Short report

Towards an empirical relationship between root length density and root number in windbreak-grown cadaghi (*Corymbia torelliana*) trees

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Abstract: Because windbreaks are planted for sustainable agriculture but may lower crop yields near them due to competition, suitable competition mitigation methods must be applied at the windbreak-crop interface to increase crop yields. Effective underground competition management requires information on important root variables such as preferential root growth direction and root length density (RLD, root length per unit volume of soil). This study examined root isotropy (i.e., uniformity in all directions) in windbreak-grown cadaghi (*Corymbia torelliana*) trees in south Florida and developed an empirical relationship between RLD and number of roots (N) per unit of surface of soil exiting the trench face. Numbers of roots exiting the frontal face parallel to the windbreak (N_X), vertical face perpendicular to the frontal face (N_Y), and basal horizontal face (N_Z) of 10 x 10 x 10 cm soil cubes were counted. Cadaghi roots were anisotropic and had horizontal growth preference. Average root numbers were ranked $N_X > N_Y > N_Z$. Both N_X and the average root number exiting X, Y and Z faces of the soil cube (N_{AVG}) were significant variables for estimating RLD. The coefficients of N_X and N_{AVG} were 1.1 and 3.1. These results should be helpful to manage underground competition effectively at the windbreak-crop interface to improve crop yields.

Keywords: competition mitigation, root isotropy, root management, trench profile, windbreak

Abbreviations: RLD, root length density; N, number of roots; N_X, number of roots exiting the frontal face of soil cube parallel to windbreak; N_Y, number of roots exiting the vertical face perpendicular to the frontal face; N_Z, number of roots exiting the basal horizontal face; N_{AVG}, average root number exiting faces X, Y and Z of soil cube; DBH, diameter at breast height; WB, windbreak; m, meter; cm, centimeter; mm, millimeter

Introduction

Windbreaks are widely planted to mitigate wind-related agricultural issues such as soil erosion, physical damage to crops (Sudmeyer and Scott 2002), and crop disease (Gottwald and Timmer 1995). On the other hand, competition between windbreak species and crops can make crop production less profitable. Underground competition at the windbreak-crop interface usually occurs because of the extension of windbreak species roots into adjacent crop fields. Competition becomes intense when both windbreak species and crop roots grow in the same soil layers and utilize the same nutrients.

Planting windbreak species that have limited lateral root extension and/or are deeper rooted than crops and pruning windbreak species roots extending in the crop field are recommended to mitigate underground competition at the windbreak-crop interface (Kort 1988; van Noordwijk and Purnomosidhi 1995;

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Schroth 1995). Both methods seem reasonable, but in practice they are challenging as root growth is influenced by genotype (Aliyu 2007; Gautam et al. 2002), soil structure (Sudmeyer et al. 2004) and soil environment (Moroni et al. 2003; Nepstad et al. 1994). Root pruning can be ineffective if deeper horizontal roots are not pruned and continue to grow (Sudmeyer et al. 2002).

A root variable that can estimate competitive potential is root length density (RLD, root length per unit volume of soil). Several RLD measurement methods are available (Box 1996), but their implementation in the field is costly. Measuring RLD takes about five times the time required to measure root number (N) (Vespraskas and Hoyt 1988). Root number is a good predictor of root length in some species (Chopart and Siband 1999; Chopart et al. 2008b; Lopez-Zamora et al. 2002), and a relationship has been developed to indirectly estimate RLD from N. When roots are randomly distributed in three dimensions (isotropic) in a small volume of soil, geometric theory has proposed a RLD=2N relationship (Kendall and Moran 1963; Melhuish and Lang 1968). When roots are anisotropic, the average number of roots in three-dimensions (N_{AVG}) can be used (Baldwin et al. 1971). This relationship has been tested in several species with varying results (Adegbidi et al. 2004; Bennie et al. 1987; Bland 1989; Chopart et al. 2008a, 2008b; Escamilla et al. 1991; Lopez-Zamora et al. 2002).

Having information on preferential root growth direction and the relationship between RLD and N in potential windbreak species facilitates the selection of the ideal windbreak species for windbreak planting or appropriate competition mitigation methods if the species has already been planted. Such information is lacking for many windbreak species, including cadaghi (*Corymbia torelliana*) which has been widely used in agroforestry systems (Sun and Dickinson 1997; Nissen et al. 1999; Tamang et al. 2010).

