
ICRAF

Current root research issues at ICRAF

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This article describes some of the major current foci in root research at ICRAF. Below-ground resource competition and the interactions between tree and crop roots in terms of complementarity and competition are discussed, as well as the development of a method of simplifying the quantification and distribution of tree root systems. Some results from recent studies of root dynamics and function are presented.

Introduction

ICRAF research currently ranges from relatively simple 'improved fallow' rotation systems to complex 'agroforests', and from studying soil processes to dialogues on modifying government policies. While it is still necessary to better understand why alley cropping has been so disappointing technically, there should be more emphasis on other systems which offer greater complementarity in resource use. Priority systems for the subhumid and semi-arid zones are relay intercropping and rotational tree fallows in which tree competition is minimal when the crops are actively growing and where deep-rooted trees can exploit residual water and nutrients after crop maturity (Sanchez, 1995; Torquebiau and Kwesiga, *in review*). For the humid tropics the main interest is in 'agroforests' and 'planned multistrata systems': the difference between these two systems is that naturally regenerating forest species are tolerated in the first, while the second mainly contain planted trees and shrubs. The overall target of our research is to complement, not substitute, the ingenuity of farmers in improving their own location-specific agroforestry systems.

Root research issues in this context focus on the following.

- Below-ground resource capture in a wide range of systems, as part of the underlying biophysical trade-offs between crop and tree growth, and short and long term productivity of the land use system.
- Quantifying tree and crop roots as part of the total storage of nutrients and carbon in the agroforestry system and as step in understanding below-ground resource capture.
- Measuring dynamics of root growth and decay.
- Root functioning in terms of water and nutrient uptake

These issues are briefly discussed.

Below-ground resource capture

Competition between crops and trees is an important attribute of agroforestry, as it may increase total resource capture. However, even when total resource capture increases, the share for both the crop and the tree will be almost certainly less than in their respective monocultures. Many of the specific hypotheses on the biophysical advantages of mixed tree-crop systems are based on a variation on the theme that 'benefits of growing trees with crops will only occur when the trees are able to acquire resources of water, light and/or nutrients that the crops would not otherwise acquire' (Cannell *et al.*, *in review*). The complementarity does not have to be complete to justify agroforestry, but without any complementarity it is a zero-sum game. If the trees are equally or more valuable per unit resources captured than the crops, competition may be acceptable to a farmer. In many agroforestry systems in the tropics, however, a major role of trees is to improve soil fertility for the crop and then the complementarity is essential.

Complementarity in light use is relatively easy to measure, as it is largely based on differences in above-ground phenology and canopy structure (Ong and Black, 1993; McIntyre *et al.*, *in press*). For water and nutrients complementarity has to consider time scales linked to the 'residence' times of the resources in the ecosystem; residence times tend to increase in the order water, nitrogen, potassium, phosphorus. For P resources used by the tree it will be difficult to measure whether or not this P might have become available to the crop in the absence of trees.

Ong (1995) proposed to separate the overall effects of trees on crop growth (I) in terms of a positive soil fertility component (F) and a negative competition term (C), all expressed as percentage of crop yield in a crop monoculture. In some studies (Akyeampong *et al.*, 1995) the F term is based on the direct effect of mulch transfer, in others it includes the residual (long term) fertility effects which become evident when the trees have been removed (Van Noordwijk *et al.*, *in press*). Separation of the F and C term shows that for the best overall crop yield the



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emphasis should not only be on F ('fast growing, N₂-fixing trees'), but at least as much on obtaining a small C value. For example, Van Noordwijk *et al.* (*in press*) reported the following values for an alley cropping experiment in Lampung (Indonesia): *Leucaena leucocephala* (F - C = 1) 152 - 159 = -7, *Peltophorum dasyrrachis* 58 - 26 = 32, *Gliricidia sepium* 19 - 60 = -41. The relatively good results with the indigenous *P. dasyrrachis* is probably based on a combination of a relatively deep root system, a compact hedgerow canopy and relatively slow recovery from pruning, at similar levels of annual above-ground biomass production. Tilander *et al.* (1995) also found that slower growing trees are more appropriate for simultaneous agroforestry systems. Desirable root patterns for sequential and simultaneous agroforestry systems were discussed by Schroth (1995) and Van Noordwijk *et al.* (*in press*).

