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Morphological indicators of stock quality and field performance of red oak (*Quercus rubra* L.) seedlings underplanted in a central Ontario shelterwood

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Application. Initial stem diameter of bareroot red oak planting stock was a better morphological indicator of future height and diameter growth in a shelterwood underplanting than were initial shoot length and number of first-order lateral roots. Stem diameter near the root collar provides an integrated measure of the growth potential of red oak planting stock because of its strong relationship with shoot and root characteristics associated with field performance. Ease of measurement and the significant, positive correlation of stem diameter with root system size, also make diameter an operationally attractive morphological feature for use as a nursery grading criteria.

Abstract. The value of initial stem diameter near the root collar, shoot length and number of first-order lateral roots (FOLR) as morphological indicators of stock quality and field performance was examined for bareroot (1+0, undercut) red oak (*Quercus rubra* L.) underplanted in a shelterwood in central Ontario. These three attributes were measured on more than 400 seedlings prior to planting, and their relationship with height and basal diameter growth two years after planting was determined using correlation and regression analysis. Initial diameter, shoot length and number of FOLR were positively and significantly correlated with second-year height and diameter. These relationships were strongest for diameter, but this variable explained less than 25% of the total variation in growth. Of the three indicators, diameter was also the best predictor of several physical characteristics of root systems two years after planting. Initial diameter was significantly correlated with root volume, root area and lateral root, taproot and total root dry mass. Weaker relationships existed between initial shoot length and number of FOLR and second-year root system features. Stem diameter two years after planting was more strongly related to root volume, area and dry mass than was initial diameter, the probable result of adjustment in root-shoot balance of planting stock to the shelterwood environment.

Introduction

Planting high quality red oak (*Quercus rubra* L.) seedlings is an essential element of any artificial regeneration prescription. Efforts to define stock quality standards for improved field performance have focused primarily on

morphological features of red oak seedlings that are easy to quantify. The number of large (≥1 mm in diameter) first-order lateral roots (FOLR) is a promising morphological indicator of stock quality. These roots provide the structural framework of the root system and many sites of new root initiation, and are active in water and nutrient uptake (Struve 1990). The number of FOLR is often correlated with outplanting growth and survival, and red oak seedlings with 5 or more FOLR have outperformed those with fewer lateral roots (Bardon and Countryman 1993; Teclaw and Isebrands 1993; Thompson and Schultz 1995).

Shoot characteristics have also been tested as indicators of field performance. Red oak seedlings with root collar diameter larger than 8 to 10 mm are reportedly more competitive than smaller stock planted in clearcuts, shelterwoods and old fields (Johnson 1984, 1992; Stroempl 1985; von Althen 1990; Pope 1993). The growth performance of red oak has also been improved by planting seedlings with larger initial shoot lengths and stem volumes (Wendel 1980; Kaczmarek and Pope 1993a). It has been recommended that red oak planting stock have shoots exceeding 50 cm long (Johnson 1981; von Althen 1990).

Despite these encouraging results, these standard morphological indicators of stock quality seldom account for a large proportion of the total variation in growth response observed in planted red oak (Zaczek et al. 1993; Thompson and Schultz 1995). Moreover, no single morphological measure of stock quality in red oak has consistently and reliably predicted performance (Kaczmarek and Pope 1993a; Thompson and Schultz 1995). As a result, it has been suggested that a combination of root and shoot morphological characteristics may be better used used to predict the growth potential of red oak bareroot stock (Kaczmarek and Pope 1993a; Thompson and Schultz 1995).

There is great interest in underplanting as a component of shelterwood management of red oak in Ontario. A field trial was conducted to compare the growth and survival of red oak underplanted in an uncut and shelterwood hardwood stand (Dey and Parker 1997). This study also provided an opportunity to examine the interaction of pre-plant morphology with field performance of 1+0 seedlings produced in Ontario. This stocktype is commonly smaller in diameter and shoot length than recommended but has adequate numbers of FOLR (Gordon 1988; Dey and Buchanan 1995). The objectives of this secondary study were to: (1) examine the relationship of initial stem diameter, shoot length and number of FOLR with survival and growth of underplanted red oak and (2) evaluate the use of these morphological indicators as predictors of growth potential.

