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Temporal and depth-related patterns of fine root dynamics in northern hardwood forests

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Summary

1 The dynamics of fine (< 2.0 mm) roots growing in two northern hardwood forests were quantified to a depth of 1 m in 10-cm increments. We hypothesized that patterns of root production and mortality would be broadly synchronous at all depths, but that deep roots would be comparatively less dynamic than shallow roots.

2 Our data showed that shallow roots were responsible for the majority of total annual fine root production and mortality. Nearly half of all roots growing and dying in the 1-m profile occurred in the upper 20 cm of the soil, while roots located at depths of 75 cm or more accounted for only 11% of annual production and 4% of annual mortality.

3 Fine root production prior to, or coincident with, canopy expansion was significant at all depths. The relative importance of early fine root growth generally increased with depth, with between 50 and 80% of annual production occurring prior to mid-June at depths exceeding 50 cm. Episodic deep root production during the growing season appeared to be related to periods of high water demand.

4 Patterns of fine root mortality were more variable among depths. Mortality was distributed rather evenly throughout the year near the soil surface, but mid-season mortality was generally low at depths greater than 50 cm.

Keywords: cohorts, mortality, phenology, production

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Introduction

The importance of fine roots in carbon and nutrient cycling in temperate deciduous forests is well documented (e.g. McClaugherty *et al.* 1982; Fogel 1983; Nadelhoffer *et al.* 1985; Joslin & Henderson 1987; Hendrick & Pregitzer 1993a). Most roots occur relatively close to the soil surface, and most studies have focused on roots growing at depths of 0–40 cm. Consequently, we know relatively little about the role of deeper roots in carbon and nutrient cycling, or about the dynamics of deep roots in general. Obviously, the categorization of roots as being ‘deep’ or ‘shallow’ is arbitrary. Such distinctions may be largely unrelated to root function, much like the classification of roots into ‘fine’ and ‘coarse’ diameter categories often is. Methodological difficulties have long complicated our attempts to understand deep root dynamics. However, more comprehensive studies of the dynamics of both deep and shallow roots should help us better understand the extent to which the root system is integrated, its response to internal and environmental stimuli, and the functional importance

of roots in material cycles and physiological processes.

In temperate forests, shallow roots (i.e. those growing at depths of ≈ 40 cm or less) typically account for 50% or more of root system mass, while a much smaller percentage of root biomass grows at greater depths (Joslin & Henderson 1987; Yin *et al.* 1989; Burke & Raynal 1994; Puri *et al.* 1994). For example, 63% of fine (< 5.0 mm) root biomass was in the upper 15 cm of a *Liriodendron tulipifera* (L) forest soil sampled to 60 cm, while 71% of biomass in a 70-cm profile was concentrated in the upper 20 cm of a soil under *Pinus taeda* (L) (Harris *et al.* 1977). One half of the biomass of all roots < 2.0 mm in diameter was in the upper 22 cm of soil excavated to a depth of 100 cm in a *Quercus alba* (L.) forest (Joslin & Henderson 1987). Approximately 37% of root system mass was located between 22 and 75 cm, and roots > 75 cm in depth accounted for the remaining 13% of total root mass. Both the length and numbers of mycorrhizal and non-mycorrhizal roots follow distribution patterns similar to that of biomass (Kochenderfer 1973; Fogel & Hunt 1979; Vogt *et al.* 1981; Singh & Srivastava 1985; Ares & Peinemann 1992).

Despite their relative scarcity, deep roots are often important in the acquisition of water. Tree roots can extract water to depths of at least 35 m (Stone & Kalisz 1991), and patterns of soil water depletion at depths of several metres appear to be closely related to patterns of root density. In both desert shrubs (Caldwell & Richards 1989) and temperate tree species (Dawson 1994), roots transfer water from deep in the soil to shallow roots via 'hydraulic lift', where it diffuses into the soil to be reabsorbed during daytime periods of high transpirational demand.

The growth of deep and shallow roots coincides with both the water needs of the plant and when water availability is highest. In temperate hardwood forests, considerable amounts of shallow fine root production can occur prior to and/or during canopy development (Lyr & Hoffmann 1967; Kuhns *et al.* 1985; Hendrick & Pregitzer 1993a; Burke & Raynal 1994; Fahey & Hughes 1994). Root growth ceases or declines substantially after leaf fall and over winter, when water requirements are at their lowest. Root growth responds positively to increased water availability at favourable soil temperatures (Teskey & Hinckley 1981; Bevington & Castle 1985; Kuhns *et al.* 1985; Bartsch 1987). Sustained increases in available soil moisture apparently increase the longevity of shallow roots (Pregitzer *et al.* 1993), but it is not known whether both shallow and deep roots respond similarly to periods of high water demand or abundant soil moisture. Moreover, there have been few published studies in which fine root longevity or patterns of mortality have been directly measured in forests. We are unaware of any studies in which fine root production and mortality have been independently measured in forests at any but the most shallow depths.