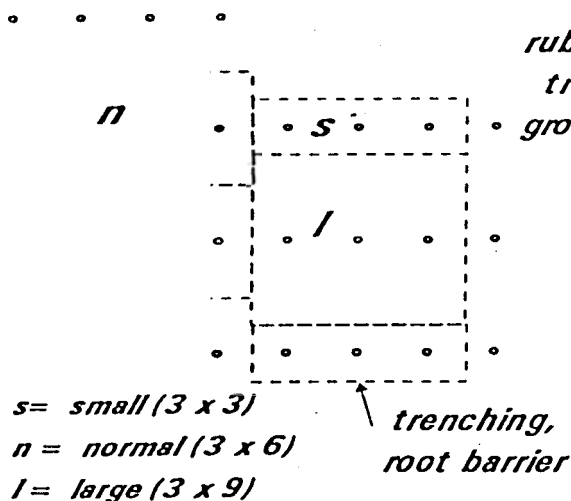
To understand tree-crop or tree-tree interactions in mixed systems a diagnosis is needed to determine whether above- or below-ground resource capture is limiting crop (tree) growth. Direct evidence for competition for below-ground resources can be obtained by introducing root barriers between the tree and crop zone (Coster, 1933; Singh *et al.*, 1989). Effects of such a root barrier can be dramatic, especially in climates where water shortages during the main crop season are likely to occur.

We are trying to adapt this method to understand rubber tree - weed interactions as part of a broad research program to test whether and how 'domesticated' rubber trees can be part of 'jungle rubber' agroforests. Rubber agroforests are based on planted rubber trees plus a wide range of spontaneously regenerating forest trees. The expectation is that trees selected for good performance in intensively managed plantations will be less competitive than the farmer-selected germplasm. In a regular plant spacing, the average amount of below-ground resources available to each tree is proportional to the inverse of plant density. Trenching off such an area of soil and preventing roots from the target tree (crop) exploiting other soil, as well as preventing other roots exploiting the soil of the target tree should have no effect on tree (crop) growth if the competitive strength of all trees is the same. By trenching we can also reduce or increase the ratio between above- and below-ground resources available per tree (Figure 1). In trials in Sumatera (Indonesia), we implemented this design with and without removing the (woody) weeds from the plots. We expect that this experiment will clarify the nature of competition. By adding specific nutrients or water to the various plot sizes (especially the smallest) the nature of the competition can be further diagnosed (cooperation with Sandy Williams, University of Wales, Bangor, UK).



For the best overall crop yield the emphasis should not only be on fast growing, N₂-fixing trees but at least as much trees with a small competitive effect

Field lay-out:



Expected results:

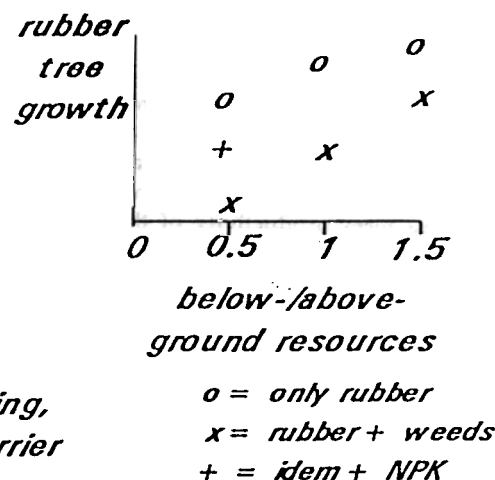


Figure 1. Design of experiment to test the hypothesis that below-ground interactions between rubber trees and secondary forest regrowth is a determinant in the 'jungle rubber' establishment phase in Sumatera (Indonesia); the expected results will allow a separation of intra- and interspecific competition above- and below-ground