Materials and methods

This study was conducted in a 20 ha mature hardwood stand located in McClintock Township, approximately 10 km north of Dorset, Ontario (45°10′ N; 79°10′ W). The stand was harvested by the shelterwood method during the winter of 1992/93 to create a moderately dense residual overstory crown cover and reduce the density of taller understory woody vegetation. Percent crown cover of the shelterwood overstory determined in the summer of 1993 averaged 66.3±11.5%. Basal area of the residual stand averaged 8.2±3.8 m^2/ha. Sugar maple (*Acer saccharum* Marsh.) accounted for 68.5% of the residual basal area, with lesser amounts of white ash (*Fraxinus americana* L.), red oak, basswood (*Tilia americana* L.), eastern hemlock (*Tsuga canadensis* [L.] Carr.) and yellow birch (*Betula alleghaniensis* Britton) in the overstory.

Red oak seedlings (1+0, undercut) were grown at the Midhurst Tree Nursery, Midhurst, Ontario. Seedlings used in this study were grown from acorns collected from the provincial seed zone of the planting site. Seedlings were lifted in the fall, overwintered in heel-in beds, and planted in the spring of 1993 within a 1 ha area in the shelterwood. Stem diameter, shoot length and number of FOLR (≥1 mm in diameter) of 434 seedlings were recorded before planting (Table 1). Stem diameter was measured 2.5 cm above the root collar. Shoot length was measured from the root collar to the base of the most apical live bud. After the first and second growing seasons, stem height and diameter were remeasured. Basal stem diameter was averaged from two perpendicular measurements taken 2.5 cm above the ground. Partial shoot dieback, followed by formation of lateral shoots, was common after planting. As a result, total shoot length often did not provide an accurate measure of seedling height. Therefore, total seedling height was measured along a perpendicular line projected from the ground to the most apical live bud.

During early May 1995 (two growing seasons after planting), 20 seedlings were randomly selected and carefully lifted from the ground to recover as much of the root system as possible. One seedling was discarded due to excessive damage during excavation. Tap root length, stem diameter, number of FOLR, root volume, root area, and dry mass of the tap root and lateral roots were measured. Tap root length was measured from the root collar to the base of the callus tissue that resulted from undercutting seedlings in the nursery. Two stem diameters were taken perpendicular to each other 2.5 cm above the root collar. Volume of the root system below the root collar was determined by water displacement and projected surface area was measured using a rhizometer (LTS Technology Devices, Thunder Bay, Ontario). Dry mass of the tap root and lateral roots were measured after drying for 48 hours at 65 °C.

Table 1. (a) Initial characteristics of red oak bareroot stock (1+0, undercut) underplanted in a shelterwood and (b) Pearson correlation coefficients and p-values (in parentheses) for the relationship among pre-plant morphological attributes.

(a)

Seedling characteristic	N	Mean	Std. Dev.
Stem diameter (mm)	434	6.12	1.14
Shoot length (cm)	434	17.69	5.06
FOLR	434	10.41	5.44

(b)

	Stem diameter	Shoot length
Stem diameter	–	–
Shoot length	0.57 (0.0001)	–
FOLR	0.55 (0.0001)	0.33 (0.0001)

Pearson product-moment correlations were used to test the strength of the linear relationship among pre-plant morphological attributes, and between these attributes and second-year basal diameter and height of underplanted red oak seedlings (SAS Institute, Inc. 1988a). Correlations were also determined between initial and second-year stem diameter and root system characteristics of seedlings excavated after the second growing season.

Regressions of nursery stock characteristics on second-year height or basal diameter were developed for underplanted red oak seedlings (SAS Institute, Inc. 1988b). Analysis of residuals indicated that second-year height and basal diameter were normally distributed and there was homogeneity of variance. Therefore, transformations of the variables were unnecessary. Residual plot analyses indicated that interactions between nursery stock characteristics were not important determinants of future seedling height or diameter. Hence, analyses were restricted to linear regressions of initial stem diameter, shoot length and FOLR on second-year height and basal diameter. Stepwise regression selection procedures were used to identify the best models for predicting second-year height or basal diameter from initial stock characteristics.

