INTERACTIVE EFFECTS OF ATMOSPHERIC CO$_2$ AND SOIL-N AVAILABILITY ON FINE ROOTS OF *POPULUS TREMULOIDES*

KURT S. PREGITZER,1,5 DONALD R. ZAK,2 JENNIFER MAZIASZ,1 JARED DEFORREST,1 PETER S. CURTIS,3 AND JOHN LUSSENHOP4

1School of Forestry and Wood Products, Michigan Technological University, Houghton, Michigan 49931 USA
2School of Natural Resources and Environment, University of Michigan, Ann Arbor, Michigan 48109-1115 USA
3Department of Evolution, Ecology and Organismal Biology, Ohio State University, Columbus, Ohio 43210-1293 USA
4Department of Biology, University of Illinois, Chicago, Illinois 60607-7060 USA

Abstract. The objective of this experiment was to understand how atmospheric carbon dioxide (CO$_2$) and soil-nitrogen (N) availability influence *Populus tremuloides* fine-root growth and morphology. Soil-N availability may limit the growth response of forests to elevated CO$_2$ and interact with atmospheric CO$_2$ to alter litter quality and ecosystem carbon (C) and N cycling. We established a CO$_2$ × N factorial field experiment and grew six genotypes of *P. tremuloides* for 2.5 growing seasons in 20 large open-top chamber/root-box experimental units at the University of Michigan Biological Station in northern lower Michigan (USA). In this paper we describe an integrated examination of how atmospheric CO$_2$ and soil-N availability influence fine-root morphology, growth, mortality, and biomass. We also studied the relationship between root biomass and total soil respiration.

Over 80% of the absorbing root length of *P. tremuloides* was accounted for by roots <0.4 mm in diameter, and specific root length (100–250 m/g) was much greater than reports for other temperate and boreal deciduous trees. Elevated atmospheric CO$_2$ increased the diameter and length of individual roots. In contrast, soil N had no effect on root morphology. Fine-root length production and mortality, measured with minirhizotrons, was controlled by the interaction between atmospheric CO$_2$ and soil N. Rates of root production and mortality were significantly greater at elevated CO$_2$ when trees grew in high-N soil, but there were no CO$_2$ effects at low soil N. Fine-root biomass increased 137–194% in high-N compared to low-N soil, and elevated atmospheric CO$_2$ increased fine-root biomass (52%) in high soil N, but differences in low soil N were not significant. Across all treatments, dynamic estimates of net fine-root production were highly correlated with fine-root biomass (soil cores; $r = 0.975$). Mean rates of soil respiration were more than double in high-N compared to low-N soil, and elevated atmospheric CO$_2$, when compared to ambient atmospheric CO$_2$, increased mean rates of soil respiration 19% in 1995 and 25% in 1996. Across all treatments, total root biomass was linearly related to mean rates of soil respiration ($r^2 = 0.96$).

Our results indicate that atmospheric CO$_2$ and soil-N availability strongly interact to influence *P. tremuloides* fine-root morphology, growth, and C turnover. Aspen-dominated ecosystems of the future are likely to have greater productivity fueled by greater nutrient uptake due to greater root length production. Further, it appears that elevated atmospheric CO$_2$ will result in greater C inputs to soil through greater rates of fine-root production and turnover, especially in high-fertility soils. Increased C inputs to soil result in greater rates of soil respiration. At this time, it is not clear what effects increased rates of root turnover will have on C storage in the soil.

Key words: atmospheric CO$_2$ and soil-N availability; interaction; carbon and nitrogen; fine-root turnover and biomass; global climate change; minirhizotrons; morphology; roots; nitrogen; nutrient cycling; *Populus tremuloides*; root growth and morphology; soil respiration.

INTRODUCTION

Understanding the direct and indirect ecological effects of increasing atmospheric carbon dioxide (CO$_2$) is one of the most important ecological issues facing humankind. With a partial pressure of ~35 Pa and a relatively uniform distribution around the planet, CO$_2$ is a trace gas in the atmosphere that currently limits the rate of photosynthesis in most plant species. Using meta-analysis to summarize 500 experiments, Curtis and Wang (1998) reported that doubling atmospheric CO$_2$ increased average rates of photosynthesis 54%.
and increasing primary productivity could have a profound influence on such ecological processes as nutrient cycling, natural selection, competition, and succession.

Leaf nitrogen (N) is directly related to photosynthetic rate (Field and Mooney 1986, Evans 1989), and N limits primary production in many temperate ecosystems (Vitousek and Howarth 1991). Most of the N in leaves is acquired from the soil, and trees depend upon fine absorbing roots and mycorrhizae for the uptake of N and other growth-limiting nutrients. Trees growing in an atmosphere increasingly rich in CO2 have the potential to fix more carbon (C) in photosynthesis if they can acquire enough N. As pointed out by BassiriRad et al. (1997), plants can potentially meet the increased physiological demand for soil N by either producing a more extensive root/mycorrhizal system and/or increasing the physiological capacity of roots/mycorrhize to acquire soil N. Potential alterations in the deployment of fine roots are, therefore, a critical direct response to elevated CO2 (Berntson and Woodward 1992). Most of the existing literature indicates that root growth is enhanced under elevated CO2 (Rogers and Runion 1994, Curtis and Wang 1998). However, there are very few studies longer than 360 d in duration (<10 worldwide, Curtis and Wang 1998). One of the objectives of this study was to understand the direct effects of elevated atmospheric CO2 and soil-N availability on Populus tremuloides fine-root growth and morphology. Changes in mycorrhizal colonization and the physiological capacity of roots to assimilate N were evaluated in companion studies (J. Lussenhop, unpublished data, Rothstein et al. 2000). Our hypothesis was that elevated atmospheric CO2 would increase fine-root growth and mortality regardless of soil-N availability, and that this response would be sustained over the course of the experiment.

