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An approach for using general soil physical condition–root growth relationships to predict seedling growth response to site preparation tillage in loblolly pine plantations

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Abstract

Tree seedling root growth rate can be limited by any one of three soil physical factors: mechanical resistance, water potential or soil aeration. All three factors vary with soil water content and, under field conditions, root growth rate will depend on the soil water content as a result of its relationship to each factor. For a specific site, the relationship between soil water content and each factor can be developed from periodic measurement in the field or estimated from intact soil core samples. A STELLA^{TM} model of first-year pine seedling growth response to soil tillage was developed using previously established relationships between root growth and these growth-limiting factors. The model predicts reductions in root growth below optimal conditions from soil water content. Accumulated root length is then used to estimate aboveground size from an available allometric relationship. Model predictions were compared to results from a site preparation tillage study on an upland site for which soil water content had been measured bi-weekly. Treatments used for this comparison were: no tillage, bedded, subsoiled and bedded plus subsoiled. Seedling height predicted by the model differed from measured mean seedling height by −1 to +14% with absolute differences in height of 0.1 m or less. Predicted aboveground biomass was −12 to +41% of mean measured biomass. Our results suggest that this modeling approach is useful for integrating results from controlled greenhouse experiments with field results and may prove useful for predicting soil tillage response in young loblolly pine plantations.

Keywords: *Pinus taeda*; Site preparation; Mechanical resistance; Aeration; Root growth; STELLA^{TM}; Modeling

1. Introduction

Mechanical site preparation has been considered essential to southern pine plantation establishment since the 1950s. The benefits of site preparation depend on both the treatment regime and site characteristics. Slash reduction treatments, such as shearing and piling, chopping or burning, generally have minimal impact on soil physical conditions. Their major purpose is to improve site operability and their major impact is on the nature and level of plant competition and soil nutrient availability (Morris and Lowery, 1988). These treatments can be contrasted with site preparation treatments that involve soil tillage, such as bedding, mounding, disking or subsoiling, that can dramatically alter soil physical conditions that influence root growth of planted seedlings. For instance, bedding of poorly drained sites increases surface soil aeration (Scheerer et al., 1995; Dulohery et al., 1996; Aust et al., 1998) and reduces soil mechanical resistance (Aust et al., 1998; Miller et al., 2004). Disking or bedding of upland sites reduces surface soil mechanical resistance and improves aeration, particularly on sites compacted by harvesting (Gent et al., 1984; Gent and Morris, 1986). Subsoiling, used alone or in combination with surface tillage, can reduce soil mechanical resistance at greater depths and can increase water availability in the rooting zone (Wittwer et al., 1986; NCSFNC, 2000a,b; Lincoln et al., in press).

Relatively few studies of site preparation have isolated the contribution of improved soil physical conditions resulting from tillage from other benefits of site preparation, such as competition control or improved nutrient availability. Results from recent studies indicate only modest growth responses to

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tillage with both positive as well as negative growth responses to the same tillage treatment occurring on sites that appear quite similar (NCSFNC, 2000a; Wheeler et al., 2002; Schilling et al., 2004).

Attempts to correlate seedling growth with post site preparation measurements of soil physical properties have achieved limited success. Attempts to relate tree growth to soil bulk density, which is relatively stable over time and is easily measured, are most common (Foil and Ralston, 1967; Stransky, 1981; Mitchell et al., 1982; Will et al., 2002; Schilling et al., 2004) but correlation with other soil properties (e.g. macropore volume, hydraulic conductivity) have also been investigated. Unfortunately, while significant relationships may exist between these properties and growth for the specific conditions of the study for which they are developed, such relationships are not easily generalized to other sites with different soil texture, soil structure or soil water regime. Moreover, these stable measures do not reflect the dynamic nature of the soil physical environment. Factors that limit root growth change during normal wetting and drying cycles. Under wet conditions, poor aeration may limit root growth of planted pine even though mechanical resistance to growth is low, while under drier conditions, aeration may be adequate but mechanical resistance may limit root growth (Kelting et al., 2000).

Recently, attempts have been made to incorporate the effects of seasonal variation in soil water content into evaluations of root growth conditions and prediction of seedling growth response to tillage. These include regression approaches to predict soil resistance based on measures of soil water content (Colbert, 2001) as well as the use of the least limiting water range (LLWR). The LLWR, proposed by Letey (1985), is the range in soil water content between a wet limit to growth and a dry limit to growth. The wet limit is defined as either field capacity or the moisture content when less than 10% of the soil pores are air-filled. The dry limit is the moisture content at which mechanical resistance is greater than 2.0 MPa or water potential is less than −1.5 MPa. Soil water conditions between these two limits are considered suitable for root growth. Using this approach, along with information on the depth of oxidation and site fertility, Kelting et al. (2000) found that 87% of the variation in loblolly pine growth on rutted and compacted lower coastal plain sites could be explained.