Results

The size of red oak seedlings used in this study was typical of those produced for operational planting by Ontario Ministry of Natural Resources nurseries (Gordon 1988; Dey and Buchanan 1995). Seedlings had sufficient numbers of FOLR (Thompson and Schultz 1995), but shoot length and stem diameter

Table 2. Pearson correlation coefficients and p-values (in parentheses) for the relationship between pre-plant morphological indicators and second-year total seedling height and basal diameter of red oak (N = 401) underplanted in a shelterwood.

	Pre-plant morphological indicators		
	Stem diameter	Shoot length	FOLR
Total height	0.29 (0.0001)	0.18 (0.0002)	0.16 (0.0014)
Basal diameter	0.47 (0.0001)	0.32 (0.0001)	0.30 (0.0001)

Table 3. Summary of the best models selected by stepwise regression for prediction of second-year total height and basal diameter of red oak seedlings planted under a shelterwood (N = 401).

Regression model	R^2	F value	P > F
BD = 1.8282 + 0.5792*ID + 0.025*IHT	0.23	59.2	0.0001
HT = 15.7165 + 3.7681*ID	0.08	36.0	0.0001

Note: BD = second-year basal diameter (mm), HT = second-year total height (cm), ID = initial diameter (mm) and IHT = inital shoot length (cm).

were smaller than generally recommended (Johnson 1984; Stroempl 1985; von Althen 1990) (Table 1). Stem diameter, shoot length and number of FOLR were significantly and positively correlated with one another at the time of planting (Table 1). Seedlings with shoots of larger diameter and length had root systems with more FOLR. Survival of planted oaks under the shelterwood averaged 99.6% after the second growing season. Because survival was so high, we did not investigate relationships between stock quality and survival.

Initial stem diameter, shoot length and number of FOLR were significantly correlated with second-year basal diameter and height (Table 2). Linear regressions were developed to determine the usefulness of initial seedling characteristics in predicting growth performance of underplanted red oak bareroot stock. The best models identified by stepwise regression were highly significant, but explained <25% of the total variation in future basal diameter (Table 3). The initial number of FOLR was not as important as shoot length or diameter for predicting either future height or diameter of seedlings grown in the shelterwood. In all these models, initial stem diameter was the best predictor of future seedling size. Seedlings with larger initial diameters grew more in height and basal diameter in two years than smaller diameter planting stock (Figure 1).

The three stock quality indicators were often correlated with root system attributes of excavated seedlings two years after planting. Initial diameter was significantly correlated with most of the second-year root characteristics

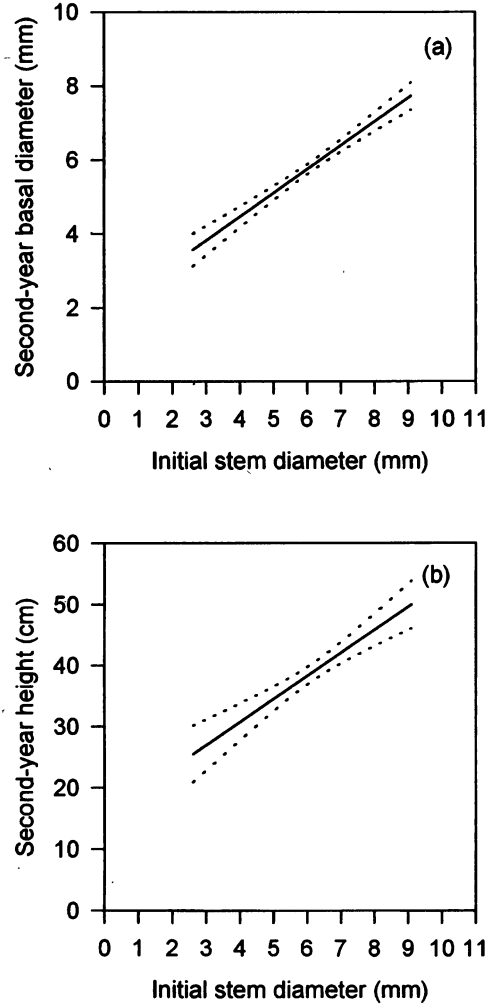

Figure 1. Relationship between initial stem diameter and (a) second-year basal diameter and (b) second-year height for red oak seedlings planted under a shelterwood in central Ontario. The dotted lines represent the 95% confidence intervals for the regression. Prediction of second-year basal diameter (BD) is based on the equation: $BD = 1.893 + 0.6411 * ID$ ($R^2 = 0.22$, $P < 0.0001$). The equation for second-year height is presented in Table 3.

