Biomass Partitioning and Root Architecture Responses of Loblolly Pine Seedlings to Tillage in Piedmont and Coastal Plain Soils

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ABSTRACT: *In the southeastern United States, site preparation methods often involve surface and subsurface tillage used singly or in combination. However, growth responses to these treatments are often inconsistent across sites and physiographic regions. In an effort to gain insight into how pine growth is affected by tillage, the effects of two treatments, machine planting and combination tillage (i.e., disking, subsoiling, and bedding), were examined in terms of biomass partitioning and root system architecture of loblolly pine seedlings (*Pinus taeda *L.) on Piedmont and Upper Coastal Plain sites in Alabama and Georgia. Our objectives were to evaluate the effects of combination tillage on root system development and examine whether potential effects were related to aboveground measures. Seedling allometry indicated that for all sites and both physiographic regions, machine planting and combination tillage treatments resulted in similar biomass partitioning above- and belowground. Furthermore, on both Piedmont and Coastal Plain sites, root architecture was primarily influenced by the presence of the subsoil "rip" regardless of treatment. These conclusions suggest that compared to machine planting, combination tillage did not affect biomass partitioning on the functional rooting zone of these young pines to a degree that was biologically significant. South. J. Appl. For. 28(2):76–82.*

Key Words: Loblolly pine, *Pinus taeda*, combination tillage, machine planting, biomass partitioning, root architecture.

Soil manipulation during site preparation has long been noted to be beneficial in some cases (Lantagne and Burger 1983, Wittwer et al. 1986) and less effective in others (Haines 1978, Berry 1979). Site cultivation treatments typically employ surface tillage (i.e., disking, harrowing, and/or bedding) and subsurface tillage (i.e., ripping) that can be used either singly or in combination. Disking is thought to reduce belowground root competition, improve infiltration, and increase nutrient availabilities by incorporating organic matter into surface soil horizons (Fox et al. 1986, Morris and Lowery 1988). Bedding may increase seedling growth and survival by increasing soil rooting volume, decreasing soil bulk density, improving infiltration, and increasing nutrient availabilities since organic matter is concentrated in the bedded planting row (Morris and Lowery 1988, Lowery and Gjerstad 1991).

Other intensive cultivation treatments such as ripping or subsoiling have become popular because this practice is thought to increase water infiltration rates and improve root growth and exploitation of naturally and/or anthropogenically compacted subsurface soils (Morris and Lowrey 1988). The broader use of subsoiling was partially a response to the Conservation Reserve Program where the presence of plow pans often proved to be an obstacle to successful pine regeneration of fields (USDA Forest Service 1988). Furthermore, machine planting also provides a small degree of tillage through creation of the planting slit, which may increase the soil volume and depths used by seedlings in the first year of growth.

In agriculture, appropriate tillage tends to improve soil physical properties so that a more hospitable rooting environment is created, thus leading to greater acquisition of water and nutrients and, ultimately, higher aboveground productivity. However, excessive tillage and/or bad choices regarding the mode of tillage can degrade soils (Ogburn et al. 1983) and negatively influence long-term soil and stand

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productivity (Fox 2000, Grigal 2000). Based on the agricultural experience, similar improvements should occur in the rooting zones of trees and increases in aboveground growth could logically be expected to follow. However, studies of loblolly pine rooting dynamics are rare compared to the rather extensive studies comparing survival and aboveground growth responses to various silvicultural and site preparation treatments. Little is known about root biomass and distribution within mature managed pine plantations (Parker and Van Lear 1996), or developing stands that have undergone intensive site preparation involving surface and subsurface tillage (Will et al. 2002). Conceptually, the Piedmont, with its eroded terrain and exposed subsurface horizons, with inherently high bulk densities, seem a logical place to expect major responses to tillage (Morris et al. 1988). Given the growth accelerations that seemed possible in response to intensive silviculture, anticipated rates of return are sufficient to make investment in tillage attractive. More recently, efforts to maximize productivity have renewed interest in intensive operations such as combination tillage (i.e., surface + subsurface tillage) that have the potential to facilitate growth and survival (North Carolina State Forest Nutrition Cooperative 2000).