One major drawback exits to the use of the LLWR approach for predicting growth response to tillage. The LLWR does not distinguish between growth conditions within the suitable range. On upland sites, the wet limit (air-filled pore space) is seldom reached and most tree growth response is likely to be determined by differences in soil conditions below the dry limit of the LLWR. As Eavis (1972) showed, both soil mechanical resistance and soil water potential contribute to root growth limitations in this soil water content range. In a recent study, Siegel-Issen et al. (2005) explored the value of the LLWR approach for predicting pine seedling root growth under controlled greenhouse conditions. Using a 7×7 factorial study they created a matrix of different bulk density and volumetric water contents in cores in which they grew pine seedlings. They concluded that the LLWR had potential to indicate soil quality, but that seedling growth was not consistently predicted by the LLWR. However, as part of this same study, these investigators developed a root length density response surface to soil bulk density and volumetric water content which they suggest could be used in conjunction with field measurements of seasonal soil water content to predict tree growth response to soil physical limitations.

General relationships between pine root growth and (1) mechanical resistance (Torreano, 1992), (2) water potential under non-mechanically resistant conditions (Torreano and Morris, 1998; Ludovici and Morris, 1997) and (3) aeration (Torreano, 1992) have been established for loblolly pine as well as for other commercially important pine species (e.g. *P. ponderosa and echinata*, Siegel-Issen et al. (2005); *P. radiata*, Zou et al. (2001a,b); *P. caribaea*, Constantini et al. (1996a,b)) under controlled greenhouse or rhizotron conditions. In this paper, we evaluate the potential for using these types of general relationships as a means for predicting growth response to soil tillage when integrated with site-specific characterization of soil properties and periodic measures of soil water content. A simple STELLA™ model is developed to predict seedling growth and results are compared with results of a site preparation study installed in the upper coastal plain of Georgia.

2. Materials and methods

2.1. Model development

2.1.1. General structure

The overall structure of the model is illustrated in Fig. 1. At its core, are three relationships: the relationship between root growth and mechanical resistance, root growth and soil water potential and root growth and air-filled pore space. These relationships are not site-specific and, as discussed in Section 2.1.2, we used relationships established in previous greenhouse studies in our model. To provide input to these general relationships for specific site and soil moisture conditions, a second set of site-specific relationships is used: the soil moisture characteristic, the relationship between soil water content and soil strength and the relationship between soil water content and the fraction of air-filled pores. Each of these relationships can be estimated from one-time or limited periodic sampling of the site and, once established, field measurements of volumetric soil water content drive the model. For example, soil water potential can be determined from a moisture characteristic curve developed from intact cores, soil mechanical resistance can be estimated from measurements of cone penetrometer resistance made over a range of soil water contents and air-filled porosity can be calculated from soil bulk density if volumetric water content is known.

In the model, potential root growth within 10-cm increments is determined for each day based on these relationships and summed over the growing season. Total accumulated root length is converted to aboveground size, either height or mass, based on an allometric relationship. The distribution of roots is not considered in this relationship, only the total length.