Respiration is a critical component of net ecosystem carbon exchange, and understanding the relationships among net canopy assimilation, root respiration, and microbial respiration is a prerequisite for understanding C budgets estimated by eddy correlation (Russell and Voroney 1998). There are only a few measurements of soil respiration from long-term elevated-CO2 experiments conducted in the field (Luo et al. 1996, Vose et al. 1997, Ball and Drake 1998, Edwards and Norby 1999). These studies all suggest that elevated CO2 will increase soil respiration, but concurrent field studies of root growth and soil respiration remain mostly unexplored. It is important to understand the direct relationship between root growth and soil respiration because more than half of the C assimilated in many ecosystems is allocated to the production and maintenance of fine roots (Vogt et al. 1986, Hendrick and Pregitzer 1993), making soil respiration the major flux of C back to the atmosphere in many ecosystems (Hungate et al. 1997, Russell and Voroney 1998). Our second objective was to quantify the relationship between root biomass and soil respiration across atmospheric-CO2–soil-N treatments.

There are also important indirect ecosystem feedback mechanisms that could limit the growth response of terrestrial ecosystems to increasing atmospheric CO2. This aspect of understanding ecosystem response to elevated atmospheric CO2 is controversial and remains unresolved (but see Norby and Cotrufo [1998]). The controversy revolves around the widely observed influence of elevated CO2 on litter chemistry. A common observation from elevated-CO2 experiments is an increase in leaf C/N ratio (Bezemer and Jones 1998), in part driven by a decline in leaf N at elevated CO2 (Bezemer and Jones 1998, Curtis and Wang 1998). This observation has fostered the hypothesis that greater inputs of recalcitrant litter will decrease soil-N availability and, in time, dampen the growth response of terrestrial ecosystems to elevated atmospheric CO2 (Shimmel 1990, Diaz et al. 1993).

The alternative N-cycling hypothesis centers on the idea that elevated CO2 will increase inputs of easily metabolized C compounds through increased root/mycorrhizal turnover (root exudation, and death and decay of fine roots/mycorrhizal hyphae; Zak et al. 1993). In reality, both of these arguments are gross simplifications of a complex set of organic-matter transformations that are mediated by soil microbes and soil invertebrates (Klironomos et al. 1996). It is clear, however, that processing of plant detritus by the soil biota will regulate N availability and C storage in the soil as the concentration of CO2 increases in the earth’s atmosphere. A dominant fraction of the C assimilated in net primary production passes rapidly through the plant biomass into the soil in all terrestrial ecosystems, mostly as leaf and root/mycorrhizal litter. The time steps involved are relatively short—new leaves and roots have life spans that range from days to a few years. In elevated-CO2 experiments, Arnone and Körner (1995) estimated that for each mole of C sequestered in aboveground living-plant biomass in tightly controlled artificial ecosystems, 5 mol of C were sequestered in the soil (roots/mycorrhizae, microbes, and soil organic matter). Understanding the mechanisms that control soil C and N cycling under elevated CO2 remains one of the most uncertain and important pieces of the global-change puzzle (Vitousek 1994). Fine roots play an important part in this unresolved issue.

As noted above, fine-root turnover is an important source of substrate for microbial and invertebrate metabolism simply because fine roots and mycorrhizae account for a large percentage of net primary production (Fogel and Hunt 1979, Vogt et al. 1986, Hendrick and Pregitzer 1993, Hungate et al. 1997). Fine roots are modular plant organs, and they have life expectancies that are often shorter than leaves (Hendrick and Pregitzer 1992, Pregitzer et al. 1993). Dynamic esti-
mates of fine-root growth and mortality for trees growing under elevated CO2 have only been quantified in a handful of studies (Pregitzer et al. 1995, Berntson and Bazzaz 1996, Tingey et al. 1996, Kubiske et al. 1998). In deciduous trees, most root length can be accounted for by short-lived, absorbing roots that have diameters <0.5 mm (Hendrick and Pregitzer 1993, Pregitzer et al. 1997), and these roots, their exudates, and their associated mycorrhizal hyphae represent the majority of belowground C input to the soil. We know almost nothing about the litter quality of these ephemeral organs and how root litter quality will respond to different atmospheric CO2 and soil N treatments. Our final objective was to quantify the C/N ratio of fine roots. Our hypothesis was that trees growing in soil with greater available N would have roots with significantly lower C/N ratios, and that elevated CO2 would not significantly influence fine root C/N ratio. Although C/N ratio is a very crude estimate of litter quality, understanding C/N ratio is a first step toward understanding how elevated CO2 and soil N influence belowground litter quality. To summarize our introduction, the overall goal of this study was an integrated examination of how atmospheric CO2 and soil-N availability influence the fine-root systems of Populus tremuloides, the dominant timber species in the Lake States and the most widely distributed tree in North America.

**METHODS**

**Experimental design**

The experiment was conducted at the University of Michigan Biological Station (UMBS; 45°35’ N, 84°42’ W), near Pellston, Michigan, USA. The immediate area was open and level (<1% slope), and the soil was a uniform, well-sorted Rubicon sand (Entic Haplorthod). In the summer of 1993 we removed the O, A, and upper B soil horizons (15 cm) over the entire area with a backhoe.

The experiment was a two-factor, randomized complete-block design. One fixed effect, soil N, consisted of two soil treatments. Soil with high N availability consisted of 100% A horizon collected from a nearby Kalkaska sand (Typic Haplorthod). Soil with low N availability was prepared by mixing 20% A-horizon Kalkaska sand and 80% C-horizon Rubicon sand. Both of these soils are very common in northern Lower Michigan. We have successfully used these soil preparations to alter N availability in other experiments (Pregitzer et al. 1995, Kubiske et al. 1997). Differences in organic matter between the two soil treatments in this experiment (low N = 3.6 g C/kg; high N = 12.5 g C/kg) resulted in net N-mineralization rates of 62 ng N-g⁻¹-d⁻¹ in the low-N soil and 318 ng N-g⁻¹-d⁻¹ in the high-N soil. Extractable PO₄³⁻, assayed using the Bray P1 method (Kuo 1996), was 13.7 mg/kg in the low-N soil and 10.4 mg/kg in the high-N soil (see Curtis et al. [2000] for additional soil characterization). After the two soil treatments were prepared, 10 open-bottom root boxes (3.3 m² × 0.45 m deep) lined with 1.3-cm-thick styrofoam insulation and plastic film were filled with one of the two soil treatments (2 soil treatments × 10 boxes = 20 soil boxes total). Before the boxes were filled with soil, eight minirhizotron tubes were installed in each (see below). The boxes were filled with soil in the fall of 1993 and allowed to settle to a uniform bulk density over winter.