Among the techniques that have proven particularly useful in root research, minirhizotrons (small, clear tubes buried within the soil) can be used to study both deep and shallow root dynamics relatively easily and in a replicated fashion. We have used minirhizotrons, along with traditional sampling methods, to describe the dynamics of shallow fine roots in two northern hardwood forests (Hendrick & Pregitzer 1993a,b). We previously concentrated on roots growing between 0 and 30 cm, assuming that the dynamics of all roots within that increment were similar. The objective of this study was to understand better the spatial and temporal dynamics of roots in the same two forests, particularly those roots growing below 30 cm in depth. Here, we present distribution, growth and mortality data for roots growing at depths of 0–100 cm, stratified into 10-cm increments. We hypothesized that relative root distribution, production and mortality would be concentrated near the soil surface, and that deeper roots would be comparatively less dynamic than shallow roots. We further postulated that there would be a large degree of temporal synchrony in production and mortality

dynamics of both relatively deep and shallow fine roots.

Materials and methods

SITE DESCRIPTION

The two study sites have been described previously (Hendrick & Pregitzer 1993a,b). Both are northern hardwoods forests located in the northern lower peninsula of Michigan (USA), separated by a north-south distance of 80 km (Table 1). We refer to them as the northern and the southern sites. The understorey and overstorey in both forests are dominated by *Acer saccharum*. Other tree species present include *Acer rubrum* (L.), *Fagus grandifolia* (L.), *Prunus serotina* (Ehrh.) and *Quercus rubra* (L.). The herbaceous community is sparse, covering less than 3% of the forest floor, and shrubs are rare. The soils at the northern site are Alfic and Typic Haplorthods, while those at the southern site are Entic and Typic Haplorthods. All soils are on glacial till deposits. Further site and soil descriptions can be found in MacDonald *et al.* (1991) and Pregitzer & Burton (1991).

We established three 30-m × 30-m plots at each site in 1987, selected to minimize heterogeneity in physiography, soils and vegetation (Burton *et al.* 1991). In June 1988, four minirhizotrons (2 m long × 5.08 cm inside diameter) were permanently installed in each plot at a 45° angle to the soil surface by inserting 165 cm of the tube to a depth of 110 cm. The portion of the minirhizotrons extending above the soil surface was painted and capped with a rubber stopper to exclude rainfall and light. Numbered image frames, orientated along the upper surface during installation, were etched onto the exterior surface of each minirhizotron at 1.2-cm intervals prior to installation so that we could return to the same location within the minirhizotrons at all sampling dates. The minirhizotron images were collected on VHS videotape with a Circon Microvideo 9011 Colour Agricultural Camera (Circon Co., Santa Barbara CA), and were 1.2 cm × 1.6 cm in size. Each minirhizotron

Table 1 Selected stand, soil and climatic characteristics of the study sites. Values are means across plots, plus or minus standard errors of the mean ($n = 3$) where shown

General stand characteristics	Southern forest	Northern forest
Latitude	43°40'	44°23'
Longitude	86°09'	85°50'
Overstorey age (years)	78 ± 5	74 ± 11
Basal area ($m^2 ha^{-1}$)	30 ± 2.0	30 ± 2.8
Canopy height (m)	24 ± 1	28 ± 1
1989 leaf area index ($m^2 m^{-2}$)	7.9 ± 0.3	7.1 ± 0.9
Mean annual air temperature (°C)	7.6	5.8
Mean annual precipitation (mm)	850	810
Growing degree days (> 5.6 °C)	2083	1944

was filmed to a depth of 1 m at 1.2-cm intervals at \approx 1-month intervals throughout the 1989 and 1990 growing seasons. The data presented in this paper were collected at the northern site on 27 April, 11 June, 22 June, 18 July, 18 August, 16 September and 14 October in 1989, and on 24 April in 1990. The corresponding sampling dates at the southern site were 25 April, 7 June, 21 June, 18 July, 16 August, 16 September and 14 October in 1989 and 25 April in 1990.

IMAGE AND DATA ANALYSIS

An interactive PC-based software program (MSU-ROOTS, Michigan State University, East Lansing, USA) was used to analyse the minirhizotron video images (Hendrick & Pregitzer 1992a; Atkinson 1992). The length of all roots present in each frame at each filming was traced using a mouse, and the measurements (in mm) were written to a database file (dBASE III +, Borland, Scotts Valley, CA) by ROOTS. The coordinates of each root within a frame, and a unique numeric identifier, were saved by ROOTS in files stored on diskette. Roots were characterized as live or dead at the time they were traced and digitized on the basis of colour, obvious signs of decay and disappearance (Hendrick & Pregitzer 1992a, 1993a).