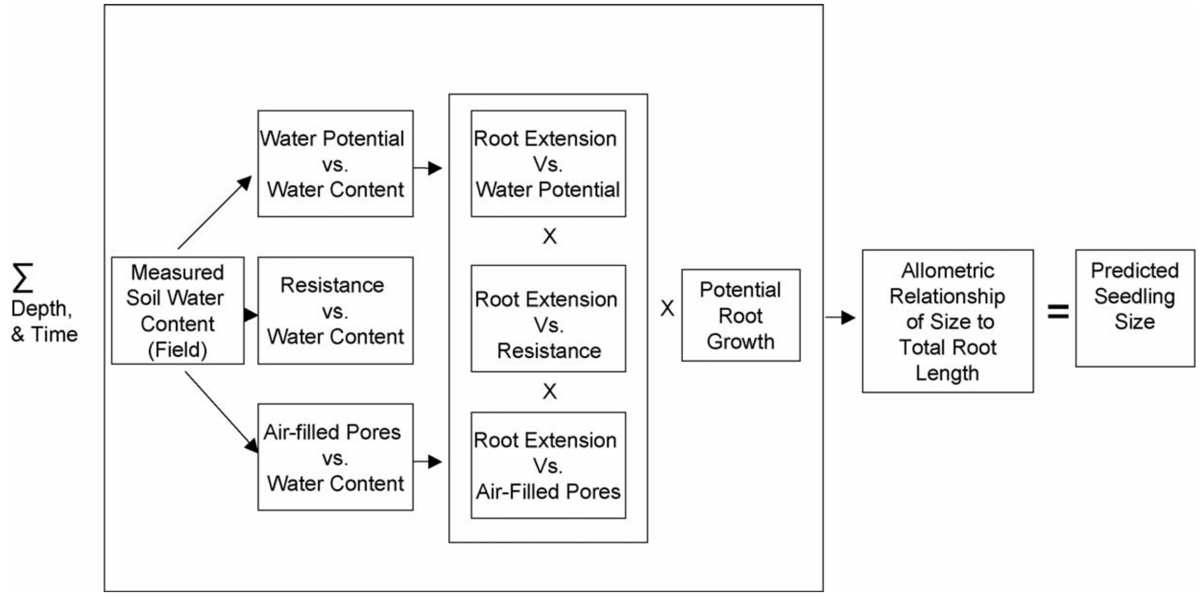


Fig. 1. Schematic diagram illustrating general structure of model predicting seedling growth. Soil water content is used to estimate soil water potential, mechanical resistance and air-filled pore space based on site-specific and generalized relationships. Root growth is reduced below potential growth (optimal) and converted to above-ground growth using an allometric relationship.

2.1.2. *Relationships between root growth and limiting soil factors*

Three root growth-limiting factors described by Eavis (1972) were incorporated into the model. The relationship between root elongation of loblolly pine under minimal mechanical resistance relative to elongation under increasing mechanical resistance established by Torreano (1992) was used to assess soil strength impacts (Fig. 2). The relationship between root elongation and soil water potential was that of Torreano and Morris (1998) (Fig. 3) and the relationship between air-filled porosity and root growth was that of Zou et al. (2001a) (Fig. 4). The relative root growth relationship provided by Torreano (1992) was already normalized to 1.0 for optimal growth. The other two relationships, which were originally expressed as root mass (g) and root elongation (mm day^{-1}) were normalized to similarly express optimal conditions as 1.0. In this approach, optimal growth occurs when no mechanical resistance exists, soil water potential is at field

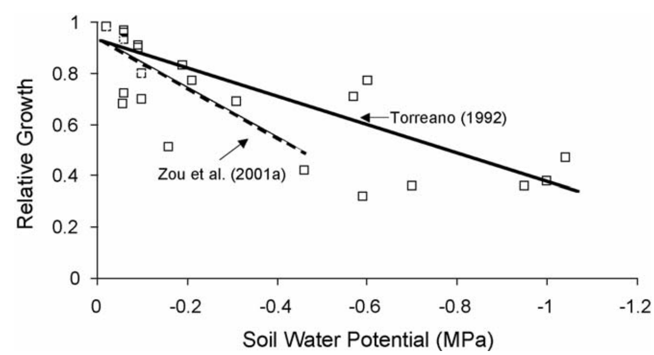


Fig. 3. Relationship between relative root growth and soil water potential for loblolly pine (solid line) in rhizotron study of Torreano (1992) and for a similar relationship for radiata pine (dashed line) of Zou et al. (2001a) normalized to 1 for maximum observed growth.

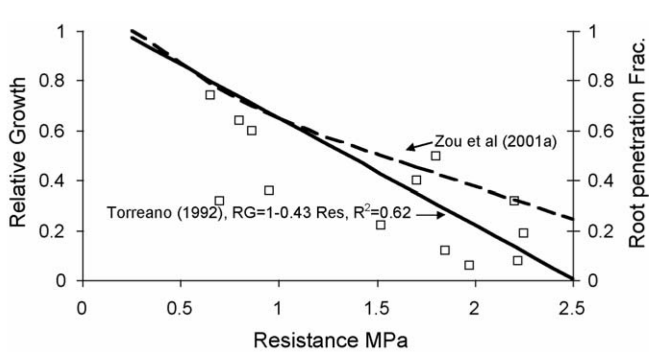


Fig. 2. The relationship between root growth and mechanical resistance of Torreano (1992) (solid line, symbols) used in model simulation is shown along with a similar relationship developed for radiata pine (dashed line) of Zou et al. (2001a) normalized to 1 for maximum observed growth.

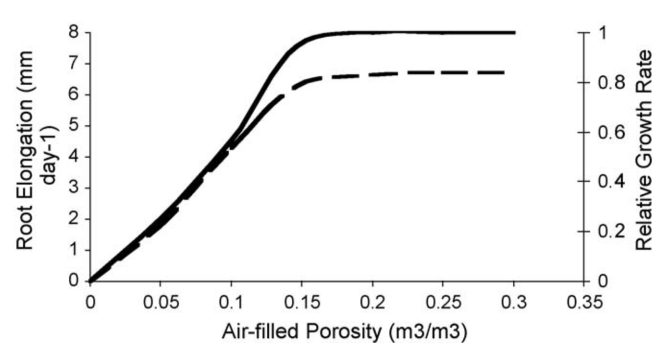


Fig. 4. Relationship between air-filled porosity and root growth used in model simulation in its original form (dashed line) plotted against root elongation and as relative root growth (solid line) normalized to 1 for maximum observed growth (adapted from Zou et al., 2001a).