Open-top chambers (Heagle et al. 1989) were constructed and placed over the 20 root boxes in early spring 1994. These were used to control the second fixed effect, atmospheric CO2. Ambient daytime (0701–1900) atmospheric CO2 (35.7 ± 0.06 Pa over the 2.5 growing seasons) was maintained in one half of the chambers and the daytime atmosphere was elevated to twice ambient CO2 in the other 10 chambers (70.7 ± 0.06 Pa). Further details about the open-top chambers and their operation and performance can be found in Curtis et al. (2000). The experiment was balanced (4 main treatments × 5 replications = 20 chamber/root-box experimental units).

On 7 June 1994 we planted two softwood cuttings of six different local genotypes of Populus tremuloides Michx. into each chamber. Before planting, the cuttings were graded for uniformity; individuals averaged 17.3 (±0.45) cm in height with 12.3 (±0.3) leaves. The parent aspen clones grow on the Pellston plain which is a part of UMBS. In the field, three genotypes exhibit early leaf senescence and three exhibit late senescence (Barnes 1959). Harvest of the entire experiment began by block on 8 July 1996 following ~2.5 growing seasons. The largest trees were 3.3 m tall and had basal diameters of 10 cm at the time of harvest. Additional information about tree propagation, growth, physiology, and destructive harvest can be found in Curtis et al. (2000) and Zak et al. (2000b).

**Root morphology**

Root samples were collected during August and September of 1996 as the experiment was harvested to study fine-root morphology, and relationships between fine-root morphology and root carbon and nitrogen concentration. A portion of one horizontal woody lateral root, ~20 cm long and 1.0 mm in diameter, was randomly collected from each chamber in blocks 3, 4, and 5 of the experiment. Each of the root segments was very carefully excavated from the soil, making every effort to extract the roots without disrupting the small lateral branches. Following excavation each segment had several attached lateral branches. Four individual segments from the intact root systems were detached and preserved in a 20% methanol solution and later scanned and digitized in order to provide a representative picture of the variation in fine-root morphology.

The remainder of the root systems were immediately frozen and later thawed for analysis. Once the root
system was unfrozen, it was kept at 1°C in deionized water to prevent desiccation.

Each of the 15 branching root systems was dissected by order using methods described by Pregitzer et al. (1997, 1998). The smallest lateral roots were considered first-order roots following the approach of Fitter (1982, 1987). Individual root diameters and lengths were measured with a microscope (15×) fitted with an ocular micrometer. The diameters and lengths of 4877 individual roots, 1003–1507 per treatment, were measured. This amounted to 8.14 m of total fine-root length. Individual roots were composited by order within each of the 15 chambers, weighed to enable calculation of specific root length (in meters per gram), and then analyzed for C and N concentration with a Carlo Erba NA 1500 Series II elemental analyzer (CE Elantech, Lakewood, New Jersey, USA).

To illustrate the distribution of fine-root length by root diameter across all treatments, we prepared a relative cumulative root-length distribution function for all the dissected roots. The 4877 individual roots that were hand-dissected were sorted into 0.05-mm-diameter classes ranging from 0.05 through 3.0 mm, and the cumulative length of roots in each class was calculated. Relative cumulative length (percentage of total length) was then plotted by root-diameter class.

Root-morphology treatment effects and interaction terms were analyzed for significant differences using a three-factor (soil N, atmospheric CO₂, root order) balanced, randomized block design ANOVA (n = 3). All variates were tested for normality using Bartlett’s test for equality of variances. All variates met the assumption of normality following the transformation of root length (square root), C and N concentration (arcsine), and C/N ratio (arcsine). Separate ANOVAs were run for root length, root diameter, specific root length, C and N concentration, and C/N ratio using the GLM procedures in SAS 6.12 (SAS Institute 1990). A posteriori pairwise comparisons of interaction means within and among root orders were tested for significance using Tukey’s hsd test in the GLM procedure of SAS.

Fine-root biomass

Live fine-root biomass was estimated using soil cores (45 cm long by 10 cm in diameter) collected in June 1996, 2 wk before the beginning of the final harvest. Twelve soil cores were extracted from each of the 20 chambers by dividing the chambers into quarters and randomly removing three cores from each quarter. Cores were immediately transported on ice to Michigan Technological University where they were separated from soil using a hydropneumatic root elutriator (Gil-lison Variety Fabrication, Benzonia, Michigan, USA). Recovery of roots from a washed soil sample is >99% (Smucker et al. 1982). We have found that careful hand sorting of soil cores only recovers ~60% of the fine-root biomass we can recover using the root elutriator (A. J. Burton, unpublished data).

After washing, all roots >1.0 mm in diameter were removed from the samples. Live roots 0.5–1.0 mm in diameter were sorted by hand, oven-dried, and weighed; dead roots were discarded. The biomass of live roots <0.5 mm in diameter was estimated using a modified Newman’s line-transect method (Newman 1966, Hendrick and Pregitzer 1993). All dry masses were corrected for ash content, which was always <5% of total dry mass. Root N content for the 0.5–1.0 mm diameter size class was determined by combusting samples from the biomass cores (Carlo Erba NA 1500 Series II elemental analyzer), and multiplying N concentration by dry mass. Root N content for the roots <0.5 mm diameter was determined by using the weighed treatment mean N concentration of roots from the first four orders dissected by hand and multiplying this concentration by the biomass in each chamber. The weighed mean N concentration was determined for each treatment by weighting the mean N concentration of the four root orders dissected by hand by the proportional length of roots in each of the four orders.

A mixed model (randomized complete block design) was used to statistically analyze the fine-root biomass and N-content data after testing to be sure all variates were normally distributed. If significant interactions were found, then a posteriori pairwise comparisons were investigated using Tukey’s hsd test in the GLM procedure of SAS 6.12 (SAS Institute 1990).