We were able to identify and re-measure the same roots at later dates by using ROOTS to recall and overlay the tracings and identifiers from an image at time $t-1$ when analysing time t images. Records from the four minirhizotrons on each plot were composited into one database (Hendrick & Pregitzer 1992b), and eventually the records for the entire year were combined. The overall database for each replicate plot at each site was a time series of survivorship and length data for each root. Prior to the calculation of root length production and mortality, these databases were subdivided into 10 portions, corresponding to ten 10-cm increments from the root surface to a depth of 100 cm.

To calculate the contribution of each depth increment to total root length production, new length production was first summed within and across each depth increment for each plot for each of the intervals t to $t+1$. Production was defined and measured as the length of new roots present at time $t+1$ that were not present at time t , as well as the length growth of pre-existing roots. The length of any roots that were dead when they first appeared at time $t+1$ was also counted. Relative production of each depth increment (as a proportion of total production across the entire 100-cm profile) was also calculated. Total and relative length mortality was calculated similarly, and was measured as the length of roots that died or disappeared during a given time period t to $t+1$, plus the length of any roots that were dead when they first appeared at time $t+1$. We can not rule out the possibility that we underestimated actual length pro-

duction and mortality because we were unable to account for roots that both appeared and disappeared between sampling intervals. However, the amount missed is likely to have been small (Hendrick & Pregitzer 1993a; Pregitzer *et al.* 1993), and would not affect the relative data presented here.

The proportional distribution of length production and mortality throughout the year was calculated by dividing the periodic (monthly) production or mortality for a given time interval by the sum of annual production and mortality for a particular depth increment. In order to standardize the observation periods into \approx 1-month intervals, the 25 April – 25 May and 26 May – 21 June monthly productivity and mortality values were calculated by summing the appropriate mean daily production and mortality values from the April – early June and early June – late June filming intervals.

STATISTICAL ANALYSES

Statistical tests of the distribution of production and mortality by depths within time periods, and by time periods within depths, were analysed in a split-plot model, with repeated measures on time and depth. The two sites (northern, southern) were the whole plot factors in both the within-time and within-depth analyses. When there were no significant interactions, significant main effects were evaluated with unplanned comparisons using Tukey's honestly significant difference Studentized range test ($P = 0.05$).

Results

At both sites, relative root production near the soil surface was significantly greater than at increasing depths ($P < 0.001$) at all times of the year (Fig. 1). There were no statistically significant differences among sites or time of year, nor were there any significant interactions between site, depth or time. Relative production in the surface 10 cm was significantly ($P = 0.05$) greater than at all other depths, but there were no significant differences among increments between 10 and 60 cm, 20 and 70 cm, and 30 and 100 cm (Table 2).

Relative root mortality varied more among depths (Fig. 2). Length mortality was concentrated near the soil surface, and deep roots contributed relatively little to total root mortality throughout the year. Roots in the upper 20 cm accounted for $> 50\%$ of all root length dying from April through September. Both the depth main effect ($P = 0.001$) and date \times depth interaction ($P < 0.01$) were statistically significant, indicating that the depth-related mortality effect was not consistent across all dates. Although the general tendency was for mortality to be concentrated near the soil surface in the 0–20-cm depths, notable exceptions to this trend are for June–July at 30–40 cm and August–September at 50–60 cm at the northern site.