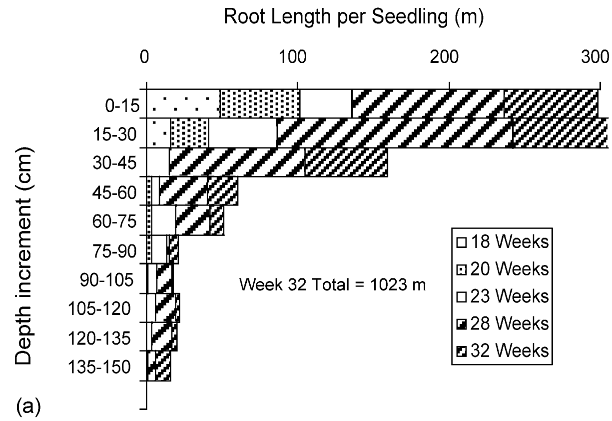
capacity and air-filled pore space exceeds $0.15\ m^3\ m^{-3}$. Reductions in optimal root growth associated with any of these three fundamental relationships were assumed to act independently of one another. Such independence has been shown between root elongation and soil water potential at different soil bulk densities and for mechanical resistance by Zou et al. (2001a). It was assumed that the net effect of the three factors on root growth is the product of the fractional reduction of each factor below the potential (optimum) root growth. For example, if the relative root growth associated with mechanical resistance, water potential and air-filled porosity were 0.7, 0.5 and 1.0, respectively, the predicted root growth would be 0.35 of the optimum ($0.7 \times 0.5 \times 1.0$).

2.1.3. Defining unrestricted (optimal) root growth

In order to utilize this relative root growth approach, an estimate of root growth under optimal conditions was needed. Two studies of loblolly pine root growth under near-optimal soil conditions combined with very large potential rooting volumes have been reported. Torreano and Morris (1998) reported root growth of loblolly pine grown in 1 m × 1 m × 1.8 m (l × w × d) rhizotron cells that were filled with a rounded sand-fritted clay mixture, which offered little mechanical resistance and had high air-filled porosity. One treatment in their study included seedlings that were watered to maintain soil near field capacity. Seedlings exhibited little reduction in mid-day stomatal conductance throughout the 9-week study period. Ludovici and Morris (1996, 1997) used the same rhizotron facility to grow loblolly pine seedlings in well-watered, competition-free conditions. For both studies, total root length and periodic root extension by depth increment were tracked at the rhizotron window. Root lengths measured at the rhizotron window were later converted to total root length per seedling based on lengths of roots separated from soil cores collected within the rhizotron. Root extension data from these studies are presented in Fig. 5(a and b). It was assumed that the development of root systems under these conditions represents loblolly pine root growth and configuration under ideal soil physical conditions. In both studies, seedlings were regularly fertilized with both macronutrients and micronutrients; therefore, nutritional limitations were not considered the major factor limiting growth. However, significant differences in the depth-distribution of roots do exist between the studies with the distribution measured by Ludovici (1996) (Fig. 5a) having a greater concentration of roots near the soil surface. This is more typical of root distributions under forested conditions and this distribution was used to establish the ideal distribution used in the model.

2.1.4. Relationship between root growth and aboveground growth

Ludovici (1992) found a close relationship between aboveground size and total root length density of rhizotron-grown loblolly pine seedlings. Using these data, regressions were developed between tree height and aboveground mass (Fig. 6). These relationships were used to predict aboveground size from root length accumulation predicted by the model.



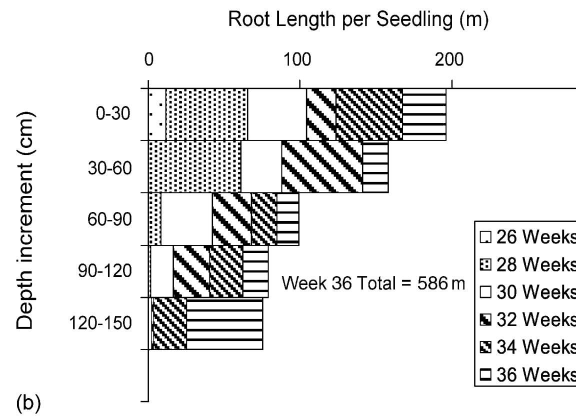


Fig. 5. Length distribution of loblolly pine roots for seedlings grown in a rhizotron filled with a soil mix that provided minimal mechanical restriction and which was maintained near field capacity (optimal moisture availability) for the major portion of the growing season computed from data of (a) Ludovici (1996) and (b) Torreano (1992).