Fine-root dynamics

Eight 2-m-long clear plastic minirhizotron tubes (Ann Arbor Plastics, Ann Arbor, Michigan, USA) were installed in each of the 20 root boxes before the treatment soil was placed into the boxes at the beginning of the experiment. Six tubes were installed horizontally, four at 10-cm soil depth, and two at 20-cm soil depth; two additional tubes were installed at a 30° angle to sample the soil to a vertical depth of 45 cm. Tubes were installed on all sides of the root boxes. The goal was to completely sample the treated soil space, with more intensive sampling near the surface where the majority of the fine roots are concentrated (Hendrick and Pregitzer 1993). One-hundred-sixty individual 9 × 13 mm “root windows” were sampled along each of the 160 minirhizotron tubes on each sample date using a BTC-2 Minirhizotron Video Camera System (Bartz Technology, Santa Barbara, California, USA). Each root window was robotically etched into the plastic and numbered sequentially in a line along the long axis of the tube. The individual tubes were securely anchored to ensure that images of the same roots were collected each time we used the video camera system.

There were no roots at the beginning of the experiment. Plants were allowed to grow until 1 August 1994 (57 d) when the first minirhizotron images were col-
lected. Three sets of images were collected in 1994 (1–
7 August, 29 August–14 September, and 29 September–
14 October) and six sets in 1995 (31 May–2 June, 21–
23 June, 17–21 July, 7–11 August, 23–28 August, and
26–29 October). In total, the growth and mortality of
16,646 individual roots was monitored over the 1994–
1995 growing seasons following methods previously
described (Hendrick and Pregitzer 1992, Pregitzer et
al. 1993, 1995). Additional images were collected in
1996, but a lack of funding prevented their analysis.

Cumulative root production was calculated as a running
total of new root length produced during each time
interval. Cumulative root mortality was calculated as
the running total of root loss during each time interval.
Net root production was calculated as cumulative root
production minus cumulative root mortality for each
time interval. Sample interval midpoints were used in
statistical analyses. Treatment main effects and inter-
actions were assessed using repeated-measures ANO-
VA (Meredith and Stehman 1991) in which orthogonal,
quadratic polynomials were fitted to the data as cal-
culated for unequally spaced sample dates (Robson
1959). The polynomial coefficients were then used as
primary data to test for treatment effects using standard
ANOVA (Steel and Torrie 1980). Data were log-trans-
formed to meet the assumptions of ANOVA when neces-
sary; ANOVA assumptions were evaluated by in-
spection of residuals and normal probability plots. Ad-
ditional statistical details are described by Pregitzer et
al. (1995). To investigate the relationship between re-
sults obtained using the minirhizotrons and soil cores,
we correlated (Pearson’s product-moment correlation
coefficient) treatment mean net production (minirhi-
zotrons) with treatment mean fine-root biomass <0.5
mm in diameter (soil cores).

Soil respiration

Soil respiration in each of the 20 chambers was mea-
sured using the static-chamber technique (sensu Good-
road and Keene 1984, Steudler et al. 1989, Raich et
al. 1990). In 1993 we permanently located a 400-cm²
aluminum sampling base for gas sampling in each
open-top chamber. Each sampling base extended 3 cm
below the soil surface and was constructed with a
U-shaped gutter into which the static chamber was
placed for in situ gas sampling. Sample frames were
located in each open-top chamber one year prior to our
measurements of soil respiration so that roots were able
to fully colonize the soil below each chamber. During
the 1995 and 1996 field seasons we placed static cham-
bers on sampling frames in a block and collected ali-
quots of headspace gas at 5-min intervals over a 20-
min collection period. All field sampling occurred on
a block basis. Gas samples (5 mL) were stored in evac-
uated 3-mL serum vials and transported to the labo-
ratory for analysis. Carbon dioxide concentration in
headspace gas was determined by gas chromatography,
Fine-root length production and mortality

Fine-root length production and mortality both exhibited a very clear treatment response. The mean ($P < 0.001$), linear ($P < 0.001$) and quadratic ($P < 0.01$) effects were all highly significant terms in both the production (Fig. 3A) and mortality (Fig. 3B) functions. Atmospheric CO$_2$ ($P < 0.05$), soil-N availability ($P < 0.001$) and the interaction between atmospheric CO$_2$ and soil-N availability ($P < 0.05$) were significant mean effects. Soil-N availability also exhibited significant linear ($P < 0.001$) and quadratic effects ($P < 0.001$), and the quadratic interaction term between atmospheric CO$_2$ and soil-N availability was significant ($P < 0.05$). The significant mean effect interaction terms are obvious in Fig. 3A and B. Atmospheric CO$_2$ had no influence on fine-root length production and mortality at low N availability, but rates of root length extension and mortality were greater at elevated CO$_2$ when trees were grown in high-N soil. The linear and quadratic effects are also obvious in Fig. 3A and B. Rates of root length extension and mortality were much greater at high soil N, especially when the trees were grown at elevated atmospheric CO$_2$.

Net root production is the difference between root length growth and root length mortality (production minus mortality), and net production controls the shape of the fine-root growth-response curves. Again, the mean ($P < 0.001$), linear ($P < 0.01$) and quadratic ($P < 0.01$) terms in the net root-production functions were all statistically significant. Soil N ($P < 0.001$) was the only significant mean effect. Net production was statistically greater at high soil N compared with low soil N (Fig. 3C). The soil-N linear ($P < 0.001$) and quadratic $P < 0.001$) terms were also significant. This means that rates of net root production were greater at high soil N compared with low N, but that CO$_2$ did not significantly influence net production (Fig. 3C). It is
soil treatment. of root growth and mortality, but only in the high-N CO₂ soil-N interaction term was not significant (Table 3).

Roots influenced fine-root biomass. Roots CO₂ increased biomass 52% (main effects, Table 3). Soil N increased the biomass of the smallest diameter roots 194%, while atmospheric treatments (Table 3). Soil N increased the biomass of the first four root orders of Populus tremuloides. It is interesting to note that the statistical treatment responses from these two methods are identical. Both methods document a highly significant response to elevated CO₂ at high soil N and no response to atmospheric CO₂ at low soil N. To document the correspondence of results from two independent methods we correlated final cumulative net root length production measured with the minirhizotrons in each chamber to the biomass of roots <0.5 mm in diameter in each chamber. The Pearson product-moment correlation coefficient between these two measures of fine-root response was 0.975 (P = 0.02). The fine-root biomass estimates in Table 3 represent a “snapshot” of the treatment response 2.5 growing seasons after the treatments were initiated, while the minirhizotron data depict the dynamic response measured over two growing seasons (Fig. 3). The correspondence in results among the two independent methods of measuring fine-root response is noteworthy.