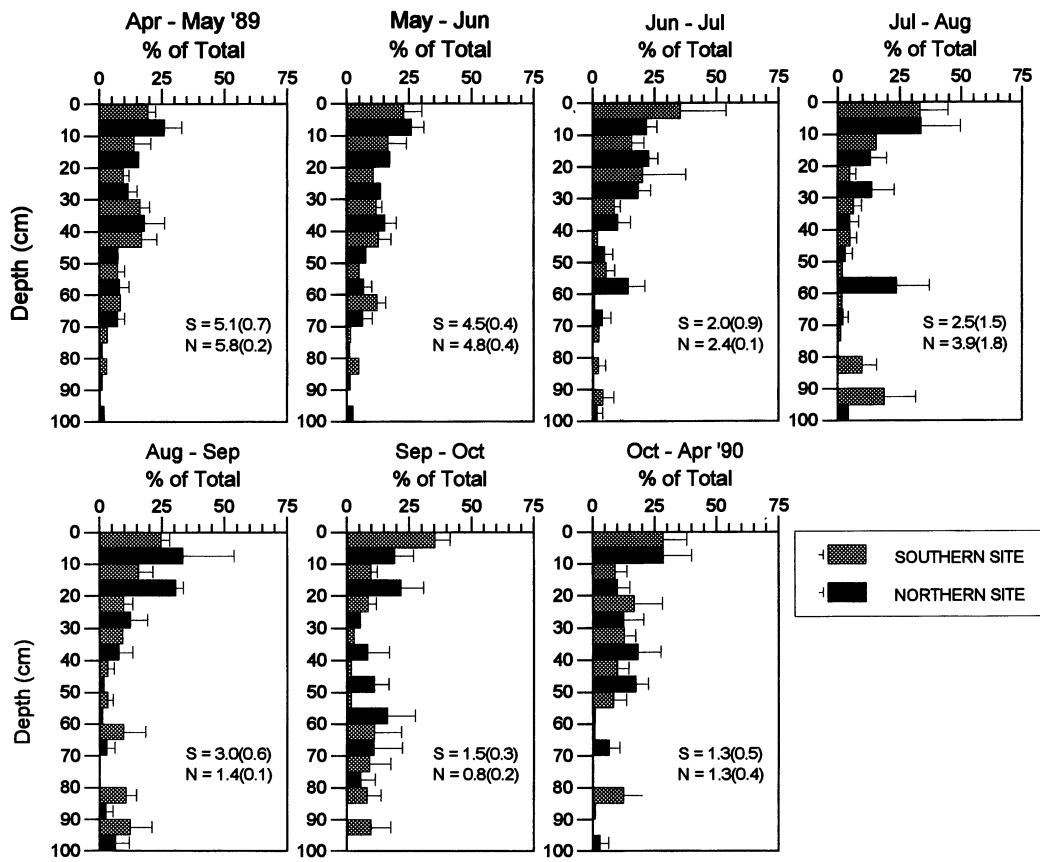


Fig. 1 Percentage distribution of fine root length production among depth increments during each observation interval. Bars are site means, with standard errors ($n = 3$) where shown. Numeric values within each figure are total length production and standard errors (mm root per cm^2 of minirhizotron surface, summed across all depth increments) for each time interval. S = southern site, N = northern site.

A separate analysis showed that 80% of all roots dying during August–September in the 50–60-cm increment at the northern site were those produced during the pulse of production during July–August at the same depth (Fig. 1). There was not a similar pattern in the age of those roots dying during June–July at 30–40 cm, although root mortality from the May–June production contributed disproportionately to the loss of root length during that time interval. There

was little or no contribution of deep (>70 cm) roots to overall mortality until late summer at either site.

There were broadly similar patterns in the temporal distribution of production among both deep and shallow roots throughout the year (Fig. 3). Production declined progressively throughout the year (date main effect, $P < 0.001$), but with no significant depth or site effects, nor any significant interactions. Significant differences among overall means for each date are shown in Table 3.

There was less consistency in patterns of root mortality (Fig. 4). The site–depth–date interaction was significant ($P = 0.0041$), indicating that date-related effects are dependent upon both site and depth. For example, mortality was spread rather evenly throughout the growing season at 0–50-cm depths, although there was a general tendency for mortality to increase in mid-to-late summer. Conversely, mortality was minimal below 80 cm at both sites during the early to-mid growing season, and was instead concentrated in the autumn and winter. There was one growing season period of high mortality at each site at 70–80 cm, although in successive rather than contemporaneous time intervals (Fig. 4). Even though a considerable amount of root length at the deeper depths was lost over relatively short periods of time, it contributed

Table 2 Treatment means (averaged across dates and sites) of percentage total root production by depth. Values with the same letter are not significantly different ($P = 0.05$, Tukey's honestly significant difference Studentized range test)

Depth (cm)	% Production
0–10	27.9 ^a
10–20	16.3 ^b
20–30	12.2 ^{bc}
30–40	11.0 ^{bcd}
40–50	7.7 ^{bcd}
50–60	7.7 ^{bcd}
60–70	6.2 ^{cde}
70–80	2.0 ^d
80–90	4.8 ^{cde}
90–100	4.3 ^{cde}