Below-ground complementarity should be based on an assessment of below-ground resources which are underutilized by current cropping systems

Below-ground complementarity should be based on an assessment of below-ground resources which are underutilized by current cropping systems. Unfortunately this first step is seldom taken seriously and it is common to assume that the first requirement is N₂ fixation even when soil N is abundant. For example, on deeply weathered soils, such as in the highlands of western Kenya the main problem is low P rather than low N supply, yet agroforestry research has, until recently, concentrated on N₂-fixing trees.

Quantifying roots

Indications of complementarity in below-ground resource use can be obtained by observing the root distribution of both components. Actual uptake of resources will, however, depend on resource and root distribution as well as demand factors, and thus the degree of overlap in root distribution *per se* is not sufficient to predict competition (Jama *et al.*, 1995).

Fractal root branching models hold a promise of simplifying observation methods on tree root distribution (Van Noordwijk *et al.*, 1994; Van Noordwijk and Purnomosidhi, 1995). Fractal branching properties of (dicotyledonous) trees may be based on the process of secondary growth of the transport tissue in roots in response to the degree of local branch root development. The 'pattern' in the apparent 'madness' of a root system may be a reflection of the developmental history of each root axis. Root diameter may therefore reflect the number of branch roots possibly connected to that axis. A knowledge of root architecture may thus allow statements about the potential competition

between crops and trees. Actual competition estimates at any point in time will have to come from models which include the dynamic character of resource supply during the growing season, as well as from crop and tree demand factors. For the model we need eight parameters:

- the proportionality factor α indicating whether total cross-sectional area increases, decreases or remains constant in each branching event, and its standard deviation,
- the allocation parameter q , indicating whether the branch roots are equal or differ in diameter, and its standard deviation,
- the average length of a link (distance between two branching points) and its standard deviation,
- the maximum root diameter (at stem base: proximal root diameter) and the minimum diameter D where branching stops.

We are currently investigating at which level of parameter variability the overall predictability breaks down (cooperation with Dr Louise Spek, University of Utrecht, NL).

In as far as one has confidence that the essential assumptions of fractal branching are met, a three-step approach can be followed (Figure 2) to quantify the total below-ground biomass as a component of the carbon and nutrient content per tree:



The degree of overlap in root distribution *per se* is not sufficient to predict competition

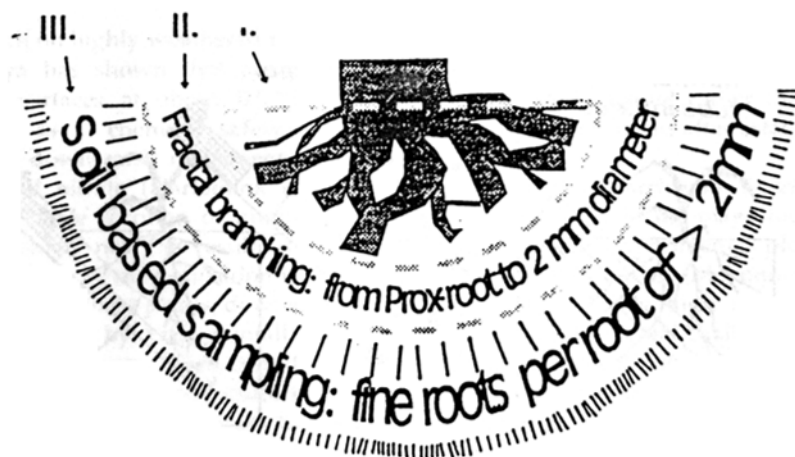


Figure 2. Three-step approach to quantify the total below-ground biomass and its carbon and nutrient content per tree, based on fractal root branching patterns to extrapolate from 'proximal roots' to the roots with the finest branches




