiving high N, particularly with ambient CO<sub>2</sub>. Starches in taproots were greater for plants in elevated CO<sub>2</sub> and high N; however, in low N, starch concentration in taproots was greater for ambient CO<sub>2</sub>-grown plants. Lignin concentration was lower while the concentration of cellulose was higher in fine roots in plants grown under ambient CO<sub>2</sub>. Lignin concentration in taproots tended to be lower when plants received both elevated CO<sub>2</sub> and elevated N. Tannin concentration in taproots was higher for plants in elevated CO<sub>2</sub> and high N.

#### *Allocation (% in tissue of total tree)*

Biomass partitioning was higher in needles, but was lower in taproots and fine roots, when plants received high N (Table 2). Biomass partitioning to needles was greater for plants in ambient CO<sub>2</sub> in both N treatments. CO<sub>2</sub> concentration had no effect on N partitioning among tissues. A greater percentage of N was allocated to needles, and less to taproots and fine roots for plants receiving the high N treatment.

Partitioning of sugars to needles and lateral roots tended to be increased in plants receiving high N; however, allocation of sugars to taproots was lower for high N-grown plants (Table 2). Treatment effects on allocation of cellulose were seen only in needles, where allocation was greater for plants receiving high N. Allocation of tannins to taproots was lower in the low N treatment for elevated, compared to ambient, CO<sub>2</sub>-grown plants; also, allocation was higher for plants grown in high N and elevated CO<sub>2</sub>, compared to plants receiving low N and elevated CO<sub>2</sub>. Allocation of tannins to lateral roots was greater for plants receiving high N, particularly for ambient CO<sub>2</sub>-grown plants.

#### *Ratios among C components in tissues*

Treatment effects on ratios involving structural C (SC = cellulose + lignin + tannins) were infrequent and, with the exception of the ratio of tannins to total structural C (Tan:SC), were only observed for belowground tissues (Table 3). There were no treatment effects on the distribution of lignin as a percentage of total structural C (Lig:SC). The ratio of tannin to structural C (Tan:SC) was higher in taproots of elevated CO<sub>2</sub>-grown plants receiving the high N, compared to low N, treatment. The ratio of nonstructural carbohydrates (NSC = starches + sugars) to total structural C (NSC:SC) tended to be higher in needles, taproots, and fine roots of plants receiving the high N treatment.

Table 2. Allocation of N and C fractions in *Pinus palustris* tissue after 20 months of growth at ambient and elevated CO<sub>2</sub> with high and low N soil fertility in open top chambers

Tissue	Treatment		Biomass (%)	Nitrogen % of total	Carbon Fractions (% of total in tissue)					
	CO <sub>2</sub> (μmol mol <sup>-1</sup> )	Nitrogen (kg ha <sup>-1</sup> yr <sup>-1</sup> )			FWO <sup>a</sup>	Sugar	Starch	Cellulose	Lignin	Tannin
Needles	365	40	29.6 b <sup>b</sup>	41.1 ab	19.3 ab	32.6 bc	33.0 c	37.4 ab	26.8 b	32.6 a
	720	40	24.9 c	32.1 b	12.1 b	29.3 c	38.0 b	32.4 b	22.2 b	38.7 a
	365	400	40.5 a	47.4 a	30.7 a	42.4 a	43.3 a	48.1 a	37.4 a	27.2 a
	720	400	33.7 b	43.6 a	17.6 b	39.0 ab	37.7 b	44.9 a	36.1 a	27.8 a
Stems	365	40	16.4 a	9.6 a	18.1 a	15.7 a	12.3 a	18.5 a	15.2 a	16.5 a
	720	40	21.0 a	16.3 a	23.4 a	19.2 a	18.4 a	21.3 a	18.9 a	22.1 a
	365	400	16.0 a	17.4 a	16.3 a	16.5 a	15.4 a	16.1 a	15.7 a	24.2 a
	720	400	17.8 a	18.6 a	22.2 a	15.6 a	12.9 a	18.4 a	17.2 a	15.8 a
Taproots	365	40	21.7 a	14.7 ab	18.8 a	21.1 a	31.5 a	17.6 a	20.2 a	31.1 a
	720	40	19.4 ab	16.7 a	21.8 a	17.1 ab	14.6 b	18.6 a	21.9 a	15.8 b
	365	400	11.8 c	8.3 c	14.2 a	10.8 c	11.5b	9.9 a	11.2 b	19.3 ab
	720	400	13.6 bc	9.6 bc	12.3 a	13.2 bc	21.7 ab	9.6 a	8.8 b	31.1 a
Laterals	365	40	20.1 a	17.8 a	27.1 a	15.0 b	16.6 a	16.2 a	19.5 a	11.3 b
	720	40	20.6 a	18.8 a	21.6 a	18.7 ab	22.8 a	17.8 a	21.6 a	14.7 ab
	365	400	23.2 a	17.7 a	31.2 a	20.2 ab	23.2 a	17.2 a	22.9 a	23.1 a
	720	400	26.3 a	20.0 a	37.3 a	21.6 a	23.3 a	20.0 a	24.3 a	18.9 ab
Fine Roots	365	40	12.2 ab	16.8 a	16.7 ab	15.6 a	6.5 a	10.4 a	18.2 a	8.5 a
	720	40	14.0 a	16.2 a	21.1 a	15.8 a	6.3 a	9.9 a	15.4 a	8.7 a
	365	400	8.5 b	9.3 b	7.6 c	10.2 a	6.6 a	8.7 a	12.7 a	6.2 a
	720	400	8.6 b	8.2 b	10.7 bc	10.7 a	4.5 a	7.7 a	13.6 a	6.3 a

<sup>a</sup>FWO = fats, waxes and oils.