(Table 4). However, initial diameter was strongly but not significantly related to the number of FOLR after two growing seasons. Seedling shoot length and number of FOLR before planting were significantly correlated with fewer second-year root characteristics. Surprisingly, the correlation between initial and second-year FOLR was very weak and not significant. Stronger relationships with root system attributes were exhibited by second-year than initial

Table 4. Pearson correlation coefficients and p-values (in parentheses) for the relationship among selected morphological characteristics of red oak seedlings underplanted in a shelterwood (N = 19). Root characteristics were measured on seedlings excavated two years after planting.

	Initial stem diameter	Initial FOLR	Initial shoot length	Second-year stem diameter
Second-year stem	0.66	0.29	0.39	–
diameter	(0.002)	(0.23)	(0.10)	–
FOLR	0.44	0.17	0.48	0.53
	(0.06)	(0.49)	(0.04)	(0.02)
Root volume	0.69	0.49	0.34	0.90
	(0.001)	(0.03)	(0.16)	(0.0001)
Root area	0.48	0.35	0.18	0.81
	(0.04)	(0.14)	(0.47)	(0.0001)
Tap root dry mass	0.74	0.39	0.27	0.94
	(0.0003)	(0.10)	(0.27)	(0.0001)
Lateral root dry mass	0.54	0.44	0.26	0.80
	(0.02)	(0.06)	(0.28)	(0.0001)
Total root dry mass	0.68	0.43	0.28	0.92
	(0.001)	(0.06)	(0.25)	(0.0001)

stem diameter. Second-year diameter was significantly and often highly correlated with second-year root characteristics including number of FOLR, root volume, root area, tap root dry mass and lateral root dry mass.

Linear regressions were developed to further explore the relationship between diameter and individual root characteristics (Table 5). All regressions between initial diameter and individual root characteristics were significant for the excavated seedlings with the exception of number of FOLR ($p \leq 0.05$). However, second-year diameter explained a larger proportion of the variation in root characteristics than did initial stem diameter. Second-year stem diameter explained from 66 to 88% of the variation in root volume, area and dry mass, while initial diameter accounted for 23 to 54% of the variation in these three features.

Discussion

Shoot length, FOLR and stem diameter near the root collar have been used to relate stock quality to future growth performance of red oak planted in a variety of field conditions (Johnson 1984, 1992; Kaczmarek and Pope 1993a; Thompson and Schultz 1995). These three commonly used indicators of stock quality were significantly correlated with future height and diameter in red oak

Table 5. Linear regressions of (a) initial and (b) second-year stem diameter on individual root characteristics for red oak seedlings grown for two years under a shelterwood (N = 19).

Regression	R^2	F value	P > F
(a)			
RVOL = −40.0468 + 10.1092*ID	0.47	15.34	0.0011
RAREA = −7.7031 + 11.6141*ID	0.23	5.12	0.037
TRDM = −12.8696 + 3.3435*ID	0.54	20.27	0.0003
LRDM = −7.0576 + 1.9027*ID	0.29	6.84	0.018
TOTRDM = −19.9272 + 5.2462*ID	0.47	14.83	0.0013
FOLR = 3.6215 + 1.4950*ID	0.19	3.98	0.063
(b)			
RVOL = −31.3665 + 5.1796*D	0.81	70.85	0.0001
RAREA = −16.8226 + 7.6896*D	0.66	32.58	0.0001
TRDM = −9.4998 + 1.6677*D	0.88	120.38	0.0001
LRDM = −7.0616 + 1.1241*D	0.65	31.36	0.001
TOTRDM = −16.5614 + 2.7918*D	0.85	99.83	0.0001
FOLR = 5.4887 + 0.7129*D	0.28	6.58	0.0201

Note: RVOL = total root volume (cm^3), RAREA = total root area (cm^2), TRDM = total root dry mass (g), LRDM = lateral root dry mass (g), TOTRDM = total root dry mass (g), ID = initial stem diameter (mm) and D = second-year basal stem diameter (mm).

underplanted in a moderately dense (i.e., 66% crown cover) shelterwood in central Ontario. The best predictor of second-year seedling height and basal diameter in our study was initial stem diameter. Of all the single-variable models tested, diameter produced the highest coefficients of determination (R^2). The addition of shoot length or number of FOLR to regression models containing diameter only marginally increased the ability to predict future height or basal diameter. These results agree with those of Kaczmarek and Pope (1993a,b), who found that initial height and especially stem diameter were more strongly related to future growth in red oak than was the number of FOLR.