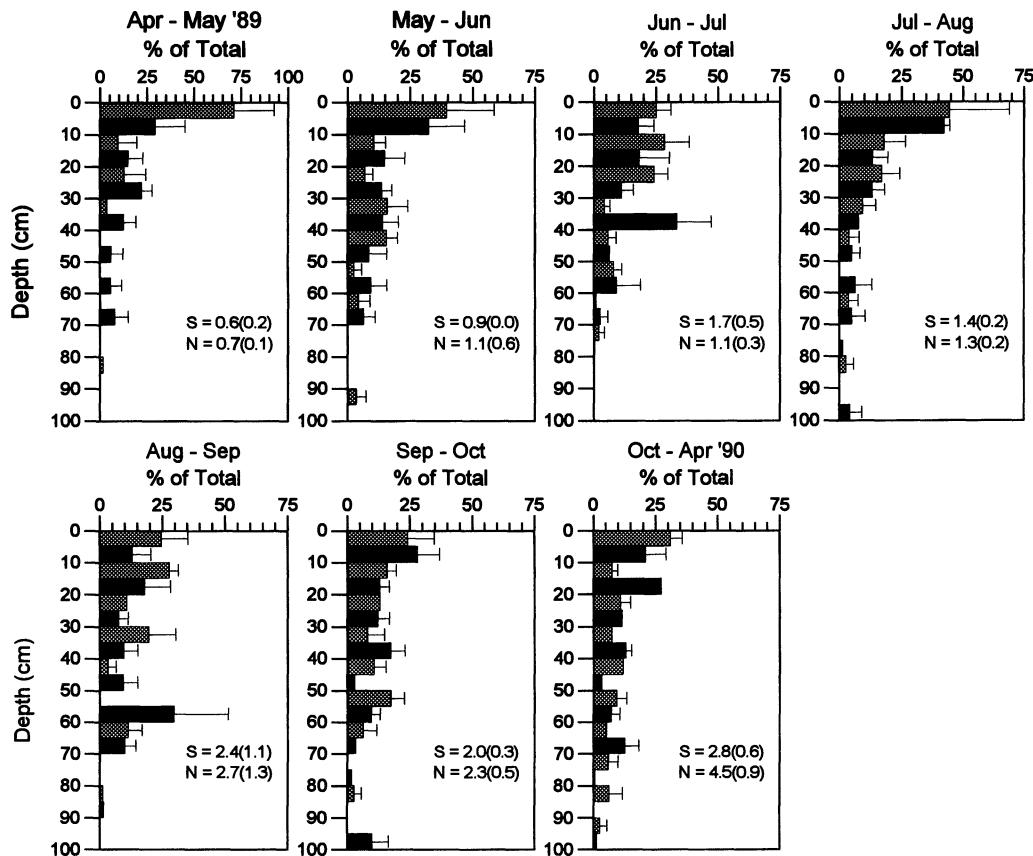


Fig. 2 Percentage distribution of fine root length mortality among depth increments during each observation interval. Bars are site means, with standard errors ($n = 3$) where shown (legend as in Fig. 1). Numeric values within each figure are total length mortality and standard errors (mm root per cm^2 of minirhizotron surface, summed across all depth increments) for each time interval. S = southern site, N = northern site.

little to total mortality summed across all depths because of the relatively small contribution of deep roots to total root length (Fig. 2).

Discussion

As expected, our data clearly show that shallow roots are responsible for the majority of annual fine root production and mortality in both of these forests. Only Joslin & Henderson (1987) estimated total root production in temperate hardwood forests to depths of 100 cm or more, and their results are similar to ours. At both of our sites, 44% of total annual production occurred between 0 and 20 cm, and only 11% at depths greater than 70 cm. The corresponding values for relative mortality are 49 and 4%, respectively. By assuming that turnover rates were similar for roots at all depths, Joslin & Henderson (1987) estimated that 50% of all production and mortality occurred at depths less than 22 cm, and only 13% at depths greater than 75 cm in a white oak forest.

McClugherty *et al.* (1982) separated roots into forest floor and mineral soil components. The proportional annual production of fine roots in the forest floor (6.3 cm in thickness), 0–15 cm mineral soil and 15–30 cm mineral soil depth increments occurred in ratios of 0.56:0.33:0.11, respectively. (We used their

monthly sampling data because the time interval more closely resembles our minirhizotron filming intervals than that associated with their min-max data.) The corresponding production ratios for roots growing in the soil depth increments 0–10, 10–20 and 20–30 cm at our sites are almost the same: 0.50:0.29:0.22. Powell & Day (1991) stratified root production in the upper 40 cm of soil by 10-cm increments in four forest communities within the Great Dismal Swamp. Ratios of production in the four depth increments (from surface to 40 cm) were 0.25:0.38:0.19:0.18 and 0.53:0.25:0.12:0.09 for a 133-day December–July and 94-day April–July period, respectively, in an elevated mixed hardwood forest. Corresponding annual data for the upper four increments at our sites are 0.44:0.24:0.18:0.16. Root distribution in any ecosystem will be strongly modified by local soil physical and chemical properties. Further differences between forest types can be expected from differing morphologies among species. However, there is a high degree of correspondence in all of the data cited above, including our own.

The roots of many tree species are capable of growing to depths of 5–40 m or more (Stone & Kalisz 1991). These deep roots may be an important source of soil C in some tropical forests (Nepstad *et al.* 1994) and grasslands (Fisher *et al.* 1994). However, our data