1. Destructive sampling of the 'root stool', the irregularly-shaped biomass from the lower part of the trunk to the zone where the 'proximal roots' can be measured (20-50 cm from the trunk, depending on the size of the tree and the shape of the roots). Total fresh weight is recorded and subsamples are taken to estimate total dry weight. Subsamples of the root stool are analyzed for C and/or nutrient concentrations on a dry weight basis.
2. The major part of the 'transport roots' can be predicted from fractal branching models, on the basis of proximal root diameters, the average parameters α and q , and their respective variances; model predictions of root length and root volume will extrapolate up to a root diameter D_{min} of say 2 mm. Parameters for these branching models can be obtained from measuring say 40 branching points on exposed roots (Van Noordwijk *et al.*, *in press*). Subsamples of transport roots of various root diameters are taken to determine the relation between calculated volume (on the basis of length and diameter) and measured dry weight. Subsamples of transport roots are analyzed for C and/or nutrient concentrations on a dry weight basis.
3. The ratio of fine roots (<2 mm diameter) and transport roots (>2 mm diameter) is estimated from a 'soil-based' sampling method (Anderson and Ingram, 1993); this can be either: a) washed soil monoliths (record root length and dry weight of both root classes), or b) root profile maps (record number of intersections of both root sections), with calibration subsamples to relate number

of intersections to root length and root dry weight. Subsamples of fine roots are analyzed for C and/or nutrient concentrations on a dry weight basis.

Root dynamics

Measurements of the dynamics of root growth and decay can best be done by repeated observations of small soil surfaces, well distributed over the profile. We are now using a modified version of the inflatable minirhizotron technique (Gijsman *et al.*, 1991) in both Lampung and Machakos. The technique has been simplified by replacing the fibre optic system by a macro lens, which captures the image directly from a mirror at observation depth (Figure 3). This technique was developed in cooperation with the University of Groningen and AB-DLO Haren (the Netherlands).

Initial observations indicate a rapid turnover of nodules and fine roots in Machakos (Kenya) under frequent wetting-drying cycles and a slower root turnover in Lampung (Indonesia) in a more humid climate. We expect that data on root turnover can help both in understanding the dynamics of water and nutrient uptake and in a better understanding of soil organic matter dynamics. Although the total amount of carbon inputs to the soil from root turnover may be less than above-ground inputs via litterfall, the location and 'low' quality of root inputs may make the contribution to longer-term stabilized C pools larger than for above-ground inputs (Kooistra and Van Noordwijk, 1996).

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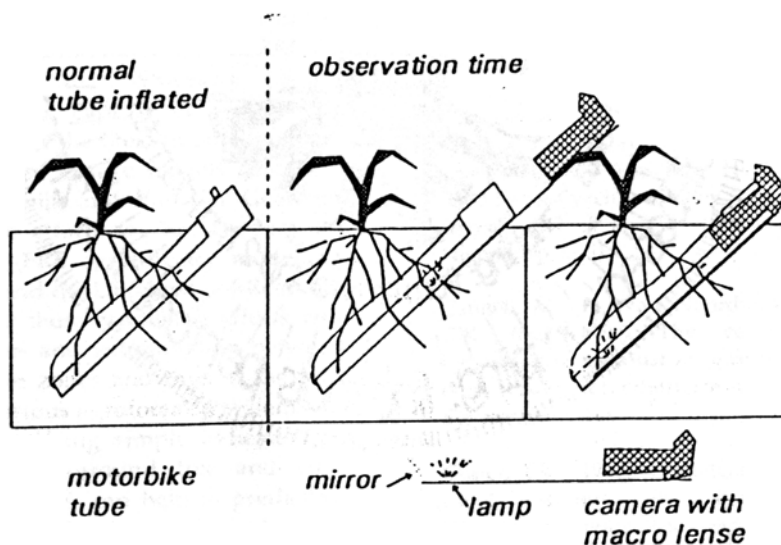


Figure 3. Schematic design of 'inflatable' minirhizotron system, made from motorbike tubes, a camera with macro-lens, a mirror and a lamp