Will et al. (2002) examined loblolly pine seedling allometry across several Piedmont and Coastal Plain sites and found that tillage treatments did not influence biomass partitioning between aboveground and belowground components. However, their study limited sampling of roots to an area of 1 $m^2 \times 40$ cm deep volume of soil and did not include fine roots. Consequently, Will et al. (2002) may not have captured the entire seedling root system. While fine roots constitute a lesser percentage to overall root biomass, they are the major pathway for water and nutrient acquisition (Pregitzer et al. 1997). Thus, following tillage, we might expect to see shifts in the partitioning of belowground resources to fine roots in response to differing soil moisture and nutrient levels. For example, increases in nutrient and water availabilities have been shown to decrease biomass allocation belowground (Bongarten and Teskey 1987, Griffin et al. 1995) an effect that might be anticipated as a result of increased nutrient availability due to bedding and subsoiling (Morris and Lowery 1988). Furthermore, examining tillage influences on root architecture (i.e., the spatial configuration, or the geometric deployment of roots within the soil profile) may also be informative since altering the soil profile could influence fine root production and growth patterns, and ultimately nutrient and water uptake (Lynch 1995). However, a detailed understanding of tillage influences on rooting dynamics, particularly, fine roots, still eludes forest managers and practicing foresters.

To date, reports and observations regarding growth responses to tillage operations applied singly or in combination remain inconsistent. This has been particularly evident for pine growth responses to subsoiling and combination tillage in the Piedmont (Morris et al. 1988, North Carolina State Forest Nutrition Cooperative 2000, Wheeler et al. 2002) where the potential for tillage-induced improvements in aboveground growth seemed high given the vast acreages of eroded and/or compacted soils (Dennington 1989). Consequently, this study was installed to evaluate whether combination operations including subsoiling caused changes in loblolly pine root biomass, biomass partitioning, and root architecture on Piedmont and Coastal Plain sites. Our objective was to evaluate the effects of tillage on root biomass and root system development and to examine whether those changes were related to aboveground measures.

Materials and Methods

The study comprised five sites owned by MeadWestvaco Corporation in the Piedmont and Upper Coastal Plain of east Alabama and west Georgia. Sites were chosen to represent a range of soil types (Table 1) and contained one set of paired plots that compared machine planting (MP) to combination plowing + machine planting (CP+MP). Prior to treatment, all plots were sheared using a V-blade. In Sept. of 1999, a broadcast aerial spray of hardwood competition control was applied on the Russell County, AL site with 0.56 kg a.i./ha of imazapyr. Tillage for the CP+MP treatment included disking, bedding, and subsoiling followed by machine planting. Combination tillage was performed in a single pass using a Savannah combination plow pulled behind a bulldozer in the late summer and

Table 1. Site locations, soil descriptions, and general soil horizon characteristics of the three Piedmont and two Coastal Plain sites located in Alabama and Georgia.

Site location	Series	Geology	Description	General horizons[a]
Lee Co., AL	Cecil	Felsic	Clayey, kaolinitic, thermic Typic Kanhapludult	0–15 cm sandy loam 15–25 cm sandy clay loam 25–75 cm clay
Lee Co., AL	Madison	Felsic	Fine, kaolinitic, thermic Typic Kanhapudult	0–15 cm sandy loam 15–23 cm sandy clay loam 23–75 cm clay
Meriwether, Co., GA	Gwinnett	Mafic	Fine, kaolinitic, thermic Rhodic Kanhapludult	0–20 cm sandy loam 20–30 cm clay loam 30–75 cm clay
Schley, Co., GA	Troup	Sandy-Loam Marine	Loamy, kaolinitic, thermic Grossarenic Kandiudult	0–20 cm sand 20–75 cm loamy sand
Russell, Co., AL	Conecuh	Clayey Marine	Fine, smectitic, thermic Vertic Hapludalf	0–13 cm sandy loam 13–23 cm clay loam 23–75 clay

[a] Horizon descriptions taken from Soil Survey Division, USDA-NRCS.

early fall of 1999. On average, the combination plow subsoil shank resulted in subsurface soil fracture to a depth of 45 cm across all sites. The MP treatment also performed minimal subsurface tillage since the shank created a planting slit approximately 20 cm deep. Seedlings were planted during the winter months of 2000. All sites were machine planted with genetically improved 1-0 loblolly pine (*Pinus taeda* L.) seedlings at a 1.83 × 3.05-m spacing. On all sites, in late Mar. and early Apr. 2000, banded herbaceous weed control consisted of 105.5 ml a.i./ha of sulfometuron methyl and 0.56 kg a.i./ha of hexazinone.