The total amount of N (N content = N concentration × biomass) of the fine roots was primarily driven by changes in root biomass (Table 3). The treatment responses were significant and correspond more or less directly with the changes in fine-root biomass. The ex-
exception to this generalization is due to the fact the elevated-CO2 treatment stimulated biomass production, especially at high soil N, but decreased N concentration (Table 2). This resulted in N-content treatment responses that were not as pronounced as biomass treatment responses (Table 3).

Soil respiration

Mean rates of soil respiration in 1995 and 1996 were strongly affected by the two main treatments. Soil N increased mean rates of soil respiration by 123% in 1995 and 104% in 1996 (Table 4). This response is not surprising because the high-N soil had 3.5 times as much organic C as the low-N soil and because the soil N treatment had a highly significant impact on root growth (Table 3). Elevated CO2 also had a pronounced impact on mean rates of soil respiration, increasing mean rates by 19% in 1995 and 25% in 1996 (Table 4). The interaction between the atmospheric CO2 and soil N treatments was highly significant in 1996, with a response parallel to that of fine-root biomass. The mean rate of CO2 flux from the high-N soil surface was significantly greater at elevated CO2 compared to ambient CO2, but there were no significant differences among the CO2 treatments at low soil N (Table 4).

Across all treatments, there were highly significant linear relationships among mean 1996 rates of soil respiration and root biomass (Fig. 4). By comparing the slopes of the regressions among fine-root biomass vs. coarse-root biomass with mean rates of soil respiration (Fig. 4A vs. B) it is clear that, per gram of C, fine roots contribute much more to total soil CO2 flux than do coarse roots. The linear relationship between total root biomass and mean rates of soil respiration is remarkable (Fig. 4C).

DISCUSSION

Fine-root morphology

The availability of sufficient nutrients to sustain plant growth is a key factor in understanding the response of terrestrial ecosystems to rising atmospheric CO2. Plants could facilitate increased nutrient acquisition by changing the morphology of their root systems. There are numerous ways this could happen, e.g. an increase in root hairs, number of lateral branches, or the length of individual lateral branches to increase absorptive root length, or an increase in specific root length (SRL) to facilitate greater exploration of the soil. Because rates of photosynthesis commonly increase at elevated CO2 (Curtis and Wang 1998), the energy to support the cost of increased fine-root growth and maintenance is potentially available. Given the importance of root morphology to nutrient acquisition, especially absorbing root length (Nye and Tinker 1977), it is surprising how few studies of root morphology have been conducted.

We found that both the length and diameter of individual short lateral roots were significantly greater under elevated vs. ambient atmospheric CO2, but SRL exhibited no statistical treatment response and decreased with root order. These results are similar to other studies, Bernston and Woodward (1992), Rogers et al. (1992), King et al. (1997) and Crookshanks et al. (1998) all report that elevated CO2 increased root length. In the more anatomical study, Crookshanks et al. (1998) report that elevated CO2 accelerated cortical-cell expansion rates and increased formation of lateral roots in Arabidopsis thaliana. Although there is very little literature documenting the influence of elevated CO2 on root morphology, it is very consistent—all studies suggest that elevated CO2 changes root morphology by increasing absorbing root length. It is especially important to understand how the deployment of absorbing root length is influenced by elevated CO2, because this factor, along with nutrient uptake capacity per unit root length, is critical in regulating nutrient acquisition (Caldwell et al. 1992). Given the fact several studies report that elevated CO2 does not increase rate of nutrient uptake per unit root length (BassiriRad et al. 1997, Rothstein et al. 2000), additional research focusing on root morphology and nutrient acquisition is needed.
Almost nothing is known about species-specific differences in root morphology and how root morphology will respond at the species level to elevated CO$_2$. A comparison of the fine-root morphology of two deciduous trees that grow sympatrically in northern Michigan, *Populus tremuloides* and *Acer saccharum*, illustrates some of the differences that can occur among taxa. The great majority of absorbing roots of both species have very small diameters; median diameters range from 0.2 to 0.3 mm (Fig. 2; Pregitzer et al. 1997). Specific root lengths are variable among the two species. The mean specific root length of first-third order roots of *P. tremuloides* ranges from 245 to 124 m/g (Table 2), while the mean SRL of first-third order roots of *A. saccharum* ranges from 131 to 80 m/g (Pregitzer et al. 1997). These changes mirror the different architecture of the two species. *P. tremuloides* has a more exploratory root system with long, thin axes and relatively fewer lateral branches (Fig. 1), while *A. saccharum* has a much more highly branched root system (Pregitzer et al. 1997, 1998). Based on differences in SRL, the C cost of constructing first-third order roots of *P. tremuloides* is 35–47% less than the cost of constructing first-third order roots of *A. saccharum*. It is important to realize that root-system morphology, although very poorly understood, may vary widely among species, just as leaf morphology and leaf function vary among species (Reich et al. 1992). *P. tremuloides* with its long, thin, relatively inexpensive fine roots (compared to those of *A. saccharum*) may exhibit a different demographic response to rising atmospheric CO$_2$ than a species with roots that have lower SRL. At this time, there is no reason to expect different taxa to exhibit identical morphological and demographic responses to elevated atmospheric CO$_2$.

**Fine-root carbon and nitrogen concentrations**

Contrary to our original hypothesis, the two soil-N treatments did not significantly alter fine-root N concentration (Table 1). High soil N greatly increased fine-root biomass (Table 3), total plant biomass (Zak et al. 2000b), and the total amount of N in trees (Zak et al. 2000b), but the concentration of N in fine roots was only marginally higher in this treatment. Elevated atmospheric CO$_2$, on the other hand, resulted in significantly lower fine-root N concentrations, averaging 15% less across the first four root orders (Table 2). Root N concentration decreased with root order (Table 2), a pattern we have observed in other deciduous trees (Pregitzer et al. 1997). Rates of fine-root respiration are correlated with fine-root N concentration (Ryan et al. 1996, Pregitzer et al. 1998), making the small-diameter roots at the distal end of the root system the most metabolically active.