In south Florida where cadaghi is now widely planted in windbreaks, soil characteristics and soil environment influenced melaleuca (*Melaleuca quinquenervia*) root growth and distribution (Lopez-Zamora et al. 2002). Most of the roots were laterally distributed in the topsoil. The RLD=2N relationship was also invalid. Cadaghi roots may also show similar growth patterns. If preferential root growth direction of cadaghi trees is identified and a relationship is estimated between RLD and N, it can significantly minimize time and cost for root management at the windbreak-crop interface.

Our study a) examined root isotropy and b) developed an empirical relationship between RLD and N in windbreak grown cadaghi trees, but the relationship has not been validated due to the lack of independent data. We hypothesized that cadaghi tree roots are anisotropic.

Materials and Methods

Study Area

The study was conducted at C&B Farms (26°27'30"N, 80°58'46"W), a vegetable farm near Clewiston, Florida, USA. The soil was poorly drained Myakka sand (Sandy, siliceous, hyperthermic Aeric Haplaquods). Single-row cadaghi windbreaks oriented east-west and north-south were planted along irrigation channels. The farm had both functional and young windbreaks. Weed free areas ranging between 6 and 8 m wide (used for access to crop plots) were always maintained between crops and windbreaks. Prevailing wind direction is from the east.

Methods

Three functional windbreaks (WB1, WB2 and WB3) were selected for the study (Table 1). The 8-year-old WB1 and WB3 were oriented east-west with WB3 ~300 m south of WB1. The 6-year-old WB2 was oriented north-south and intersected both WB1 and WB3.

Tree height, diameter at breast height (DBH, measured at 1.3 m above ground), and spacing between trees were measured in 45 m long windbreak sections in September 2008. Five, five, and four non-overlapping sections were randomly selected within WB1, WB2, and WB3, respectively.

Two trenches were dug parallel to each windbreak in October/November 2008 using a backhoe at 2 m

Table 1 Characteristics of cadaghi windbreaks at C&B Farms (mean value ± standard error)

Windbreak	Orientation	Age (Yrs)	Height (m)	DBH (cm)*	Spacing (m)
WB1 (n=51)	East-West	8	11.1 ± 0.2	26.7 ± 0.8	4.9 ± 0.1
WB2 (n=72)	North-South	6	8.8 ± 0.2	19.9 ± 0.5	3.3 ± 0.1
WB3 (n=37)	East-West	8	10.0 ± 0.2	24.9 ± 0.7	4.5 ± 0.2

n = total number of trees in selected 45 m long sections.
*Diameter at breast height. Measured at 1.3 m above ground

from a tree of average height and DBH within the selected 45 m windbreak sections. Each trench was 2 m long (parallel to the windbreak) x 1 m wide x 1 m deep. The 2 m long trench wall was smoothed to facilitate root count, and a 1 x 1 m frame divided into 10 x 10 cm grids was fixed on the wall for counting roots. Occasional weeds were present in the area between vegetable crops and the windbreaks, but experience in growing cadaghi seedlings in the greenhouse for windbreak planting and the distinctive features of its roots from weed roots minimized the chances of considering roots of other species. The number of living roots (N_X) in each grid was counted, and their diameters were also measured. Roots were classified into fine (<2 mm), small (2-5 mm), medium (5-10 mm), and large (10-20 mm) diameter classes (Böhm 1979). Roots were present only up to 40, 50, and 20 cm depths in WB1, WB2, and WB3 trees, respectively.

Three 10 x 10 cm grids were selected from each depth as described in Lopez-Zamora et al. (2002) to estimate RLD. Using a 10 x 10 x 10 cm metal container similar to one described and illustrated by Chopart et al. (2008a, b) but open only on one side, a 1000 cm^3 of undisturbed soil cube was removed from each selected grid. The edges of the open side were sharpened to facilitate penetration while driving the cube on the trench wall. The cube was driven on the trench wall until the back end leveled with the trench wall. Living roots exiting the vertical face perpendicular to the frontal face (N_Y) and basal horizontal face (N_Z) were counted and their diameters measured. Roots were counted only from the front, left, and bottom side of the X, Y, and Z cube faces, respectively. The sample sizes varied for each windbreak as the soil cubes were removed only from depths where roots were present. Soil samples were transported to the lab and washed to separate roots. Total root length in 1000 cm^3 soil samples was estimated with Tennant's (1975) intercept counting technique using 1 x 1 cm grids.

