ROOT RESEARCH METHODS FOR HUMID TROPICAL AGRO-FORESTRY SYSTEMS - A MANAGEMENT PERSPECTIVE

Götz Schroth[1], Sammya Agra D'Angelo[2], Michaela Schaller[3], Daniel Haag[4] and Maria do Rosário Lobato Rodrigues[2]

Abstract

Agroforestry is a promising land use option for humid tropical ecosystems. Tree root systems are assumed to play a vital role in the maintenance of soil fertility under agroforestry, but they are also the organs with which the trees compete with associated crops for soil water and nutrients. Progress in the understanding of the complex root ecology of agroforestry associations depends on the employment of sensitive and time-efficient research methods. In this paper, four examples of root research projects in humid tropical agroforestry and plantation ecosystems are discussed. The methods used include sequential soil coring for root turnover; root excavation for total biomass determinations; the profile wall method for the analysis of spatial patterns of root distribution in topsoil and subsoil; and descriptive graphic representation of root systems for the analysis of small-scale interactions between different root systems. Strengths and weaknesses of each method are explained, and the necessity of selecting suitable methods according to clearly defined research objectives is stressed.

Introduction

From the various land use alternatives for the humid tropics, agroforestry is presently in the focus of interest of many scientific institutions and development agencies. The term agroforestry comprises a wide variety of practices, such as rotations of crops with tree fallows, permanent associations of annual or perennial crops and pastures with trees, and forest-like systems in which useful tree species are enriched and exploited in a more or less systematic way. As trees are invariably part of the system, agroforestry tends to be closer to the natural vegetation of the humid tropics than pure agriculture. Also, the association of several species of crops and trees gives agroforestry a flexibility that may often match the needs of tropical smallholder farmers better than conventional agriculture because of their restricted access to credits and markets.

Agroforestry has often been shown to protect the soil more efficiently and to maintain the soil fertility at a higher level than conventional agriculture (Rao et al., 1998). Reasons for this are thought to be the permanent soil cover provided by the trees and the presence of the perennial tree root systems, which contribute to more efficient nutrient cycling, feed the soil biomass and maintain a favourable soil structure. Although tree root functions are thus an integral part of soil fertility management in agroforestry, the competition between tree and crop roots for water and nutrients is also a probable reason for frequent failures of agroforestry to rise crop yields above those obtained in agricultural control plots.

[1] University of Hamburg, Institute of Applied Botany, c/o Embrapa Amazônia Ocidental, C.P. 319, 69011-970 Manaus-AM, Brazil, Tel. +55-92-622 2012, Fax +55-92-622 1100, email: schroth@internext.com.br

[2] Embrapa Amazônia Ocidental, C.P. 319, 69011-970 Manaus-AM, Brazil

[3] University of Bayreuth, c/o CATIE, 7170 Turrialba, Costa Rica

[4] University of Hohenheim, Institute of Plant Production and Pastures, D-70599 Stuttgart, Germany

These contradictory roles of tree root systems in agroforestry have attracted the attention of numerous researchers, who have enriched the scientific literature in recent years with both experimental and theoretical work on the root ecology of agroforestry systems. Several recent reviews have summarized the existing concepts and information on tree and crop root distribution, root interactions between associated plants, root interactions with the soil environment, and methods of manipulating root systems to increase favourable and reduce unfavourable root effects (Schroth, 1995; van Noordwijk et al., 1996; Schroth, 1999).

There is a general consensus among researchers that two of the major impediments to progress in agroforestry root ecology are 1) the tedious and time-consuming nature of root studies in the field, and 2) the spatial and temporal variability of tree and crop root systems in heterogeneous land use systems such as agroforestry. In the following, four examples of root research are briefly presented, in which different methods have been used to investigate the distribution and dynamics of tree and crop root systems in the field in the humid tropics of Africa and Latin America. All examples are of direct relevance for agroforestry.