Total fine root C concentrations were not influenced by the atmospheric-CO$_2$ or soil-N treatments (Table 1). The C/N ratios of fine roots were higher at elevated CO$_2$ compared to ambient CO$_2$ across both levels of soil-N availability, but most of these differences were not statistically significant (Table 2). In general, root C/N ratio increased with root order (Table 2), a pattern consistent with previous studies (Pregitzer et al. 1997).

There is very little information on the influence of elevated atmospheric CO$_2$ on tree root tissue quality. Both King et al. (1997), and Rothstein et al. (2000) found that elevated atmospheric CO$_2$ did not affect the concentration of total non-structural carbohydrates (TNC) in fine roots, although Rothstein et al. (2000)
Main-effect means (trees the smallest roots, generally as leaf litter quality. We emphasize that in deciduous be as responsive to elevated CO2 and soil-N availability litter quality suggests that root litter quality may not * find combined with the few other studies on root litter quality suggests that root litter quality cannot be as responsive to elevated CO2 and soil-N availability as leaf litter quality. We emphasize that in deciduous trees the smallest roots, generally <0.5 mm in diameter, account for most of the fine-root litter inputs. These very fine roots have much lower C/N ratios than larger diameter roots; C/N ratios of very fine roots are similar to those of leaf litter (Table 2; Pregitzer et al. 1997). More studies on the effects of varying soil-N availability and elevated CO2 are needed to determine the generality of these results.

**Fine-root length production and mortality**

Soil-N availability had a highly significant influence on fine-root production and mortality. Both cumulative fine-root production and mortality more than doubled over the 2.5-growing-seasons experiment in the high soil-N treatment compared with the low-N treatment (Fig. 3). Pregitzer et al. (1995) and Kubiske et al. (1998) also found that high soil N greatly increased fine-root growth and mortality in *Populus* trees. There has been debate in the literature about the influence of soil-N availability on fine-root turnover. Some evidence suggests that increasing soil-N availability will increase root turnover, while other evidence supports the idea of decreased root turnover as soil N increases (Hendricks et al. 1993). Our results (Fig. 3), Pregitzer et al. (1995), and Kubiske et al. (1998) demonstrate without doubt that high soil-N availability increases fine-root turnover in young, fast-growing *Populus* trees. In this experiment, measurements of fine-root turnover using minirhizotrons were highly correlated with fine-root biomass estimates (Table 3) and total soil-respiration measurements (Fig. 4). All three independent sets of measurements confirm that the absolute allocation of C to fine roots greatly increases in *Populus* at high soil N. We caution that these results should not be generalized to all tree species, and they may be influenced by tree ontogeny. Just as root morphology appears to vary among taxa, so too might patterns of C allocation and root demography in response to altered soil-N availability. For example, Tingey et al. (1996) found in *Pinus ponderosa* Dougl. Ex P. Laws. that elevated CO2 increased fine-root area density and the occurrence of mycorrhizae, whereas N fertilization had no effect on fine-root area density.

Elevated atmospheric CO2 increased root growth and mortality, but only at high soil N (Fig. 3). In a 1-yr experiment, Kubiske et al. (1998) also working with *Populus tremuloides*, found similar results. Tingey et al. (1996) found that elevated CO2 increased fine-root area density in *Pinus ponderosa* regardless of soil-N availability. Pregitzer et al. (1995) reported that elevated CO2 increased fine-root production and mortality at both high and low N availability. In a short-term experiment, Berntson and Bazzaz (1996) found that elevated CO2 increased root production and mortality in *Betula papyrifera*, but not in *Acer rubrum*. Taken together, these few studies suggest that elevated atmospheric CO2 will increase root turnover if soil N does not limit photosynthesis. However, this conclusion...
Table 4. Mean rates of soil respiration (mg CO\textsubscript{2}-C·m\textsuperscript{-2}·d\textsuperscript{-1}) in 1995 and 1996.

<table>
<thead>
<tr>
<th>Year†</th>
<th>Low soil N</th>
<th>High soil N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ambient CO\textsubscript{2}</td>
<td>Elevated CO\textsubscript{2}</td>
</tr>
<tr>
<td>1995 [NS]</td>
<td>829.8 (32.4)</td>
<td>1087.9 (142.2)</td>
</tr>
<tr>
<td>1996 [**]</td>
<td>664.8 (45.5)</td>
<td>768.8 (50.2)</td>
</tr>
</tbody>
</table>

Notes: Data are means with 1 SE in parentheses. All units are milligrams CO\textsubscript{2}-C per square meter per day. Within a row, interaction means with the same lowercase superscript letter are not significantly different at $P < 0.05$ (Tukey's hsd pairwise comparisons).

† Significance of N × CO\textsubscript{2} interaction is indicated in brackets.

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; NS = not significant.

is highly speculative. Up to this point, dynamic estimates of root turnover at elevated CO\textsubscript{2} for plants growing in the field for >360 d have only come from the Placerville, California (USA) ponderosa pine experiment (Tingey et al. 1996) and our experiment. A more logical conclusion is that the evidence for generalizations about C allocation to roots and root demography is not sufficient at this time to make sweeping statements about belowground plant response to elevated CO\textsubscript{2}. Given the diversity in life-forms, physiological adaptations, and inherent patterns of carbon allocation within and among taxa, we may see different patterns of root demography and C allocation to fine roots as atmospheric CO\textsubscript{2} increases. If soil N is non-limiting, our studies demonstrate that the increase in C input to the soil from root turnover at elevated CO\textsubscript{2} can be substantial (Fig. 3, Pregitzer et al. 1995, Kubiske et al. 1998).