Statistical Analysis

Because of the close spatial relationship between root samples, all root variables were assumed spatially correlated within the trench. To examine differences in root number exiting the three faces of the soil cubes, a generalized linear mixed model with Poisson response was estimated (SAS Institute Inc. 2008). When significant differences were found between the three faces, mean separation tests were performed using LSMEANS statement. Separate tests were conducted for all roots (roots of all diameter classes combined) and fine roots (<2 mm diameter). The interaction between root growth direction and depth was also considered in the model but was not significant. The final model was:

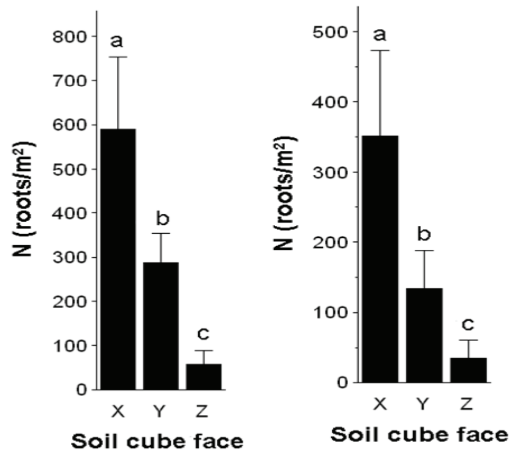

Fig. 1 Average number of a) all roots and b) fine roots exiting the frontal face of the trench wall (X), vertical face perpendicular to X (Y), and basal horizontal face (Z) of soil cubes in cadaghi windbreaks. Means with different letters are significantly different at a P-value of 0.05.

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + c_k + e_{ijkl} \quad (1)$$

where Y_{ijkl} is the number of roots exiting the faces of the soil cube l in direction i, depth j, and trench k; μ is the overall mean; α_i and β_j are the fixed effects of direction i and depth j, respectively; c_k is the random effect of trench k; and e_{ijkl} is the error.

To develop the relationship between RLD and N_X and N_{AVG}, a linear mixed model was established. Root number and RLD were converted to N per cm^2 and cm per cm^3 of soil, respectively. The number of roots exiting the three faces of the soil cube was averaged per cube to get N_{AVG}. The final models were:

$$RLDx_{jk} = \gamma_0 + \gamma_1 N_X + b_j + e_{jk} \quad (2)$$

$$RLDavg_{jk} = \gamma_0 + \gamma_1 N_{AVG} + b_j + e_{jk} \quad (3)$$

where RLD_{Xjk} is the RLD in soil cube k computed with N_X in trench j; RLD_{AVGjk} is the RLD in soil cube k computed with N_{AVG} in trench j; γ_0 is the intercept; γ_1 is the fixed effect of N_X or N_{AVG}; b_j is the random effect of trench j; and e_{jk} is the random error.

Results and Discussion

Root Isotropy

Cadaghi roots had anisotropic distributions (Fig. 1) and showed horizontal growth preference. The

Table 2 Test of fixed effects for root number: all roots and fine roots

Effect	Num DF[a]	Den DF[b]	F-value	P-value
All roots				
Direction	2	137	35.9	<.0001
Depth	4	137	0.3	0.8495
Fine roots				
Direction	2	137	20.6	<.0001
Depth	4	137	0.6	0.6495

[a]Numerator degrees of freedom
[b]Denominator degrees of freedom

number of all roots and fine roots exiting the three faces of the soil cubes were significantly different ($P<0.05$, Table 2). Average root numbers were ranked $N_X > N_Y > N_Z$. In similar Florida flatwoods soil, melaleuca roots also had anisotropic distributions (Lopez-Zamora et al. 2002); however, the number of roots in corn (*Zea mays*) (Chopart and Siband 1999) and peach palm (*Bactris gasipaes*) (Lopez-Zamora et al. 2002) growing elsewhere were identical in all three directions (X, Y and Z) in similar tests of soil cubes. Root orientation varied by root size in sugarcane (*Saccharum* spp.) (Chopart et al. 2008a) and sorghum (*Sorghum bicolor*) (Chopart et al. 2008b); larger roots (>1 mm diameter) showed horizontal growth near the surface but vertical growth in deeper soil. Fine secondary roots (<1 mm in diameter) were isotropic. Sorghum roots were isotropic when roots of all diameters were pooled together (Chopart et al. 2008b). This indicates that although roots in some diameter classes may actually be anisotropic, they may appear isotropic when pooled data (of all diameter classes) is used. In the case of cadaghi, both all roots and fine roots were anisotropic.