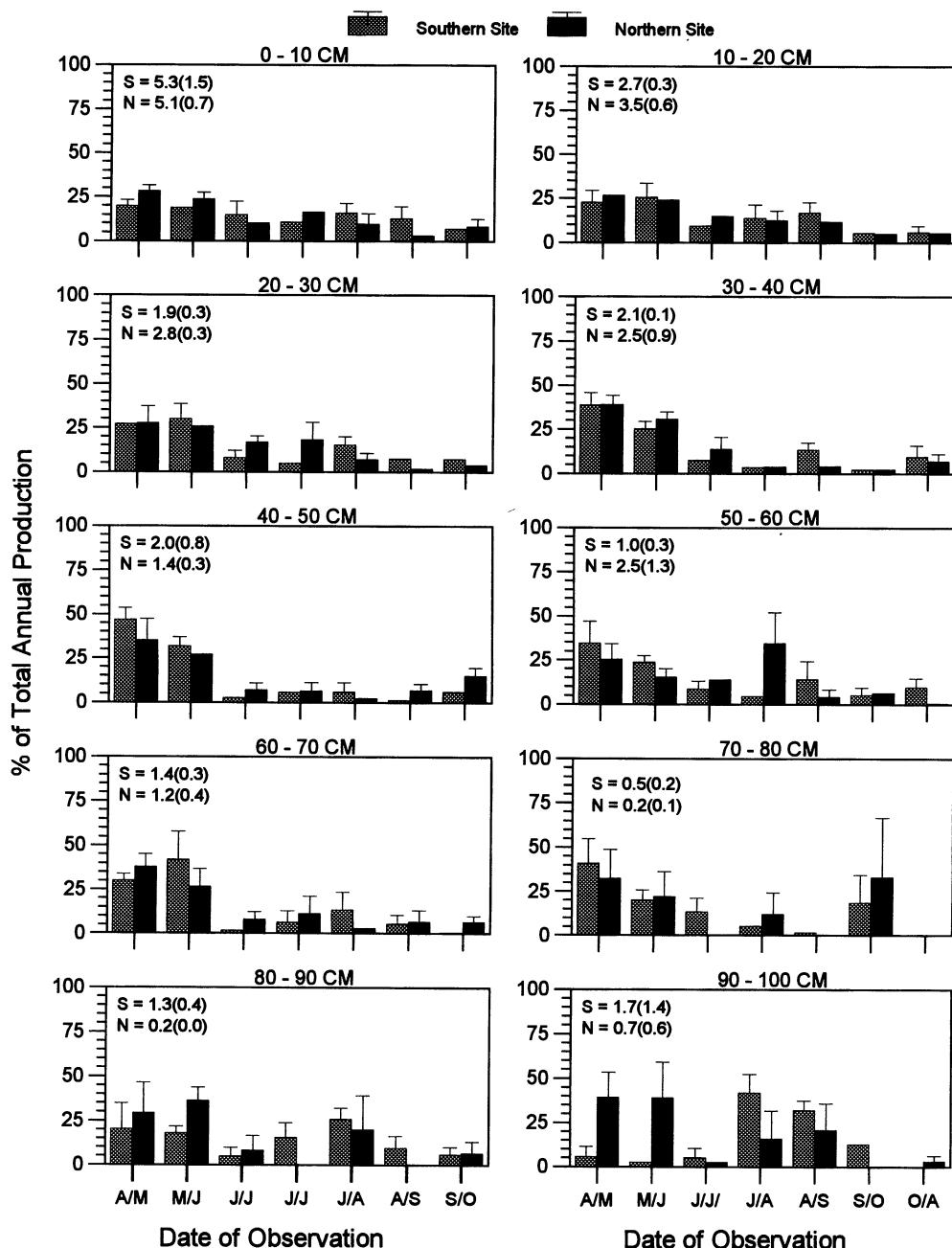


Fig. 3 Percentage distribution of total annual fine length root production among observation intervals for each depth increment. Bars are site means, with standard errors ($n = 3$) where shown. Note that the October–April (final) time period is 6 months in duration, while all others are of ≈ 1 month's duration. Numeric values within each figure are the total length production and standard errors (mm root per cm^2 of minirhizotron surface, summed across all dates) for each depth increment. S = southern site, N = northern site.

and the studies cited above suggest that deep roots probably play a relatively small role in the C and nutrient budgets of the few North American deciduous forests in which they have been studied. Sampling difficulties complicate the process of quantifying the production and mortality of anything other than shallow roots, and there are few reports of the actual amount of C or nutrients cycled via deep root turnover in temperate deciduous forests other than the study of Joslin & Henderson (1987).

The timing of root growth and mortality in relation to canopy events is poorly understood in most forest

types, but early root growth is likely to be adaptive in a seasonal climate subject to periodic droughts as in Michigan. Indeed, our data suggest fine root production is greater in spring and early summer at all soil depths (Fig. 3), and not just depths < 30 cm (Hendrick & Pregitzer 1992a, 1993a). Similar observations at shallow depths have been made in other northern hardwoods forests by Burke & Raynal (1994), Fahey & Hughes (1994) and Morrow (1950). In several temperate hardwood and coniferous species root growth can precede shoot growth by as much as 3 weeks (Lyr & Hoffman 1967). The onset of spring root growth at

Table 3 Treatment means (averaged across depth and sites) of percentage total root production by date. Values with the same letter are not significantly different ($P = 0.05$, Tukey's honestly significant difference Studentized range test)

Date	% Production
April–May 1989	30.7 ^a
May–June 1989	25.8 ^{bc}
June–July 1989	11.7 ^{cd}
July–August 1989	11.5 ^c
August–September 1989	8.7 ^c
September–October 1989	7.2 ^d
October 1989 – April 1990	5.5 ^d

all soil depths has been linked to rising soil temperatures (Lyr & Hoffmann 1967; Teskey & Hinckley 1981; Kuhns *et al.* 1985), but root growth may also be stimulated by environmentally induced changes in bud or shoot physiology and the production of growth regulators. In any event, although early season root production represents a considerable investment of stored reserves (Nguyen *et al.* 1991; Kozlowski 1992), its magnitude and timing suggests that it may be an advantageous trade-off that enables an expanding canopy to meet transpirational and assimilatory water demands.