For both treatments, plots were eight rows wide with 14 trees per row. Measurement plots were six rows wide with 10 trees per row. Within each measurement plot, three loblolly seedlings were selected for measurement and destructive sampling during July and Aug. 2002. To minimize microsite variation, sample seedlings were selected from the third of each paired plot nearest the other paired plot. Also, since natural variation in seedling size might influence some of the root response variables (independently of a treatment effect), the three seedlings were chosen to represent a small, medium, and large seedling from each plot. A total of 30 seedlings (i.e., three seedlings per plot, six seedlings per site) were sampled. After measurement of total height and root collar diameter, each seedling was destructively sampled. Seedling aboveground biomass was separated into stem, branch, and foliar components and oven-dried to a constant mass at 70° C.

Total root systems for all seedlings were carefully excavated by hand using small shovels, trowels, and hand rakes. After excavation, the root systems for each seedling were washed and separated into three-diameter classes: fine roots (<2 mm), medium roots (2–5 mm), and coarse roots (>5 mm). Even though great care was taken during excavation, not all roots could be successfully removed from the soil. Linear regression equations were developed to predict the terminal root length, as well as root weights, from the broken tip diameter. Additionally, taproot depth as well as the depth of the first primary lateral root was recorded. Dry weights of total belowground biomass and the individual diameter classes were recorded after oven drying for 72 h at 70° C. Root length was determined indirectly using the line intersect method described by Bohm (1979) for roots in fine and medium diameter classes. Coarse root length was determined by direct measurement. Root surface area was estimated by the equation $0.5 \times (2\pi r) \times$ root length for all diameter classes. In addition, visual descriptions were made of the general architecture of each excavated root system.

Soil bulk density was determined at each of the five study sites by randomly excavating three soil pits within the MP and CP+MP treatments. Within each soil pit, samples were taken at four depths (0–10, 10–20, 20–30, and 30–40 cm) using a 5-cm-deep by 5-cm-diameter soil core. Samples were oven-dried to a constant mass at 105° C, and weighed.

Relationships for MP and CP+MP treatments across Piedmont and Upper Coastal Plain sites were explored for five combinations of response variables (natural log transformed) using linear regression. Dependent and independent variable pairs were respectively: (1) total biomass and total belowground biomass (2) total aboveground biomass and total belowground biomass; (3) total aboveground biomass and fine root biomass; (4) total aboveground biomass and total root length; and (5) total aboveground biomass and total root surface area. Differences in the slope of the regression lines for the MP and CP+MP treatments were compared using a test for heterogeneity of slopes in the general linear model procedure of SAS (SAS Institute 1996). Differences in b1 coefficients between treatment specific regressions were considered significant at the $P < 0.05$ level. The Student's *t*-test was used to explore differences in means for both vegetation and soil bulk density between MP and CP+MP treatments, with differences considered significant at the $P < 0.05$ level.

Results

Combination tillage across the three Piedmont sites significantly ($P < 0.05$) decreased soil bulk density within the upper 30 cm of soil; however, at the 30–40 cm depth, soil bulk density for the MP and CP+MP treatments was not significantly different (Table 2). By contrast, soil bulk density within the two Coastal Plain sites was not significantly different between MP and CP+MP treatments at any of the four sample depths (Table 2).

Across all sites, total aboveground biomass did not differ significantly ($P = 0.85$) between the MP (1298.3 g) and CP+MP (1366.4 g) treatments (Table 3). Belowground biomass of MP (295.9 g) and CP+MP (296.0 g) treatments also were not significantly different ($P = 0.82$). In addition

Table 2. Mean soil bulk density (±1 SE) measured for machine planted (MP) and combination plow + machine planting (CP+MP) treatments at four soil depths across both the Piedmont and Coastal Plain physiographic regions.