2.2. Model testing

2.2.1. Experimental design

A preliminary test of the model was possible using a site preparation tillage study established by MeadWestvaco in the upper coastal plain of Georgia (Lincoln, 2005; Lincoln et al., in press). The site was characterized by an Orangeburg series soil (Typic Kanhapldult) with 1–6 in. of topsoil over a root restrictive clay loam B-horizon. Four tillage treatments

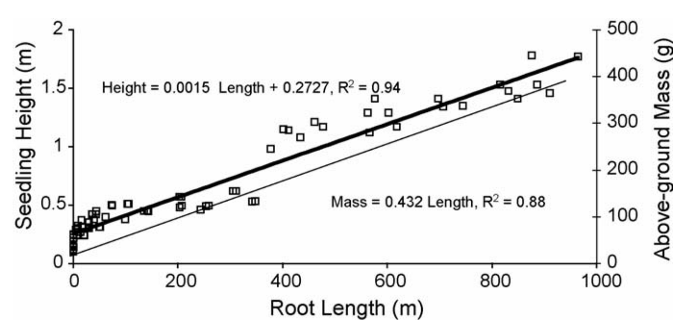


Fig. 6. Relationship between total root length and loblolly pine seedling height and aboveground biomass (data points for seedling height shown) from Ludovici (1996) and Ludovici and Morris (1996). *Note*: non-significant intercept for biomass regression.

were evaluated: no-till, bedded, subsoiled and bedded plus subsoiled. Treatments were replicated in four complete blocks. Prior to tillage treatment, all plots were sheared and raked with a V-blade, and chemically treated for weed control with a tank mix of 24 oz. of imazapyr and 4 qts. of glyphosate. The tillage treatments were installed using a Savannah^{TM} three-in-one plow pulled by a crawler tractor. The Savannah plow consists of two, 1.2 m diameter circular blades that face each other and mound surface soil into a bed up to 50 cm high, a ripping shank that is 60 cm deep and a coulter wheel. No-till treatments were flat planted at the same spacing as the tillage treatments. The plots were hand planted in January 2003 with second-generation (756 family) loblolly pine. A broadcast herbaceous weed control treatment consisting of 24 oz. of hexazinone was applied in April. To ensure total weed control, directed spraying was done throughout the year to control herbaceous and woody competition.

Three trees were chosen at random from within each measurement plot (7 rows wide by 30 trees per row) for intensive monitoring during the growing season following planting. For these trees, height and ground line diameter were measured monthly. Soil moisture was measured adjacent to these trees every 2 weeks from early April until September and monthly from September until December using time domain reflectometry (TDR) (Topp et al., 1982). TDR rods were installed from 0 to 30 cm and from 0 to 60 cm depth increments. Soil strength was measured with a Rimik^{TM} CP 20 Cone Penetrometer in May, July, September and December at the time TDR measurements were made. These measurement dates were selected to encompass a range of soil moisture conditions. Mean soil strength for each 10 cm depth increment between 0 and 60 cm was determined at each date near each measurement tree. At the end of the first growing season, all 60 intensively monitored trees were measured, above-ground mass harvested and roots excavated in order to obtain stem, foliar and root biomass. Root lengths running vertical (with the rows) in each direction and those running horizontal (against the rows) in each direction were recorded.

2.2.2. Soil water–soil root growth factor relationships

Bi-weekly measurements of soil water content provided the basis for estimating each of the three soil–root growth controlling factors. To estimate soil mechanical resistance, we used linear relationships between field measures of soil water content and mechanical resistance developed for each soil tillage treatment (Lincoln, 2005). Available soil moisture characteristic data for an Orangeburg (Typic Kandiudult) soil profile with textures corresponding to the Orangeburg soil of the study site, and for which bulk density was known, were used to estimate moisture characteristic curves. For this estimate, the mass based moisture characteristic was first converted to a volumetric water content basis using soil bulk density. This volumetric-based moisture characteristic curve was then adjusted to reflect the bulk densities we measured in the field using the ratio of field measured bulk density to the bulk density of the sample used to develop the curve. An implicit assumption in this procedure was that the shape of the moisture characteristic did not change but was offset by differences in bulk density (bulk density differences reflected the volume of voids and macropores that had little influence on moisture retained in soils drier than field capacity). These derived curves were used to convert volumetric soil water content measured in the field to the soil water potential used in the model. Air-filled pore space was calculated from measured bulk density and TDR measurements of soil water content using the following equation:

$$\mathrm{AFP} = \frac{2.65 - \mathrm{BD}}{2.65} - \mathrm{WC}$$

where AFP is the air-filled pores (v/v), BD the bulk density g cm^{-3} and WC is the water content (v/v).