<sup>b</sup>For each tissue, in each column within each tissue type, values followed by the same letter are not significantly different as determined by the Least Square Means Test ( $p \leq 0.05$ ),  $n = 5$ .

In contrast to C, ratios involving tissue N concentrations were observed for all tissues except fine roots. Lignin to N ratios (Lig:N) and ratios of structural C to N (SC:N) were higher in plants growing under low N. Lig:N and SC:N ratios of belowground tissues were not affected by CO<sub>2</sub> treatment; however, Lig:N and SC:N of needles were higher for elevated CO<sub>2</sub>-grown plants in the high N treatment, while Lig:N and SC:N in stems were higher for ambient CO<sub>2</sub>-grown plants in low N.

## Discussion

Effects of CO<sub>2</sub> and N on concentration of C compounds (FWO, sugars, starches, cellulose, lignin, and tannins) tended to occur belowground rather than aboveground, especially in the taproots and fine roots.

A similar response was observed for biomass and this tendency for atmospheric CO<sub>2</sub> to enhance belowground more than aboveground growth has been previously noted (Prior et al., 1994; Rogers et al., 1994; Wittwer, 1978). Carbon dioxide by N interactions indicated that elevated CO<sub>2</sub> increased tissue dry weights only when combined with high N. This interaction of CO<sub>2</sub> with soil fertility has been commonly reported (Griffin et al., 1993; Pérez-Soba et al., 1995; Prior et al., 1997; Walker et al., 1995), although exceptions have been noted with some tree species (Johnson et al., 1995; Norby et al., 1995).

Although previous research has investigated CO<sub>2</sub> effects on plant biomass, few studies have examined changes in plant chemistry under increased levels of atmospheric CO<sub>2</sub>, and these have been restricted to foliar effects (Lindroth, 1996; Lindroth et al., 1993; O'Neill and Norby, 1996). In this study, changes in the

Table 3. Allocation of C ratios in *Pinus palustris* tissue after 20 months of growth at ambient and elevated CO<sub>2</sub> with high and low N soil fertility in open top chambers

Tissue	Treatment		Cel/SC <sup>a</sup>	Lig/SC	Tan/SC	NSC/SC	SC/TC	Lig/N	SC/N
	CO <sub>2</sub> (μmol mol <sup>-1</sup> )	Nitrogen (kg ha <sup>-1</sup> yr <sup>-1</sup> )							
Needles	365	40	70.2 a <sup>b</sup>	25.9 a	3.9 ab	0.42 c	58.7 a	24.9 a	96.2 a
	720	40	70.0 a	25.4 a	4.6 a	0.44 bc	58.3 a	25.9 a	102.1 a
	365	400	69.3 a	28.1 a	2.5 b	0.49 ab	55.3 a	10.8 c	38.3 c
	720	400	69.6 a	27.3 a	3.1 ab	0.51 a	56.7 a	14.3 b	52.1 b
Stems	365	40	67.6 a	28.6 a	3.8 a	0.31 a	55.0 a	60.4 a	212.1 a
	720	40	65.1 a	31.1 a	3.8 a	0.31 a	49.3 a	43.2 b	146.2 b
	365	400	62.3 a	31.7 a	6.0 a	0.46 a	52.5 a	12.6 c	39.7 c
	720	400	66.2 a	29.9 a	3.9 a	0.38 a	47.3 a	16.4 c	56.4 c
Taproots	365	40	56.9 a	36.1 a	7.1 ab	0.75 ab	45.6 a	54.6 a	164.9 a
	720	40	59.4 a	37.9 a	2.7 b	0.24 b	51.1 a	51.0 a	134.2ab
	365	400	57.2 a	35.1 a	7.7 ab	0.55 ab	47.4 a	18.4 b	54.4 b
	720	400	57.2 a	27.8 a	15.0 a	1.24 a	33.9 a	16.5 b	58.1 b
Laterals	365	40	59.9 a	37.2 a	2.9 a	0.43 a	44.7 a	42.3 a	114.0 a
	720	40	59.3 a	38.2 a	2.6 a	0.40 a	45.8 a	42.6 a	111.3 a
	365	400	56.2 b	38.9 a	4.9 a	0.60 a	42.9 a	17.9 b	45.8 b
	720	400	60.0 a	35.9 a	4.2 a	0.64 a	38.7 a	22.3 b	61.8 b
Fine Roots	365	40	51.3 a	46.2 a	2.4 a	0.22 ab	54.4 a	41.7 a	90.0 a
	720	40	54.0 a	43.5 a	2.5 a	0.19 b	41.7 b	35.8 a	81.1 a
	365	400	55.7 a	41.8 a	2.5 a	0.33 a	60.3 a	18.9 a	45.2 a
	720	400	51.8 a	45.1 a	3.1 a	0.28 ab	51.8 ab	29.9 a	66.7 a

<sup>a</sup>Cel = cellulose, Lig = lignin, Tan = tannin, SC = structural carbohydrates (cellulose, lignin and tannin), TC = total carbon, NSC = nonstructural carbohydrates (sugars and starches).