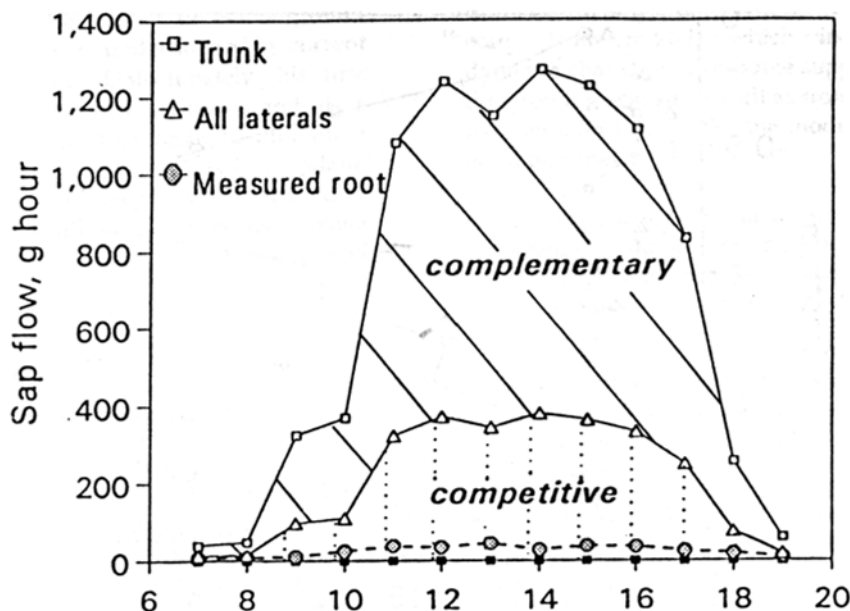


Figure 4. Diurnal trend of sap flow of three-year-old *Gliricidia sepium* tree using a heat pulse technique for a single lateral root, all lateral roots (extrapolated on the basis of cross-sectional areas) and the trunk; the uptake by all lateral roots (about 30%) would be in competition with that of shallow-rooted crops, the remainder complementary; for this measurement day the relative contribution of shallow roots to total uptake agrees with the 'index of shallow rootedness' (Machakos, long rains 1996 - Khan, unpublished)



Fast-growing trees reduced soil nitrate in the top 2 m by about 150 to 200 kg N ha⁻¹ and effectively depleted the subsoil of nitrate within 11 months after establishment while for slower-growing trees with low demand for N soil nitrate increased rather than decreased during the 11 months after establishment

Heat pulse units are installed on a few lateral roots to estimate their contribution to the total water uptake by multiplying their total cross sectional area with the mean sap flow velocity (Figure 4). Measurements during the rainy season show that in a relatively uncompetitive species, *Gliricidia sepium*, the lateral roots provided only 30% of the total tree requirement of water. We are testing the usefulness of this approach for a range of tree species at Machakos through the wet and dry seasons.

ICRAF research on highly weathered soils in western Kenya has shown that positively charged soil surfaces at about 0.5-1.5 m depth can act as a 'chemical safety net', retarding the downward movement and leaching loss of nitrate (Hartemink *et al.*, 1996). Appreciable sorption of nitrate by this 'chemical safety net' can result from a combination of high N mineralization in the topsoil, low N demand by plants, downward movement of nitrate by high rainfall and shallow rooting by plants. Such conditions were observed under a monoculture of unfertilized maize, when plant growth was limited by P deficiency (Mekonnen *et al.*, submitted).

