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Quantifying shallow roots

tree geometry makes root research easy

Roots do a lot for a plant. They provide physical support; take up water and nutrients, store carbohydrates during cold or dry seasons and produce hormones. Thicker roots close to the tree stem, the proximal roots, help anchor the plant and they contain transport tissue, while fine roots take up water and nutrients. Since agroforestry research focuses on interactions between crops and trees, most of our attention should be on fine roots. Competition for water and nutrients depends on the relative distribution of fine roots of both trees and crops. Competition is usually more severe if trees are shallow rooted and occupy the same soil layers as food crops. If the number of fine roots, especially the ones in the topsoil, can be predicted fairly accurately from the diameter and orientation of the thick roots close to the stem, then root studies will require much less labour and destruction than standard methods of trenching and coring.

Researchers have made a major effort to quantify the fine root systems of trees that are used in agroforestry around the world. There are two standard ways that they determine root parameters. One is to measure all the roots of a single plant; the other is to sample roots in a known volume of soil and extrapolate that to the soil volume of the plant. For annual crops growing in a regular planting pattern, both of these are possible. In agroforestry stands, the first approach is nearly impossible because tree-root systems are too big. For forest trees that are regularly spaced, researchers normally use the second method. However, it is labour intensive; tree-root systems can extend over large areas—up to 50 m from the stem—so a large volume of soil has to be sampled. Also, root distribution tends to be patchy so there is a lot of variability between samples and a large number of replicate samples are needed. In agroforestry systems, which are more diverse with less regular spacing of trees than plantations, the number of sample positions increases rapidly.

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Roots and their branches

Back in the 15th century, Leonardo da Vinci claimed that the cross-sectional surface area of the main stem is equal to the sum of the cross-sectional surface area of tree branches. This simple rule for tree geometry might indicate a constant resistance to water flow, whether in the main stem, the large or the small branches. For tree stems, stability and strength requirements may be as relevant as water transport capacities in determining stem diameters. A similar rule might apply to the root systems, but we have to test this assumption first.

An analogy is found in forest mensuration, where above-ground tree biomass can be estimated with

Measuring proximal roots in Lampung, Indonesia.

reasonable accuracy from measurements of stem diameter at a standardized height. Some attempts have also been made to relate root biomass to stem diameter at breast height, but such relationships probably depend on tree species and site. It may be safer to first establish relationships within a single branched root, between the diameter close to the stem and the total size, and to search later on for relations between the shoot and the sum of all roots. Groot and Soumaré (1995) found an empirical relation between proximal root diameter and the length of the root axis.

We are developing and testing a new method that should, as we claim in the title of this article, simplify and speed up root research (van Noordwijk and Purnomosidhi. forthcoming). A secondary thickening of roots occurs in response to the need for transport tissue wherever fine roots develop. If the decrease of root diameter in a branched root from the stem base (highest diameter) to the finest root tips follows the rule that da Vinci hypothesized—that the sum of the cross-sectional area (or diameters squared) remains constant, we can use a fractal model. Fractal refers to the basic unit of form or shape, irrespective of size, age or position.

A fractal model contains the essential rules of branching information required to reconstruct the whole pattern. If real root branching patterns can be defined this way, measurement of the proximal root diameter at the stem base and the branching rules as observed anywhere in the root system would be enough to predict total root length, root diameter distribution and root length per unit dry weight (specific root length).

We developed an equation to derive the relation between total size of the root system and diameter of proximal roots for two extreme branching patterns: dichotomous and herringbone (Spek and van Noordwijk 1994; van Noordwijk and others 1994). To predict total root length from the proximal root diameter, the basic information required for the equations is the internode lengths as a function of root diameter and the proportionality factor (α) between total cross-sectional surface areas, both before and after branching. For the length of the longest root, further information on the branching rules is needed, especially on the relative size of main axis and branch roots.

Theory in practice

We developed a protocol for root research based on the proximal root diameters (box 1) and for tests of the assumption of fractal branching as such (box 2). We tested the method in a preliminary survey of the root systems of 18 trees in northern Lampung in Indonesia, on an acid Ultisol. Most of the trees were in a homegarden and about 6 years old. We did not find a significant relationship between root diameter and α for any of the trees we tested, confirming that branching is similar across all root sizes. We did find considerable differences between root systems of the various trees, in the average value of the proportionality factor. There was much less variation in the stem-branching patterns of the same trees; thus root patterns cannot be predicted from stem branching.