<sup>b</sup>For each tissue, in each column within each tissue type, values followed by the same letter are not significantly different as determined by the Least Square Means Test ( $p \leq 0.05$ ),  $n = 5$ .

concentration and allocation of C compounds in long-leaf pine seedlings were observed to predominantly occur in belowground tissues, with N effects tending to be stronger than CO<sub>2</sub> effects.

In general, plant tissues receive photosynthate according to demand and plants will allocate a majority of this photosynthate to those tissues encountering the most limiting resource, i.e., greatest demand; this, of course, is dependent upon availability of photosynthate for allocation (Chapin et al., 1987; Eissenstat, 1992; Rogers et al., 1996). Both environmental variables tested in this study are undoubtedly important and plants will likely respond, if able, to attain the most limiting resource at any given time in order to maintain a balance of internal C and N pools (Rogers et al., 1996). These interactions indicate that only when sufficient N is available can the plants take ad-

vantage of the higher concentrations of atmospheric CO<sub>2</sub>.

Ratios among C components were calculated to determine treatment effects on structural C allocation to plant tissues by removing the dynamic portion of the internal C pools (i.e., nonstructural carbohydrates). It has been previously shown that concentrations of nonstructural carbohydrates can be increased by elevated CO<sub>2</sub> (Yelle et al., 1989). Effects of CO<sub>2</sub> and N on partitioning of structural C occurred belowground only, as was observed for most data in this study.

Generally, CO<sub>2</sub>-induced changes in the quality (higher C:N ratios and potential shifts in concentrations of plant defensive allelochemicals) of plant tissues is thought to influence insect herbivory (Fajer et al., 1992; Lincoln and Couvet, 1989) and could affect ecosystem structure and function (Lindroth et

al., 1993). Thus, the manner in which increases in atmospheric CO<sub>2</sub> will affect the major insect pests and diseases of the world's plants are largely unknown but may result in positive or negative impacts on plant health and productivity. Results of this study lead us to conclude that atmospheric CO<sub>2</sub> enrichment combined with elevated soil N may change plant defense compounds, such as lignin and tannins, thereby changing plant susceptibility to many insect and disease infestations (Entry et al., 1992, 1994).

By altering plant tissue quantity and quality, elevated atmospheric CO<sub>2</sub> will likely affect soil microbial composition and activity, changing C turnover and storage in soils (Goudriaan and de Ruiter, 1983; Lamborg et al., 1983). Melillo (1983) reported higher C:N ratios and higher levels of phenolics in sweetgum (*Liquidambar styraciflua* L.) leaves exposed to high CO<sub>2</sub> and hypothesized that this would result in reduced rates of decomposition and decreased soil fertility. Lekkerkerk et al. (1990) found that elevated atmospheric CO<sub>2</sub> increased the input of easily decomposable root-derived material in the soil of wheat (*Triticum aestivum* L.) and reduced turnover of more resistant soil organic matter. Coûteaux et al. (1991) demonstrated similar results for an initial decomposition period and related the reduction in decomposition rate to lower N concentration and higher C:N ratios of CO<sub>2</sub>-enriched plants. When decomposition was allowed to continue, changes in the composition of the microbial population resulted in an increased decomposition rate of CO<sub>2</sub>-enriched material which led to an overall enhancement of C mineralization of 30%.

Effects of increasing CO<sub>2</sub> on biomass production will influence microbial composition and activity and, in turn, may impact mineralization/immobilization processes. Zak et al. (1993) reported significant increases in microbial biomass C in the rhizosphere and in bulk soil associated with plants grown under elevated CO<sub>2</sub>. They also observed a significant increase in N mineralization which they related to possible increased turnover rate of microbial N and/or an increased N release from soil organic matter. We observed decreased lignin:N ratios for all tissues except fine roots under high N fertility which may increase the rate of decomposition and nutrient mineralization.

This study demonstrated that N fertility exerted a much stronger influence on longleaf pine tissue chemistry and C allocation among those tissues than did atmospheric CO<sub>2</sub>. The majority of both N and CO<sub>2</sub> effects occurred belowground; however, effects on N concentration and lignin to N ratios were observed

both above- and belowground. Also, the majority of treatment effects involved structural, rather than nonstructural, carbohydrates. Altered tissue C and N concentrations and altered lignin to N ratios suggest changes in tissue susceptibility to insect and disease attack and altered rates of decomposition and nutrient mineralization under elevated CO<sub>2</sub> and high N fertility.

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