Hartemink *et al.* (1996) and Mekonnen *et al.* (submitted) showed that *Sesbania sesban* grown in rotation with maize in western Kenya can rapidly root into this 'chemical safety net' and take up the sorbed nitrate

that was inaccessible to unfertilized maize monoculture. Research by Jama *et al.* (submitted) indicated a strong direct relationship between the demand of trees for N and the magnitude of nitrate uptake from the subsoil. Fast-growing trees, such as *Calliandra calothyrsus* and *Sesbania sesban*, with root length densities of > 0.1 cm cm⁻³ to below 1.5 m depth by 11 months after establishment from seedlings, reduced soil nitrate in the top 2 m by about 150 to 200 kg N ha⁻¹ and effectively depleted the subsoil of nitrate within 11 months after establishment (Figure 5). For slower-growing trees with low demand for N, such as *Grevillea robusta*, soil nitrate increased rather than decreased during the 11 months after establishment.

Very recent research with *S. sesban* indicates high variability in the magnitude of subsoil nitrate among experimental plots and with distance from tree (Mekonnen *et al.*, in preparation). This high spatial variability leads to experimental challenges in selection of sampling locations that are representative of the unit soil surface area in agroforestry systems.

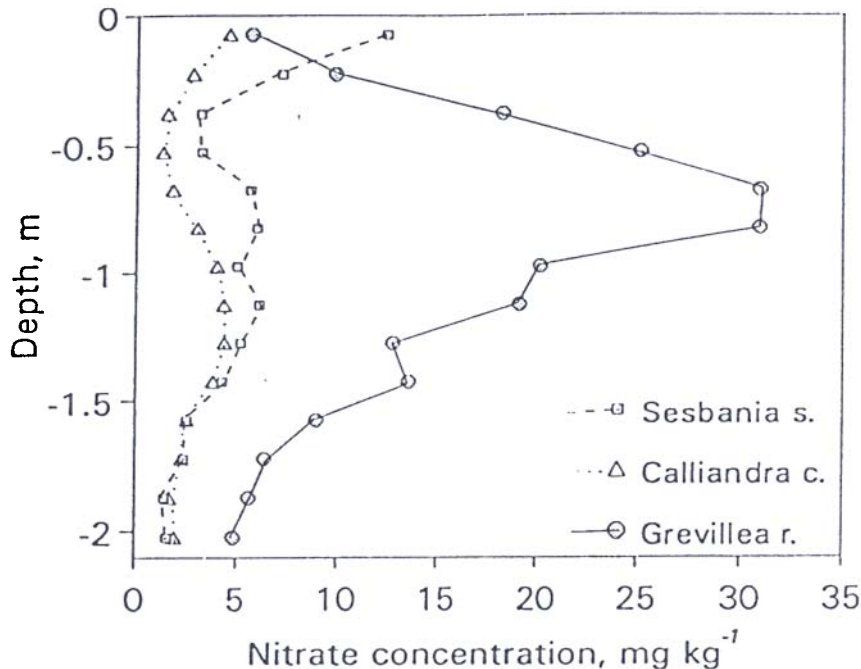


Figure 5. Effect of tree species, averaged over two levels of P addition, on soil nitrate at 11 months after establishment of the trees as seedlings on Ochiinga farm in western Kenya (based on Jama et al., submitted)

An experimental approach to complementarity of resource use can be based on using tracers (e.g. ¹⁵N) injected to the soil at different depths and recording their recovery in trees and crops. We have started such experiments including *P. dasyrrachis* and *G. sepium* as well as food crops. Preliminary data show that the relatively deep-rooted *P. dasyrrachis* has higher recoveries for deep placed ¹⁵N than the other components of the system (cooperation with Wye College, UK and Brawijaya University, Indonesia).

Integration of root distribution and soil water and nutrient uptake can be achieved in dynamic simulation models. At ICRAF we are developing the Wanulcas (water, nutrient and light capture in agroforestry systems) model in the Stella modelling shell based on nutrient uptake models described by Van Noordwijk and Van der Geijn (*in press*). In these efforts we are cooperating with the ODA-FRP agroforestry modelling project of ITE and the University of Reading. We expect that these modelling efforts will help with inter- and extrapolation between soil and climate zones and thus in the site-matching of various agroforestry systems, as well as in identifying simple indicators of above- and below-ground tree and crop characteristics which can help in predicting the suitability of plant germplasm for any such system.

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