Significant early deep root growth is believed to be critical for successful canopy development in white oak (Teskey & Hinckley 1981), and is substantial in amount in these *Acer saccharum*-dominated forests. For example, over 50% of all root production occurred prior to mid June (which is just after full canopy expansion) at depths between 60 and 90 cm at the northern site. Approximately 80% of total annual production occurred during this time at the 90–100-cm depth increment. The values for the southern site are similar, with the exception of the 90–100-cm increment, where most root production occurred from July through September. Kuhns *et al.* (1985) reported that *Juglans nigra* (L) root growth preceded bud-break at all depths up to 90 cm, although deeper roots (to a depth of 140 cm) initiated growth only after the leaves had fully expanded and available soil moisture at lesser depths had begun to decline. At all depths, we observed a substantial decline or cessation of root growth after canopy senescence. Burke & Raynal (1994) and Fahey & Hughes (1994) both observed a similar decline or cessation of root growth in other northern hardwood forests dominated by *Acer saccharum*, but substantial post leaf-fall root growth at various depths has been observed in *Quercus alba* (Teskey & Hinckley 1981) and *Juglans nigra* (Kuhns *et al.* 1985).

Seasonal patterns of fine root mortality were different than those of production. Although relative mortality was greatest during canopy senescence and after leaf fall at all depths, it was distributed rather evenly throughout the year near the soil surface (Fig. 4). The temporal patterns of shallow root pro-

duction and mortality suggest a rather constant turnover and replacement of these roots throughout the growing season. Short- or long-term drought has been implicated as a cause of accelerated root mortality (Santantonio 1982; Marshall 1986), but we did not see marked increases in shallow root mortality during mid-summer, traditionally the driest part of the growing season at our sites (Figs 2 and 4). Kasola & Eissenstat (1994) did not observe drought-induced mortality of the shallow roots of citrus in which deeper roots had access to ample supplies of soil moisture. They suggested that, for plants able to maintain a favourable leaf water balance by taking up water from deeper layers, the carbon costs of maintaining shallow roots in dry soils may be outweighed by the benefits associated with the ability to capture water and minerals following precipitation events.

Shallow and deep root mortality were not synchronous. Unlike shallow roots, mortality at depths exceeding 50 cm was concentrated during or after canopy senescence. At these depths, there was little or no fine root mortality prior to late July or August, while greater than one-half of annual mortality occurred late in the year. These data suggest that many of the deep roots are living (and presumably functional) for a majority of the growing season, and that the autumnal senescence of deep roots may be analogous to and synchronous with canopy senescence.

Some of our data provide circumstantial evidence that episodic deep root production in mid-summer may be related to periods of abnormally high transpirational demand. In particular, two periods of relatively important deep root production occurred in the July–August observation period at both the northern (50–60-cm) and southern (80–100-cm) sites (Figs 1 and 3) during a period of moisture limitation. During July of 1989, the soil water deficit at the northern site was 10.3 cm and at the southern site was 9.7 cm. These moisture deficits are considerably greater than the corresponding values for both June (2.9 and 1.4 cm) and August (0.0 and 1.4 cm). It is possible that deep root production during the July–August interval may have been stimulated by low water availability near the surface and/or high transpirational demand. The roots produced in the 50–60-cm depth increment during the July–August interval accounted for $\approx 80\%$ of the mortality in the during the August–September observation period at the northern site (Fig. 2), suggesting that they represented a short-term investment in absorbing area during a time of high water demand. Teskey & Hinckley (1981) noted a similar increase in the number of white oak roots in response to drying soils in the range of -0.4 to -0.8 MPa. However, they did not report on whether the soil drying and a corresponding increase in root numbers occurred at the same or different depths, or if these roots were short-lived.