		Treatment		
Physiographic region	Depth (cm)	MP	CP+MP	$P > T$
Piedmont	0–10	1.4 ± 0.05	1.0 ± 0.10	0.041
	10–20	1.5 ± 0.10	1.1 ± 0.10	0.004
	20–30	1.4 ± 0.02	1.2 ± 0.10	0.050
	30–40	1.3 ± 0.01	1.3 ± 0.20	0.734
Coastal Plain	0–10	1.7 ± 0.20	1.4 ± 0.02	0.177
	10–20	1.8 ± 0.20	1.5 ± 0.10	0.177
	20–30	1.8 ± 0.10	1.5 ± 0.10	0.154
	30–40	2.0 ± 0.40	1.6 ± 0.03	0.323

to the similar amounts of belowground biomass, the percentage of fine, medium, and coarse roots in the MP treatment (4.8, 12.4, and 82.8%, respectively) were very similar to those in the CP+MP treatment (4.9, 11.2, and 83.9% respectively) indicating that the two tillage treatments partitioned similar amounts of biomass into fine roots (Table 3). Furthermore, the MP and CP+MP seedling root/shoot ratios (0.24 and 0.23, respectively) did not differ significantly ($P = 0.89$) suggesting similar above- and belowground biomass partitioning for the two pooled tillage treatments. Overall, no significant differences in any of the above- or belowground biomass variables were observed for the MP and CP+MP treatments (Table 3).

Different relationships between total seedling biomass and belowground biomass were not apparent between the MP and CP+MP treatments (Figure 1A) and the regression line slopes for the MP ($b_1 = 0.94$) and CP+MP ($b_1 = 0.98$) treatments did not differ significantly ($P = 0.71$). For the relationships between aboveground biomass and belowground biomass, MP ($b_1 = 0.92$) and CP+MP ($b_1 = 0.97$) treatments also did not differ significantly ($P = 0.70$, Figure 1B). Similarly, there were no significant differences between the slopes ($P = 0.93$) of total aboveground biomass and fine root biomass for the MP ($b_1 = 1.0$) and CP+MP ($b_1 = 0.98$) treatments (Figure 1C) or between the slopes of total aboveground biomass and total root length for the MP ($b_1 = 0.90$) and CP+MP ($b_1 = 0.88$) treatments ($P = 0.96$, Figure 1D). Finally, relationships between total aboveground biomass and total root surface area for the MP ($b_1 = 0.79$) and CP+MP ($b_1 = 0.80$) treatments did not differ significantly ($P = 0.98$, Figure 1E).

Differences in root architecture between treatments were minimal and reflect the similar biomass partitioning among belowground components. Root architecture was heavily influenced by the presence of the subsoil "rip" regardless of treatment and site. Overall, seedling taproot depths on the CP+MP treatment were deeper than those of the MP treatment (Table 3).

Discussion

Examining the allometry of the seedlings indicated that for all sites and both physiographic regions, the CP+MP and MP treatments resulted in similar biomass partitioning. In addition to lack of statistically significant different slopes between MP and CP+MP regression relationships, no treatment effects are apparent in Figure 1, A–E. Generally, a high degree of data interspersion is apparent from both physiographic regions and treatments. However, in a few cases, influences of physiographic region are visually suggested. For example, when aboveground biomass is plotted against total root length (Figure 1E) most Piedmont and Coastal Plain data fall above and below, respectively, a theoretical line representing the average response. This may suggest that higher aboveground biomass is produced on Piedmont sites for a given root length.

Overall, these findings suggest that both the MP and CP+MP treatments resulted in similar and proportionate partitioning of biomass both above- and belowground. Furthermore, our data support the findings of Will et al. (2002) who noted that soil tillage, which included machine planting and combination tillage, did not influence relationships between root systems and aboveground dimensions and/or biomass partitioning. More specifically, the relationships from this study do not differ between sites that are machine planted (only) from those that are tilled using combination tillage (i.e., disked, bedded, and subsoiled).

Table 3. Selected independent and dependent variable means (±1 SE) for the machine planted (MP) and combination plow + machine planting (CP+MP) treatments averaged across both the Piedmont and Coastal Plain physiographic regions.