3. Results

3.1. Predicted seedling growth in non-restrictive soil conditions

The completed model was used to predict the expected height and aboveground mass of a seedling grown under conditions of near optimal root growth by setting soil water content to field capacity for the entire growing season in a soil with no mechanical limitations and 20% air-filled porosity at field capacity. Under these conditions, a seedling would develop 1023 m of root length, grow to 1.85 m in height and have an aboveground mass of 442 g.

The predicted size is close to the measured size of rhizotron-grown seedlings of Ludovici and Morris (1996), which, because they were used in developing the model, indicates only that the model functioned correctly. This predicted first-year height and above-ground mass is significantly greater than reported for seedlings planted on upland sites in the region (Lantagne and Burger, 1983; Wheeler et al., 2002; Will et al., 2002).

3.2. Predicted versus observed growth response to site preparation tillage

3.2.1. Measured soil water and soil mechanical resistance

Measured soil water content for the four tillage treatments during the first growing season are presented in Fig. 7. Differences in soil water content were greatest in the surface 0–30 cm depth increment between the non-tilled control and bedded treatments. Significant differences in soil water content were also measured among treatments within the 30–60 cm depth increment with greatest differences occurring between non-tilled control and subsoiled plots. These differences appear to reflect creation of large voids and macropores during the tillage operations.

Generally, the relationships between soil moisture content and mechanical resistance of were not strong and, in many instances, appear counterintuitive (Fig. 8). Rather than reduced mechanical resistance at higher soil water content as generally suggested by relationships developed with intact soil cores (Siegel-Issen et al., 2005) or in tilled agriculture fields,

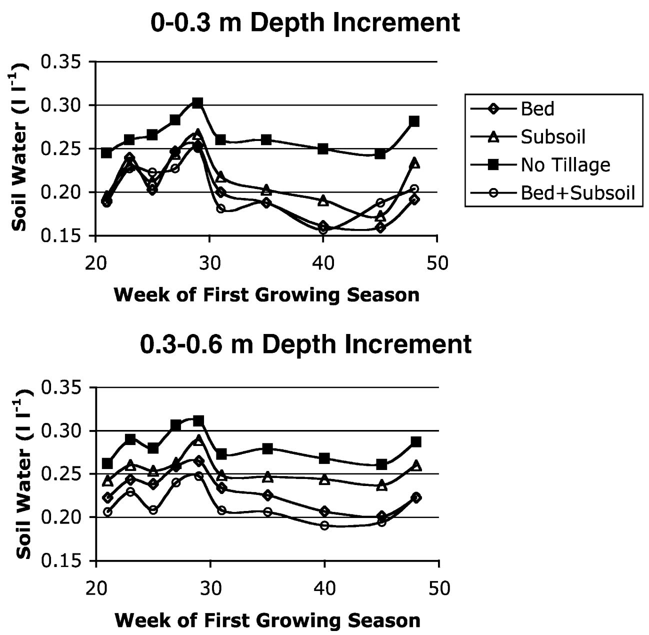


Fig. 7. Volumetric soil water content by tillage treatment during the first growing season following planting on an upper coastal plain study site used for model comparison (*source*: Lincoln et al., in press; Lincoln, 2005).