It is unclear as to why there are more pronounced

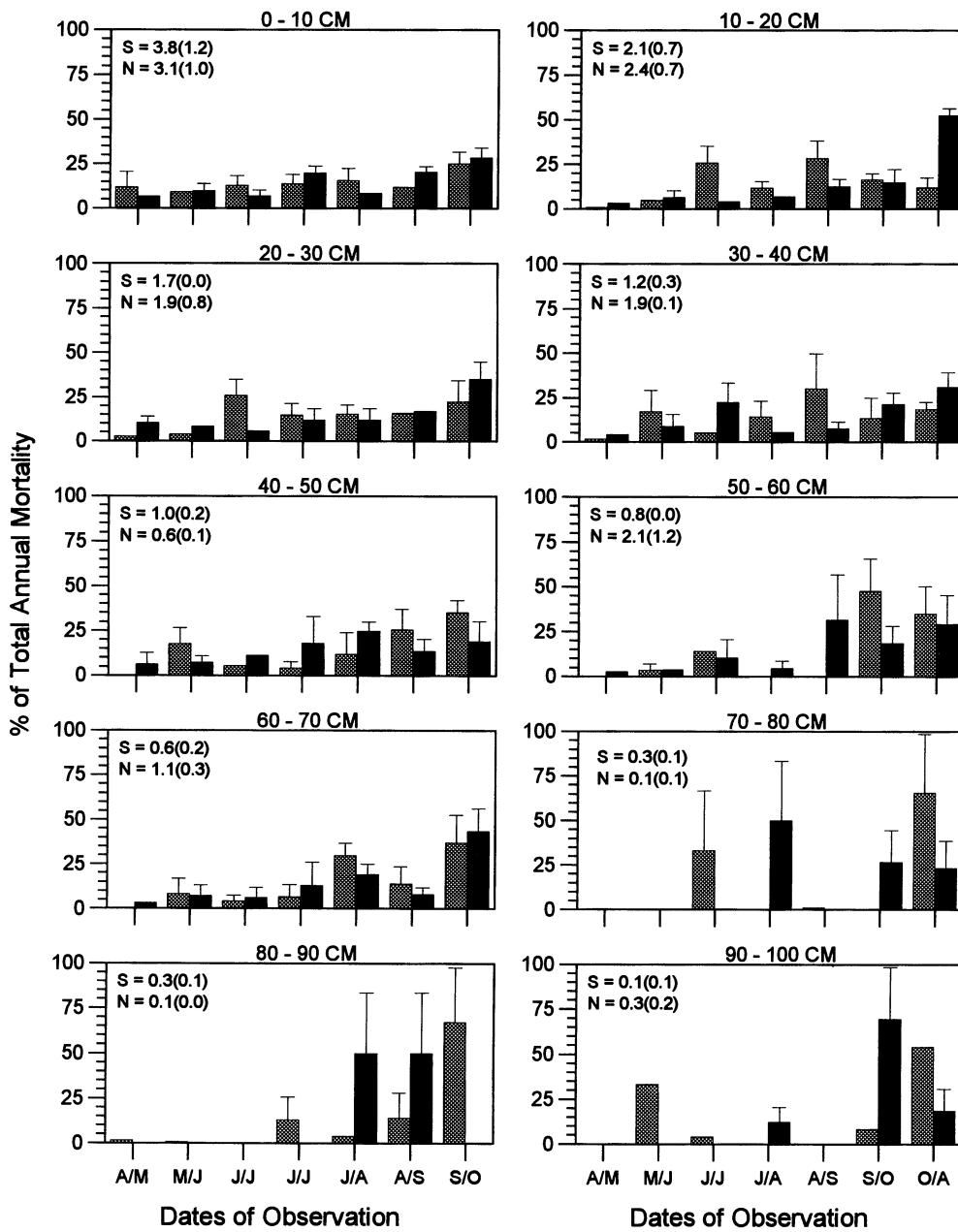


Fig. 4 Percentage distribution of total annual fine root length mortality among observation intervals for each depth increment. Bars are site means, with standard errors ($n = 3$) where shown (legend as in Fig. 3). Note that the October–April (final) time period is 6 months in duration, while all others are of ≈ 1 month duration. Numeric values within each figure are the total length mortality and standard errors (mm root per cm^2 of minirhizotron surface, summed across all dates) for each depth increment. S = southern site, N = northern site

seasonal peaks in deep than shallow root production and mortality at our sites. Nor do we know whether these patterns are peculiar to the forests we studied or are typical of other temperate deciduous forests. With respect to those factors controlling the timing of root growth, it is unlikely that deep and shallow root production can be explained by soil temperature or moisture levels alone. The means by which the shoot might stimulate roots to grow at particular times of the year or within particular volumes of soil, however, are not clearly known.

Our data indicate that there is at least some degree of temporal uncoupling between root growth and mortality both within and among soil depths. Some of the patterns we observed could be artefacts of our inability to separate roots according to species, some of which have differing morphologies and probably different temporal growth and mortality patterns as well. It is also possible that root growth may be relatively more or less abundant within different portions of the soil profile as a tree ages, and that we are witnessing the results of ontogenetic changes in root

form and activity. However, most of the trees on the study sites are within the main canopy, and have probably reached their near-maximum rooting depth. As stated previously the distinction between deep and shallow roots is highly artificial and perhaps of limited functional significance. Apparent temporal uncoupling in the dynamics of roots at different depths likely results from the close physiological coupling of all roots within a particular tree's root system, and the need for the tree to optimize allocation to those portions of the roots system most critical for ensuring adequate resource capture.

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