	Treatment		
Response variables	MP	CP+MP	$P > T$
Height (m)	2.2 ± 0.2	2.2 ± 0.2	0.77
RCD (mm)	45.6 ± 3.6	46.1 ± 4.1	0.93
Volume (cm^3)	5,618.5 ± 1,142.5	6,156.1 ± 1,322.2	0.76
Total biomass (g)	1,594.1 ± 271.2	1,662.4 ± 320.1	0.87
Total aboveground biomass (g)	1,298.3 ± 225.2	1,366.4 ± 266.6	0.85
Leaf biomass (g)	588.7 ± 98.7	578.9 ± 98.7	0.95
Stem biomass (g)	429.2 ± 85.4	497.0 ± 119.3	0.65
Branch biomass (g)	280.4 ± 51.9	290.6 ± 57.2	0.90
Total belowground biomass (g)	296.0 ± 53.2	296.0 ± 59.3	1.0
Fine roots (g)	14.1 ± 1.9	14.4 ± 2.6	0.92
Medium roots (g)	36.9 ± 4.6	33.2 ± 5.3	0.61
Coarse roots (g)	245.0 ± 49.6	248.4 ± 52.9	0.64
Total root length (cm)	5,268.7 ± 719.8	5,352.1 ± 976.3	0.95
Fine roots (cm)	2,894.5 ± 405.6	3,147.5 ± 595.5	0.73
Medium roots (cm)	1,535.8 ± 237.9	1,299.2 ± 260.8	0.51
Coarse roots (cm)	838.4 ± 246.5	905.5 ± 269.8	0.86
Total root surface area (cm^2)	19,575.1 ± 3,279.0	19,198.0 ± 3,869.3	0.94
Fine roots (cm^2)	4,546.6 ± 637.1	4,944.0 ± 935.4	0.73
Medium roots (cm^2)	8,443.7 ± 1,307.9	7,142.6 ± 1,433.7	0.51
Coarse roots (cm^2)	6,584.8 ± 1935.6	7,111.4 ± 2,118.8	0.86
Root/shoot ratio	0.24 ± 0.02	0.23 ± 0.02	0.59
Tap root depth (cm)	39.0 ± 4.8	54.8 ± 6.6	0.06
Lateral root depth (cm)	9.9 ± 1.0	10.7 ± 1.1	0.59