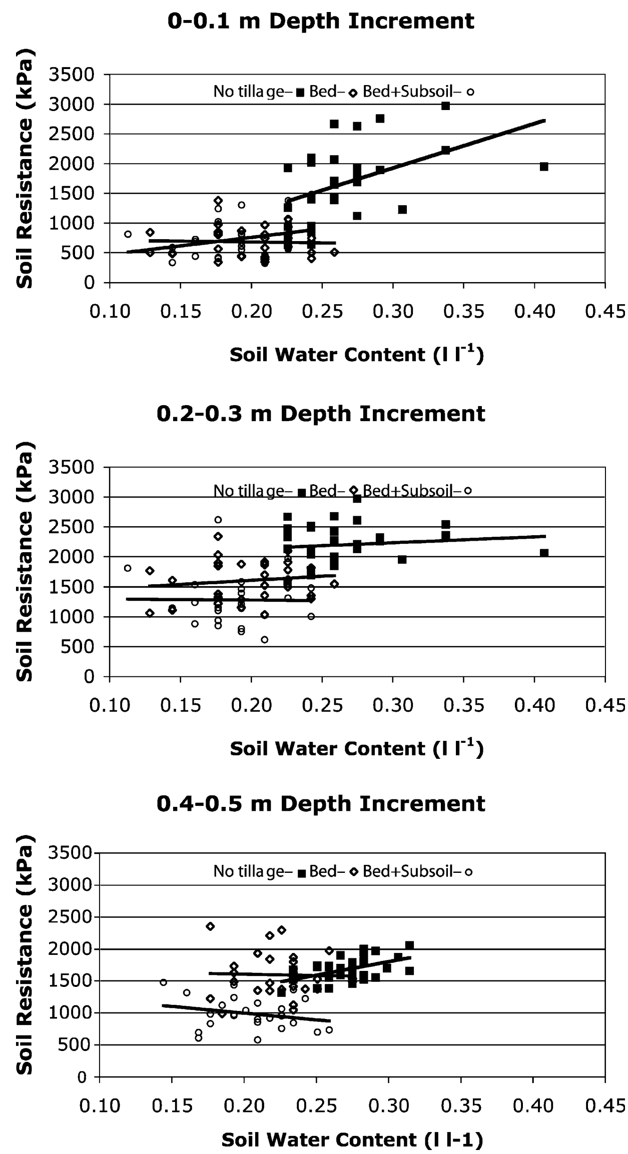


Fig. 8. Relationship between penetrometer resistance and soil water content for non-tilled (■), bedded (◇) and bedded plus subsoiled (○) tillage treatments that were constructed from measurements collected during the first growing season following planting (*source*: Lincoln et al., in press; Lincoln, 2005).

increased resistance occurred at higher soil water content for many treatment–depth increment combinations. In this field study, resistance was measured at slightly different locations during each sampling period and only plot averages were available for model testing. It appeared that in-situ soil water content measurements were controlled by the presence of voids and macropores created by tillage that did not retain high volumes of water at field capacity. These soils generally had relatively low resistance. In contrast, in non-tilled areas, large voids and macropores were absent and these soils tended to have relatively both high resistance and greater moisture content.

3.2.2. Seedling size

Model predictions of seedling size at the end of the first growing season are presented in Table 1 along with measured height and aboveground biomass at the end of the growing season. Both predicted height and mass were significantly less than would be predicted for seedlings grown under ideal root growth conditions and were close to measured values. Seedling height estimated by the model differed from measured seedling height by −1 to +14% with absolute differences in height of 0.1 m or less. Estimated aboveground biomass was −12 to +41% of measured mass. Differences in seedling height measured in the field study were small. Despite this, the model predicted the best and worst treatment. Differences in aboveground mass were greater among tillage treatments and the model correctly ranked treatment using this metric of growth.

Table 1
Comparison of predicted and measured size of loblolly pine seedlings after the first growing season on an upper coastal plain site prepared for planting using five site preparation tillage treatments (*source*: Lincoln et al., in press)

Tillage treatment	Root length (m)	Height (m)		Above-ground mass (g/seedling)	
	Predicted	Predicted	Measured	Predicted	Measured
No tillage	157	0.58	0.52 (0.03)	67.8	48.0 (6.3)
Bedded	223	0.68	0.69 (0.05)	96.3	110.1 (16.6)
Subsoiled	252	0.72	0.66 (0.06)	108.4	93.4 (18.3)
Bedded and subsoiled	308	0.79	0.69 (0.05)	133.1	102.5 (17.4)

4. Discussion

Our approach to modeling seedling growth incorporated the dynamic nature of soil physical conditions by using measures of soil water content to drive three basic relationships: soil mechanical resistance versus root growth, soil aeration versus root growth and soil water potential versus root growth. These three relationships were developed independently of our field data and should behave independently of soil texture and bulk density. Our use of them for predicting seedling growth required we establish their site-specific relationship to soil water content. Two of these site-specific relationships: the soil moisture characteristic and bulk density, are routinely measured through collection of intact soil cores and do not pose an obstacle to the use of this modeling approach. The third, the relationship between soil strength and soil water content, is best determined by on-site measurement of soil resistance over a range of soil water contents and requires four to five sampling campaigns over the course of the growing season. However, once established, soil water content was the only independent variable used to drive growth predictions and this was done without further on-site calibration of the model. There are several advantages to such a modeling approach. First, soil water content can be easily measured by TDR whereas direct measurement of soil mechanical resistance, air-filled porosity (or a surrogate like oxygen diffusion rate) or water potential are much more difficult to measure under field conditions. Second, soil water content measurement can be recorded through automated data logging as well as to predicted by climatological models. Thus, it is possible to investigate how response to soil tillage may vary among years with different rainfall patterns. Third, it would be possible to develop a data base describing how selected site preparation treatments affect bulk density, soil moisture characteristic curves and soil water content–mechanical resistance relationships on a limited number of sites that could be used as a basis for predicting tree growth response to soil tillage across a range of soils.