In plants, different roots (sizes) perform different functions. Therefore, separate isotropy tests may be required for smaller diameter roots in order to evaluate the competitive potential of a species as fine roots are used for nutrients and water absorption. In cadaghi, all roots and fine roots showed horizontal growth preference. Factors such as soil compaction and soil environment impact the growth direction of plant roots (Coutts 1989; Kaspar and Bland 1992; Onderdonk and Ketchenson 1973). In this study, a hardpan was present at 20-40 cm, and the water table remained high as the farm employed seepage irrigation. These factors might have influenced the preferential root growth direction in cadaghi. Citrus roots also grew horizontally in similar Florida flatwoods soil (Bauer et al. 2004).

Relationship between root length density (RLD) and root number (N)

Both N_X ($p = 0.0046$) and N_{AVG} ($p = 0.0022$) significantly influenced RLD (Table 3). The coefficients of N_X and N_{AVG} were estimated to be 1.1 and 3.1, respectively. As indicated by geometric theory (Kendall and Moran 1963; Melhuish and Lang 1968) and Baldwin et al. (1971), the coefficient of N should be 2 when roots have anisotropic distribution but N_{AVG} is used. Since the 95% confidence interval around the N_X coefficient did not include 2, it was significantly different from 2. The 95% confidence interval around N_{AVG} coefficient, on the other hand, was much wider and included 2. Therefore, N_{AVG} coefficient was not significantly different from 2.

This relationship has been tested in some other species using a trench profile method. For instance, the N_X coefficient was significantly different from 2 in melaleuca and peach palm (Lopez-Zamora et al. 2002) and ranged between 3 and 11 for N_X and N_{AVG}. In *Eucalyptus grandis,* the coefficient for N_X and N_{AVG} ranged between 3 and 9 (Maurice et al. 2010). Mean values per soil depth are usually considered to establish RLD=2N relationship (Lopez-Zamora et al. 2002; Maurice et al. 2010), but we used data obtained from individual soil cubes because of small sample size.

The relationship between RLD and N has been improved in young loblolly pine (*Pinus taeda*) by adding root weight and depth (coefficient = 1.4) to a model with N_X (Adegbidi et al. 2004) and leaf area index in *E. grandis* (Maurice et al. 2010). We also added depth to our models but depth, however, was not a significant variable. Using the core-break method, the coefficient was estimated to be 1.1 for slash pine (*P. elliottii*) (Escamilla et al. 1991), 1.9 for cotton (*Gossypium hirsutum*), 2 for sunflower (*Helianthus annuus*), and 1.5 for sorghum (Bennie et

Table 3 Coefficients of roots exiting the frontal face (N_X) and average number of roots (N_{AVG}) exiting the three faces of soil cube, their standard errors (SE), P-values, and lower and upper limits of the 95% confidence limits

Roots	Intercept	Coefficients	SE	P-value	Lower	Upper
N_X	0.2088	1.1	0.4	0.0046	0.4	1.9
N_{AVG}	0.1809	3.1	1.0	0.0022	1.2	5.0

al. 1987). Bland (1989) estimated the coefficient to be 2.1 for cotton, 3.9 for wheat (*Triticum aestivum*) and 7.6 for sorghum. In the literature, the coefficient of N ranges from 0.2 (Escamilla et al. 1991) to 16 (Bengough et al. 1992); thus, our results for windbreak-grown cadaghi are well within the published range.

Independent data was not available at the time of the study due to limited plantings of the species. Therefore, the relationship between RLD and N estimated in this paper is yet to be validated using independent data. The species has subsequently been planted at other sites which provides validation opportunities.

Regardless of anisotropic root distribution and horizontal growth direction preference, N_X and N_{AVG} were significant variables for RLD estimation. Therefore, the relationship should be useful in estimating cadaghi RLD using root intersection counts in soil profiles. These results could be used to manage competition at the windbreak-crop interface in cadaghi windbreaks.

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