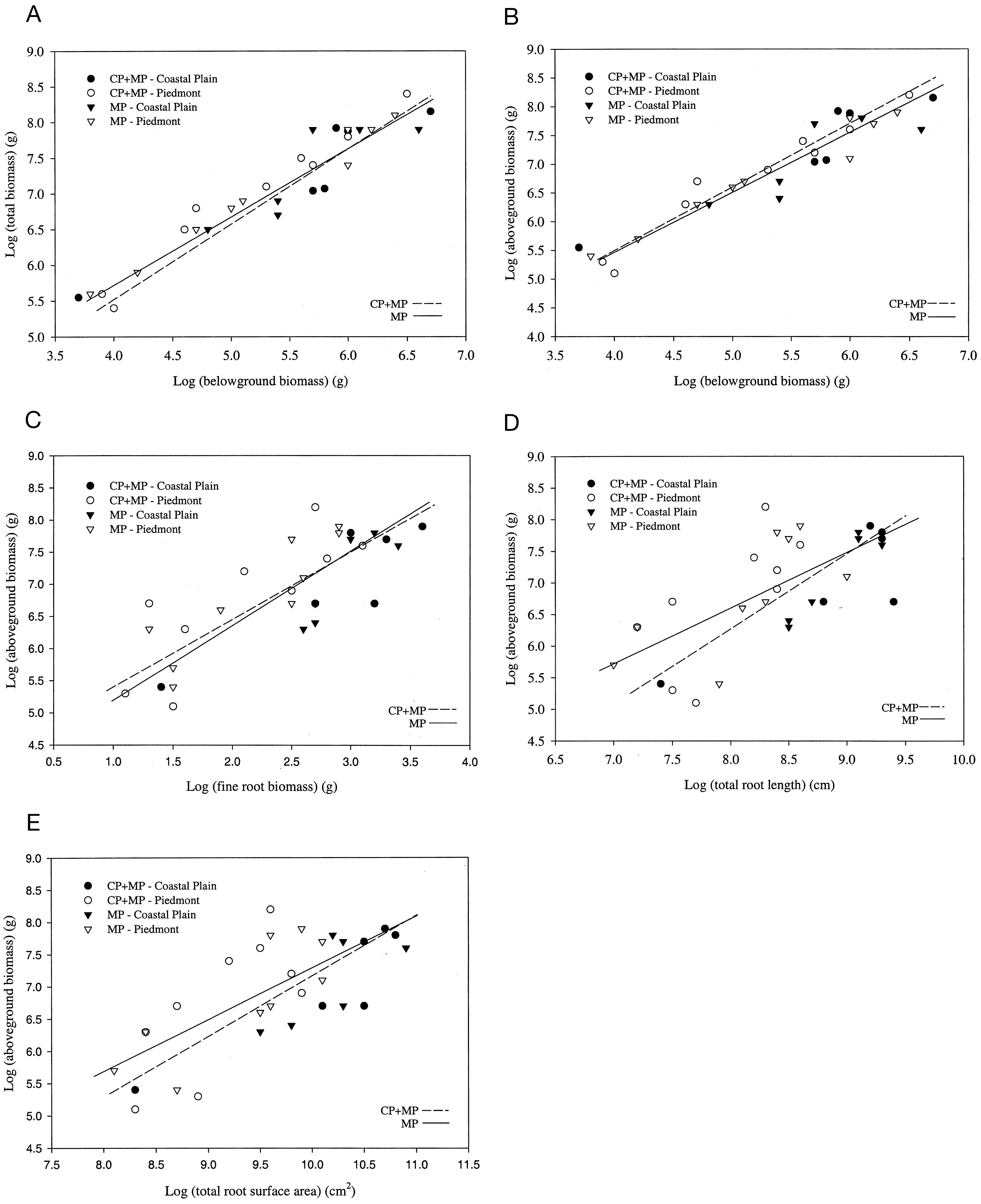

Figure 1. Treatment relationships between loblolly pine above- and belowground parameters for the two tillage treatments, machine planting (MP) and combination plow + machine planting (CP+MP), measured at five sites in the Piedmont and Coastal Plain of Alabama and Georgia. Relationships displayed are for (A) total biomass and total belowground biomass; (B) total aboveground biomass and total belowground biomass; (C) total aboveground biomass and fine root biomass; (D) total aboveground biomass and total root length; and (e) total aboveground biomass and total root surface area. The solid and dashed lines represent the slopes of the regression lines for the MP and CP+MP treatments, respectively.

In terms of belowground biomass, both the MP and CP+MP treatments had comparable levels of biomass partitioned into each of the three root categories. The similar percentages of fine root biomass for both the MP and CP+MP tillage treatments (4.8 and 4.9%, respectively) suggests that seedlings from neither treatment preferentially increased or decreased production of fine roots in response to nutrient acquisition. Will et al. (2002) found no increases in *N* availability following various forms of tillage and similar levels of fine root biomass, length, and surface areas for both the MP and CP+MP treatments may reflect similarities in nutrient availabilities.

The similar visual observations of root architecture for both the MP and CP+MP treatments may suggest similar subsoil fracture patterns following these two types of tillage. For example, most, if not all, lateral roots of both treatments were strongly oriented longitudinally along this line of soil fracture. Furthermore, the majority of fine roots were clustered at the ends of the major lateral roots within the rip often greater than 1 m, and sometimes as far as 3 m, from the main stem. In many cases, main lateral roots followed the subsoil rip and extended well into the rooting zone (within the soil rip) of adjacent seedlings. For the CP+MP treatments, particularly on the Piedmont sites, the increased volume of soil that was tilled often was not exploited by either fine and coarse roots, even though bedding typically increases nutrient availability by concentrating the A horizon and organic matter into the bed (Morris and Lowery 1988, Lowery and Gjerstad 1991).