The predicted total root length for seedlings grown under optimal soil physical conditions was comparable to root length of rhizotron-grown seedlings used in development of the model. Few studies have attempted to characterize total root length of loblolly pine seedlings during the first few years following planting. Where root lengths have been determined, as by Schilling et al. (2004), excavation procedures probably destroyed much of the fine root length and underestimated actual root length. Siegel-Issen et al. (2005) report seedling root length density (RLD) and shoot mass for several pine species grown in soil cores. Shoot weights of pine seedlings in their study ranged from about 0.2 to 0.7 g, while RLD ranged from 0.10 to 0.30 cm cm^{-3}. In their rhizotron study, Torreano and Morris (1998) reported RLD (at depths of 0–150 cm) ranging from 0.10 to 0.53 cm cm^{-3} for seedlings varying from 29 to 49 g. This agreement in seedling RLD would support the argument that the root lengths per seedling we report are reasonable.

The predicted sizes of seedlings on non-tilled and bedded plots were within a few centimetres of measured height and within 15 g of measured aboveground mass. The model slightly over predicted the size of seedlings in the subsoiled-only and subsoiled plus bedded plots but these overestimates were not large. Indeed, the results appear surprisingly good when we consider that the basic relationships between root growth and soil conditions, and root length and seedling size, used as a basis for the model were developed under quite different rhizotron and greenhouse conditions.

A number of factors could have contributed to differences between predicted and measured seedling growth. First, different genotypes were used in the rhizotron and field studies and differences in both growth potential and allometric relationships probably existed among the seedlings. Second, the model was developed for seedlings grown in the absence of competition. While herbicide treatments were generally effective in controlling competition on the field site, a low level of competition occurred and this may have been sufficient to reduce growth of field-grown seedlings below what the model predicted. Third, some tip-moth damage occurred on field grown seedlings. This damage probably played a role in reducing heights of field-grown seedlings below that predicted for seedlings maintained free of tip-moth in the original rhizotron and greenhouse studies. Fourth, considerable error in estimating soil water potential from measures of volumetric soil water content could have existed. Soil water potential was critical for estimating root growth reductions under dry but non-mechanically limiting conditions, Clearly, soil moisture characteristic curves developed for soil cores collected on site would be preferred to the derived soil moisture characteristic curves we used in this case study. Alternative methods of estimating soil moisture characteristics curves for soils where particles size fractions, organic C and bulk density are measured are also available (Da Silva and Kay, 1997) but data necessary to use this approach were not available for our study site. Finally, the original relationships of Torreano (1992), Torreano and Morris (1998) and Zou et al. (2001a) used to establish root growth response to soil physical conditions contain unexplained error and this error will contribute to errors in prediction.

Differences in nutrient availability are ignored in this modeling effort. In light of the differences in nutrient availability that certainly existed between the rhizotron used to develop the model and the field sites used to test it, and in nutrient availability that have been shown to exist among soil tillage treatments (Will et al., 2002), this would appear to be a critical limitation. Nonetheless, the model appears to provide reasonable results. The availability of nutrients on recently harvested and prepared sites is, in general, much greater than the demand placed on those nutrients by planted seedlings because of increased mineralization (Morris and Pritchett, 1983; Morris and Lowery, 1988). This is particularly true for N (Vitousek and Matson, 1985). As long as competition is eliminated and seedlings roots can grow through the soil without significant restriction, differences in nutrient availability may be not be particularly important in growth response. This appears to be the case on upland sites similar to the site we used to test model predictions. On nearby sites, fertilizer additions had no significant affect on first-year seedling growth when competition was controlled through repeated herbicide application (Lincoln, 2005).

Finally, the model assumes that the allometric relationship between root length and above-ground seedling size developed under rhizotron conditions can be applied to field-grown seedlings and that this relationship is unaffected by soil tillage treatments. Assuming that such an allometric relationship exists is necessary to convert predictions of root length reduction to aboveground growth reductions. Several recent studies of pine seedling growth following outplanting reported a close relationship between above- and below-ground biomass partitioning, and that this relationship was not affected by site preparation treatments (Will et al., 2002; Schilling et al., 2004), but neither of these studies reliably quantified total root length. Thus, use of the allometric relationships developed under rhizotron conditions for predicting aboveground size under field conditions remains an untested assumption.

5. Conclusions

Basic relationships between soil physical conditions and root growth developed under controlled rhizotron and greenhouse conditions appear to be suitable for estimating root growth of loblolly pine seedlings under field conditions. It was shown that soil water content can be used to drive a model of root growth that uses soil bulk density, the moisture characteristic curve and site-specific relationships between soil water content and mechanical resistance to estimate inputs into basic soil condition–root growth relationships. The model correctly predicted that tree growth would be improved by tillage and provided estimates of tree size that were near measured size. Our results suggest that it is possible to extend results from root growth–soil condition experiments conducted under controlled greenhouse conditions to dynamic field conditions.

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