The importance of initial diameter in predicting future height and diameter was probably a result of its highly significant correlation with many root characteristics that influence seedling performance (Johnson 1984; Johnson et al. 1984). The stem and tap root comprise the vertical axis of oak seedlings, with a strong relationship existing between stem diameter and tap root dry mass. The taproot was a dominant feature of the root systems of these seedlings and contained 65% of the total root dry mass two years after

planting (Dey and Parker 1997). As total root dry mass and root volume of these seedlings were largely dependent on the size of the tap root, their relationship with diameter was also quite strong. Weaker but significant relationships existed between diameter and root area, lateral root dry mass and numbers of FOLR. These three root system attributes are indicative of the potential for water and nutrient uptake and may be more closely associated with seedling shoot or foliar biomass than with diameter.

Correlation coefficients and R^2 of regressions for the relationship of diameter with root characteristics were larger at year two than prior to planting. These results likely reflect adjustments in root-shoot balance that occurred during acclimation to the shelterwood environment (Dey and Parker 1997). Dieback of shoots and roots followed by formation of a new shoot is not uncommon in planted red oak seedlings (Kormanik et al. 1995; Thompson and Schultz 1995).

Based on the correlation between number of FOLR and seedling growth, several researchers have suggested that the number of these roots would be among the best predictors of field performance and competitive ability of planted seedlings (Kormanik et al. 1988; Kormanik and Ruehle 1989; Schultz and Thompson 1990). Teclaw and Isebrands (1991), however, reported that there were few early advantages to red oak seedling growth in relation to the number of FOLR irrespective of overstory conditions. Kaczmarek and Pope (1993a,b) were also unable to detect a direct relationship between red oak outplanting performance and the number of FOLR. Although they recognized the importance of these roots, they suggested the abundance of FOLR should not be the sole criterion in evaluating seedling quality.

The initial number of FOLR was not as good a predictor of future growth as diameter or shoot length in our study. This result is partially attributable to the fact that most of the seedlings had large numbers of FOLR at the time of planting. More than 50% of the planted oaks had $\geq$10 FOLR. Red oak seedlings with $\geq$10 FOLR grow significantly more than seedlings with $\leq$5 FOLR, and in some cases, no significant differences in growth occur among seedlings with >5 FOLR (Bardon and Countryman 1993; Teclaw and Isebrands 1993; Thompson and Schultz 1995). Therefore, the number of FOLR was probably not limiting to future seedling growth for most of the oaks planted in our study. However, our results suggest that red oak seedlings with sufficient numbers of FOLR but larger initial diameter exhibited superior total height and basal diameter growth two years after planting.

Conclusions

Research to identify key morphological indicators of stock quality for bareroot red oak has focused on the use of stem diameter near the root collar, shoot length, stem volume and numbers of FOLR. These studies have differed in nursery cultural practices, silvicultural treatments and field environmental conditions, and often yielded variable and contradictory results. Identification of a reliable morphological predictor of red oak growth potential will require rigorous examination of the field performance of seedlings exhibiting a full array of desirable trait combinations, representing a number of stocktypes and planted on a variety of sites.

Our results suggest that, when numbers of FOLR were sufficient, stem diameter near the root collar was the best morphological measure of growth potential for 1+0 red oak seedlings produced in Ontario. Although initial numbers of FOLR were acceptable, and survival 2 years after outplanting was high, initial shoot size was below that recommended for successful establishment (Johnson 1984; von Althen 1990). Continued use of relatively small planting stock with lower growth potential will significantly hinder oak regeneration efforts in Ontario shelterwoods (Johnson 1984; Dey and Buchanan 1995). Improved growth potential and field performance of bareroot red oak seedlings depends, in part, upon: (1) further development of nursery cultural practices to produce uniform, physiologically vigorous seedlings of desired size and root morphology and (2) incorporation of morphological indicators of stock quality into nursery grading protocols.

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