It is interesting to note that combination tillage influenced soil bulk density differently across physiographic regions. The CP+MP treatment on the three Piedmont soils significantly reduced soil bulk density in the upper 30 cm of soil compared to the MP treatment. By contrast, soil bulk density for the MP and CP+MP treatments on the two Coastal Plain soil types did not differ significantly (Table 3). Seedling root growth is limited when clay soil bulk density ranges between 1.40 and 1.45 g cm^{-3} and where bulk density for sandy clay and sandy clay loam soils range between 1.55 and 1.70 g cm^{-3} (Daddow and Warrington 1983). Both the Piedmont and Coastal Plain soils of the MP treatments are within, or exceed, these reported ranges suggesting these soils limited root development. However, given the similar amounts of biomass allocated to fine, medium, and coarse roots, as well as patterns of seedling allometry, it appears that the soil bulk density of the MP treatments of both physiographic regions were not at a critical level to significantly differentiate patterns of root growth and development from the CP+MP treatments.

For CP+MP treatments in the Coastal Plain, there was a tendency for lateral roots to grow upward into the surface soils of the beds, a trend that was not observed for CP+MP treatment seedlings on the three Piedmont sites. Loblolly pine seedling root growth is reduced in sandy loam soils with a bulk density of 1.4 g cm^{-3} and often severely restricted at a bulk density of 1.8 g cm^{-3} (Mitchell et al. 1982). Thus, this observed growth response on the Coastal Plain sites may be in response to the high soil bulk densities (1.6 g cm^{-3}) observed for the CP+MP treatment at the 30–40 cm depth.

One noticeable difference in root architecture between treatments was for taproot depth (Table 3). Though not highly significant ($P = 0.06$), taproot depth for the CP+MP treatment numerically exceeded that of the MP treatment across all sites as would be expected, given the deeper shank depth (45 cm) used for the CP+MP treatment than the MP treatment (20 cm). However, advantages of increased taproot depths for the CP+MP treatment are not clearly evident given that both treatments partitioned similar amounts of biomass above- and belowground.

Overall, when comparing treatments and physiographic regions, differences in seedling root dynamics and architecture were minimal. The similarities in belowground biomass partitioning and root architecture between the MP and CP+MP treatments may explain the lack of, or inconsistent, growth trends reported for may studies examining extensive tillage practices like combination tillage (Wheeler et al. 2002, North Carolina State Forest Nutrition Cooperative 2000).

Conclusions

In combination with inconsistent and often small gains in growth reported in the literature, these findings suggest that across this range of Piedmont and Coastal Plain soils, both the MP and CP+MP treatments manipulated the rooting zones of these young pines similarly. While the CP+MP treatment did significantly decrease soil bulk density in the upper 30 cm of soil for the Piedmont sites, this did not result in changes in biomass partitioning between above and belowground components, or differential partitioning of biomass among root components. Consequently, the homogeneity of belowground biomass partitioning between treatments caused aboveground responses to be usually subtle and/or inconsistent.

It is important to note that these findings do not suggest that tillage operations are not beneficial tools for plantation establishment given certain site/soil conditions. For example, it has long been known that bedding Coastal Plain sites can ameliorate soil compaction resulting from harvest operations (Gent et al. 1983) and with their inherently shallow water tables, improve seedling survival and early growth (Mann and McGilvray 1974, Pritchett 1979, Outcalt 1984). In addition, subsoiling can increase seedling survival where subsoils have naturally high soil strength (Morris and Lowery 1988), or plow pans are present due to previous agricultural activities (USDA Forest Service 1988). Furthermore, combination tillage operations can reduce soil strength in surface soils as evidenced by the significantly decreased bulk density from the CP+MP treatments in the Piedmont soils of this study.

However, given the uncertainties in treatment responses to combination tillage across numerous Piedmont and Coastal Plain sites, it has become increasingly clear that a better understanding of fundamental tillage processes within intensively managed forest plantations is warranted. It is unclear how long changes to surface and subsoil horizons persist following combination tillage and the time period which roots are able to exploit these changes. Particularly lacking is an understanding of the types of soil fracture generated by subsoil implements and how seedling growth is influenced by these patterns of belowground soil disruption. For agricultural systems, there exists a detailed understanding of the relationship between subsoil shank design and patterns of surface and subsurface soil disruption (Raper 2002). As evidenced by seedlings from both treatments utilizing the subsoil rip similarly, it appears that the patterns of subsoil fracture for both the MP and CP+MP treatments were comparable. A more detailed understanding of the interactions between tillage types, particularly shank design, and seedling root morphology and architecture responses to these designs may provide greater clarity to the inconsistent growth responses commonly reported in the literature for combination tillage treatments.

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