Fine-root biomass

Soil N had a dramatic influence on fine-root biomass. Across ambient and elevated atmospheric CO\textsubscript{2}, mean biomass of roots <0.5 mm in diameter was 194% greater in high-N soil when compared to the low-N treatment (Table 3). The atmospheric-CO\textsubscript{2} and soil-N treatment interaction was also highly significant for this root size class, with a significant 65% increase due to elevated atmospheric CO\textsubscript{2} at high soil N, and a nonsignificant 17% increase at low soil N (Table 3). The pattern for fine roots 0.5–1.0 mm in diameter was similar, although the response was not as dramatic and the treatment interaction was not significant (Table 3). Several short-term studies of tree seedlings report a significant increase in fine-root biomass due to elevated CO\textsubscript{2} (Norby 1994). In many of these studies, fine-root biomass was very responsive to elevated CO\textsubscript{2}, with growth increases exceeding those of other plant components (Norby 1994). However, as Norby (1994) articulates, fine-root mass is only a small portion of total-tree mass and, as trees develop, fine-root mass will become a relatively less important component of whole-tree C storage.

There are only a few experiments that have documented the belowground response to elevated CO\textsubscript{2} in

---

**Fig. 4**. Linear relationships between fine, coarse, and total root biomass and soil respiration. Soil respiration values are 1996 mean fluxes from each chamber. Root biomass was measured during the final harvest (see Methods: Fine-root biomass for details). Fine roots are <1 mm in diameter; coarse roots are >1 mm in diameter.
temperate deciduous trees grown in the field for more than 360 d. Norby et al. (1996) grew *Liriodendron tulipifera* L. and *Quercus alba* L. in open-top chambers for 3 and 4 yr, respectively. They found that elevated atmospheric CO$_2$ increased fine-root biomass significantly in both species, but that this tree component comprised a relatively small percentage of total-tree biomass. Rey and Jarvis (1997) grew *Betula pendula* Roth. for 3.5 yr in open-top chambers and found that fine-root biomass increased more than any other tree component over the duration of the study. Our 2.5-growing-seasons field experiment also documents that *Populus tremuloides* very-fine-root biomass was more responsive to elevated atmospheric CO$_2$ than any other tree component (Zak et al. 2000). Although the data are few and still very short term from the perspective of forest development, all the published field experiments that have reported fine-root biomass support the idea that more fine-root C will be cycled through the soil as atmospheric CO$_2$ increases (Norby et al. 1992, 1996, Zak et al. 1993, 2000a, Johnson et al. 1994, Norby 1994, Pregitzer et al. 1995, Rey and Jarvis 1997). The exception to this generalization might be, as Fig. 3 and Johnson et al. (1998) suggest, situations where soil-N availability is limited. Our data (Fig. 3) clearly demonstrate another important point: inputs of C to soil from fine-root turnover are highly dynamic. Whether or not more C will be stored in the soil as atmospheric CO$_2$ increases root-C input is yet another unanswered question (Hungate et al. 1997).

### Unresolved C-allocation issues

As the concentration of CO$_2$ increases in Earth’s atmosphere, there are several aspects of C allocation to tree root systems that remain unresolved. Plant developmental rates may influence the way C is allocated to fine roots. In our experiment, trees were young and growing in their exponential phase in a soil matrix that, within a given treatment, was relatively uniform in terms of N availability. It is clear the *Populus tremuloides* trees we studied allocated absolutely more C to fine roots when soil-N availability was high and atmospheric CO$_2$ was elevated. Fine-root growth did not respond to elevated CO$_2$ when N was limiting given this set of experimental conditions. It remains to be seen if these patterns continue throughout the ontogeny of stand development, or if they will apply to shade-tolerant trees that have slower inherent rates of growth. Because *Populus* is a fast-growing, shade-intolerant genus, we expect the patterns found in this study to carry forward in similar situations, such as *Populus* plantations grown for fiber production. It will be interesting to compare and contrast the results of early- and late-successional tree taxa, and young and older trees as these data become available. At this point in time, it is dangerous to make sweeping conclusions about how soil N and atmospheric CO$_2$ interact to influence C allocation to tree root systems since all the experimental data in hand come from young trees growing exponentially. It is also important to remember when modeling the response of forests to rising atmospheric CO$_2$ that the landscape is composed of stands of different age classes and varying composition. In reality, many of the forests around the world are young and they continue to be utilized by an ever-growing human population. To conclude that data from young trees is irrelevant is also a mistake, since many of the issues surrounding a better understanding of C storage in terrestrial ecosystems will involve young, managed forest ecosystems. We need a much better understanding of how trees respond throughout their typical period of growth and development to rising atmospheric CO$_2$.

The issue of C allocation to tree root systems is also confounded by methodological problems and semantics. In many instances, the proportional weight of different parts of the tree is used to quantify C allocation in response to changing soil-nutrient availability and increasing atmospheric CO$_2$. Typical measures in the literature are static root-to-shoot ratios and allometric analyses. Both of these approaches to understanding plant growth and development can be very useful, and both originated in agronomy where the issues of understanding the development of plants with an annual life cycle are much simpler. Understanding C allocation in trees is more complicated. Root/shoot ratios in trees, even young trees, can be misleading because the shoot (leaves, branches, bole) represents a mixture of C accumulated on different time steps (leaves once a year, bole C is accumulated over the life of the tree). In contrast, the fine-root system is very dynamic as Fig. 3 clearly demonstrates. Little is known about how increasing atmospheric CO$_2$ changes the allocation of C to fine roots over the lifespan of a tree, and little can

### Table 4. Extended.

<table>
<thead>
<tr>
<th>Soil N</th>
<th>Low</th>
<th>High</th>
<th>Change (%)</th>
<th>CO$_2$</th>
<th>Ambient</th>
<th>Elevated</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>958.8</td>
<td>2140.4</td>
<td>123***</td>
<td>1418.3</td>
<td>(92.0)</td>
<td>(92.0)</td>
<td>19*</td>
</tr>
<tr>
<td></td>
<td>(92.0)</td>
<td>(92.0)</td>
<td></td>
<td>(92.0)</td>
<td>(92.0)</td>
<td>(92.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>958.8</td>
<td>1459.1</td>
<td>104***</td>
<td>965.3</td>
<td>(42.9)</td>
<td>(42.9)</td>
<td>25***</td>
</tr>
<tr>
<td></td>
<td>(42.9)</td>
<td>(42.9)</td>
<td></td>
<td>(42.9)</td>
<td>(42.9)</td>
<td>(42.9)</td>
<td></td>
</tr>
</tbody>
</table>