The percentage of vertical tree roots expressed as the sum of the proximal root diameter squared ranged from 11 to 85% (table 1). There was a clear relationship between the sum of squared root diameters and the square of the stem diameter at breast height. The sum of proximal root diameters squared was 50–200% of the stem diameter at breast height. We can thus use the stem diameter to obtain an index of shallow rootedness by dividing the sum of squares by the stem diameter squared. This index will be independent—or nearly independent—of tree size; in our survey, its value ranged from 0.14 to 2.13 (table 1). Leucaena was the most shallow-rooted tree on this acid soil; mango had the lowest index for shallow roots.

If the root-branching pattern is related to the functioning of tree roots, then the fractal root method will provide a simple test for root research. ICRAF scientists are now using a combination of fractal branching and direct measurements of water uptake using sapflow meters on individual roots (Ong and Khan 1993). There is also a need to determine the sustainability of fractal branching to soil types, rainfall and pruning.

Table 1. Root patterns of some multipurpose trees on acid soil in Lampung, Indonesia; preliminary survey of 5–7-year-old trees (mostly in homegardens)

Species	Root: Σroot basal area ratio, A	Stem: Σroot basal area ratio, B	Index of shallow rootedness (1–A)/B
Leucaena leucocephala	0.17	0.39	2.10
Parkia speciosa	0.23	0.46	1.60
Psidium guajava	0.11	0.74	1.20
Gliricidia sepium	0.18	0.94	0.87
Ceiba pentandra	0.45	0.95	0.58
Gnetum gnemon	0.15	1.53	0.56
Calliandra calothyrsus	0.75	0.64	0.39
Peltophorum dasyrachis	0.74	0.69	0.38
Durio zibethinus	0.75	1.14	0.22
Artocarpus integer	0.84	0.86	0.10
Mangifera indica	0.85	1.04	0.14

Box 1

Proximal roots and index of shallow rootedness

1. Carefully excavate the first part of the proximal roots at the stem base (figure 1). For a small tree, a 0.3-m half sphere may be sufficient, for larger trees a 0.5- to 1-m half sphere will be needed. While they are being excavated, all major roots should be left intact; destruction of most of the fine roots cannot be avoided. Check for 'sinker' roots (vertically oriented roots starting from horizontal roots, often close to the tree stem).
2. Measure the root diameter of all proximal roots—those roots originating from the stem base or as laterals from the top part of the tap root—and classify them by orientation (angle with a horizontal plane). Root diameter measurements should be made outside the range of obvious thickening close to the branching point or buttress roots (they normally taper off rapidly).
3. Measure stem diameter (either as 'root collar' diameter or as stem diameter at breast height, depending on the size of the tree).
4. Calculate the sum of root diameter squares for roots with a horizontal (angle less than 45°), $\Sigma D_h{}^2$, and vertical orientation $\Sigma D_v{}^2$.
5. A tentative index of shallow rootedness is then calculated as $D_s{}^2/\Sigma D_h{}^2$.

Box 2

Test of fractal characteristic of root branching and measurement of model parameters

Expose part of the root system by tracing roots from the stem base. For each branching point where both previous and subsequent internodes have been exposed, measure their diameter and length. A data registration form plus the Genstat 5 program for analysing the data can be obtained from the authors. The program first sorts roots belonging to a common previous internode and calculates the α parameter. Then, the regression of α and the link length on root diameter is analysed. If neither of these regressions has a statistically significant slope, the basic assumptions of fractal branching models are met. The average value of α and internode length can now be used in the equations for total length, surface area and volume given by van Noordwijk and others (1994); if either of these regressions has a significant slope, modified equations will have to be developed, for example the numeric model given by Spek and van Noordwijk (1994).

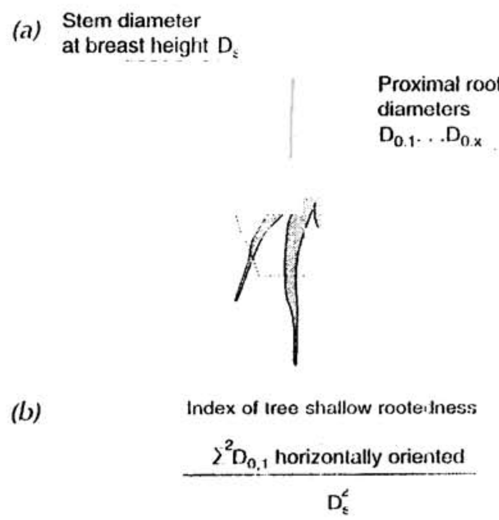

Figure 1. Comparison of stem diameter at breast height and proximal root diameters of a tree: (a) a tentative index of root competitiveness, which can be derived from each branching point; (b) calculation of index of shallow rootedness.

References

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