*Ambient and Elevated signify the concentration of CO$_2$. The change values are calculated as Ambient – Elevated, where the elevated CO$_2$ concentrations were 920 ppmv for 3 and 4 yr, respectively. They found that elevated CO$_2$ increased fine-root biomass significantly in both species, but that this tree component comprised a relatively small percentage of total-tree biomass. The exception to this generalization might be, as Fig. 3 and Johnson et al. (1998) suggest, situations where soil-N availability is limited. Our data (Fig. 3) clearly demonstrate another important point: inputs of C to soil from fine-root turnover are highly dynamic. Whether or not more C will be stored in the soil as atmospheric CO$_2$ increases root-C input is yet another unanswered question (Hungate et al. 1997).
be inferred from root-to-shoot ratios. Since fine roots represent such a large part of the total C budget of trees, the issue of understanding how ontogeny and environment interact to control C allocation on a whole-tree basis will be a fruitful area for further research.

**Soil respiration**

Both atmospheric CO₂ and soil-N availability significantly increased mean rates of soil respiration in 1995 and 1996 (Table 4). Rates of soil respiration were linearly related to root biomass across all treatments, with fine roots contributing proportionally more to total soil CO₂ flux (Fig. 4). The fact that fine roots are more active metabolically should be expected, since they are the primary site for active nutrient uptake and assimilation. The smallest roots (<0.5 mm in diameter) located in the upper part of the soil profile have higher N concentrations and much higher rates of respiration than larger roots or roots located deeper in the soil profile (Pregitzer et al. 1998).

Literature estimates for the contribution of roots to total soil respiration range from 5 to 90%, with many values near or above 50% (Nakane et al. 1983, Ewel et al. 1987, Behera et al. 1990, Haynes and Gower 1995, Ryan et al. 1996). In well-drained soil it seems logical to expect root and total soil respiration to be closely correlated, and both should increase exponentially with temperature. All the field studies that have examined the influence of elevated CO₂ on total soil respiration report a significant increase at elevated CO₂ (Johnson et al. 1994, Luo et al. 1996, Griffin et al. 1997, Hungate et al. 1997, Vose et al. 1997, Ball and Drake 1998, Walker et al. 1998), except agricultural FACE (Free air carbon dioxide enrichment) experiments (Prior et al. 1997, Ineson et al. 1998). Our experiment is unusual in that fine-root dynamics (Fig. 3), root biomass, and soil respiration are reported together (Fig. 4). Mean rates of soil respiration across the four treatments follow the pattern one would expect if total soil respiration were strongly driven by root biomass (Fig. 4). We did not attempt to subdivide total soil respiration into its root and microbial components. Nevertheless, our data provide rather convincing evidence that, in our experiment, total soil respiration was strongly correlated to live-root biomass, probably the combination of root/mycorrhizal respiration and the rapid respiration of root exudates and decomposing fine roots and their associated mycorrhizae.

**Summary and Implications**

*Populus tremuloides* (trembling aspen) is a fast-growing, shade-intolerant species that has the most extensive geographic distribution of any tree in North America. It is important to wildlife, and it is a very important source of fiber in the Lake States and Canada, where aspen abundance and productivity are critical to the forest-products industry. Today, natural stands of trembling aspen are often managed on a short-rotation basis (25–60 yr), and even-aged stands are typically regenerated by clear-cutting. Several species and artificial hybrids in the genus *Populus* are also being planted on former agricultural fields throughout the United States in an effort to increase the supply, and decrease the cost, of fiber to the forest-products industry. The genus is also the target of intensive efforts to improve the genetic basis for pulp productivity, for example, by inserting herbicide- or insect-resistant genes into the genome or by decreasing lignin content (Stettler et al. 1996). Fast-growing plantations also have the potential to be used in atmospheric-C trading schemes. Obviously, the growth responses of trembling aspen to increasing atmospheric CO₂ have important ecological applications.

Our results demonstrate atmospheric CO₂ and soil-N availability strongly interact to influence *Populus tremuloides* fine-root morphology, growth, and C turnover. When sufficient soil N is available, aspen-dominated ecosystems of the future are likely to have greater productivity fueled by greater nutrient uptake due to greater root-length production. Further, it appears that elevated atmospheric CO₂ will result in greater C inputs to soil through greater rates of fine-root production and turnover, especially in high-fertility soils. Increased C inputs to soil result in greater rates of soil respiration. At this time, it is not clear what influence increased rates of root turnover will have on C storage in the soil, but since there is clearly more C moving into the soil at high N, it is entirely possible that some fraction of this C will find its way into stable soil organic matter.

In this experiment, limiting soil N did not statistically increase root growth and mortality. It is difficult to predict long-term trends in belowground production when soil N is limiting since ecosystem feedback on N availability is likely to work on longer time steps than the immediate growth responses we measured in this experiment. Still, it is clear that trembling aspen may not increase root growth when soil N is limiting and this could eventually result in leaf-level N deficiency. Low leaf N might eventually limit photosynthesis. We need longer term experiments to resolve these uncertainties. Our experiment also clearly demonstrates the critical role soil-N availability and root growth will play in determining ecosystem responses to increasing atmospheric CO₂.

**Acknowledgments**

This research was supported by the Department of Energy’s National Institute of Global Environmental Change, and the Program for Ecosystem Research (PER Grant DE-FG02-93ER6166). Additional funding came from the U.S. Forest Service Northern Global Change Program. James A. Teeri, Director of the University of Michigan Biological Station, provided significant in-kind and moral support, and we are grateful to him for his encouragement. Chris Vogel, Mark
Kubiske, John King, Carl Mikan, Andy Burton, Gregg Zogg, Tony Sutterley, Rich Spay, Jennifer Ashby, and Scott Pugh deserve special recognition for their help, and helpful attitudes.

**Literature Cited**


Barnes, B. V. 1959. Natural variation and clonal development of *Populus tremuloides* and *P. grandidentata* in Northern Lower Michigan. Dissertation. University of Michigan, Ann Arbor, Michigan, USA.