Example 1: Tree and crop root turnover by sequential soil coring

Root turnover is the renovation of root systems through the death of old roots and the growth of new roots. As the dead roots decompose, they add carbon to the soil and provide a substrate for the soil biomass. Root turnover is generally considered an important component of the carbon cycle in forest ecosystems, but very little data are available from tropical agroforestry systems. Such data would be required to assess more precisely the contribution of agroforestry to the maintenance of soil organic matter levels.

A frequently used method for the estimation of root turnover in forest ecosystems is sequential soil coring (Vogt et al., 1998). This is the repeated collection of volumetric soil samples in the field, usually with cylindric sampling devices of 2 to 10 cm diameter, from which the roots are quantitatively extracted by washing over a sieve (*e.g.*, 0.5 mm). The roots are then cleaned from mineral soil and organic debris and separated into live and dead material and size classes, using magnification (~10x) if necessary. For agroforestry studies, the separation of tree and crop roots is particularly important, but may be difficult in some cases, *e.g.*, when certain leguminous trees are associated with legume crops. As root systems are very heterogeneously distributed in the field, it is important to collect soil from a sufficiently large number of points in a plot to obtain a representative sample, although guidelines for the necessary number of sampling points per hectare as a function of the heterogeneity of a land use system do not exist at present. To reduce the amount of work for the washing and separation of the roots, several soil samples can be homogenized and a subsample be taken for further processing. Schroth and Kolbe (1994) demonstrated that a subsample of 5 to 10% may already be representative for the whole sample, allowing important economies in processing time. Following the sorting process, root length is determined, using the line transect method (Tennant, 1975) or scanning/image analysis, and the roots are dried and weighed. The weight is often corrected for the ash content of the roots to avoid errors due to adhering mineral soil. Root length and weight are related to the volume of the collected soil sample (cm cm^{-3}) or to the ground area (kg ha^{-1}).

Different methods have been proposed for calculating root turnover from the measured fluctuations in live and dead root mass (Publicover and Vogt, 1993). The principle difficulty is that root growth and root death occur simultaneously, so that root turnover is not necessarily accompanied by changes in the standing root mass. When the decomposition rate of dead root mass is known, root mortality (M), production (P) and disappearance (D) between one sampling date (t) and the preceding one (t-1) can be calculated according to the "compartment flow method", using the following formulae:

$$M_t=kt[DFR_t-DFR_{t-1}e^{(-kt)}]/[1-e^{(-kt)}];\ P_t=LFR_t-LFR_{t-1}+M_t;\ D_t=DFR_{t-1}-DFR_t+M_t;$$

with LFR=live fine roots; DFR=dead fine roots; k=exponential decay constant, related to the disappearance rate (DR) by k=-ln(1-DR) (Publicover and Vogt, 1993). If no decomposition rates are available, the balancing transfers method (Fairley and Alexander, 1985) can serve as a, theoretically less well-founded, substitute.

Sequential soil coring was used by Schroth and Zech (1995) to study the root dynamics in an alley cropping experiment with *Gliricidia sepium*, maize and groundnut in the rainforest zone of Côte d'Ivoire (Fig. 1). The mass of live fine roots in the soil under the annual crops reflected the cropping cycle, with maxima under maize and groundnut and minima when no crop was present. In contrast, the live root mass under the trees exhibited an annual cycle, with decreasing values during the cropping season (April to October) and increasing values during the long dry season (November to April). This "anti-cyclic" root development of the trees was presumably an effect of frequent shoot pruning of the trees during the cropping season to avoid shading of the crops. As an effect, root competition between trees and crops was insignificant, but the carbon input into the soil from the tree roots was also relatively modest (approximately 800 kg ha^{-1} of new root production under the trees at 0-50 cm soil depth in 13 months as compared to approximately 1200 kg ha^{-1} under the crops in the agroforestry plots and 1000 kg ha^{-1} in sole cropping). It was concluded that the intimate association of trees and crops in alley cropping gives little flexibility for managing carbon cycles, because the trees need to be pruned frequently to avoid shading of the crops, and this reduces their potential to enrich the soil carbon pool through their root systems. On the other hand, the study showed that shoot pruning of trees can be an efficient tool for manipulating tree root systems, thereby reducing competition with the crops for soil resources.

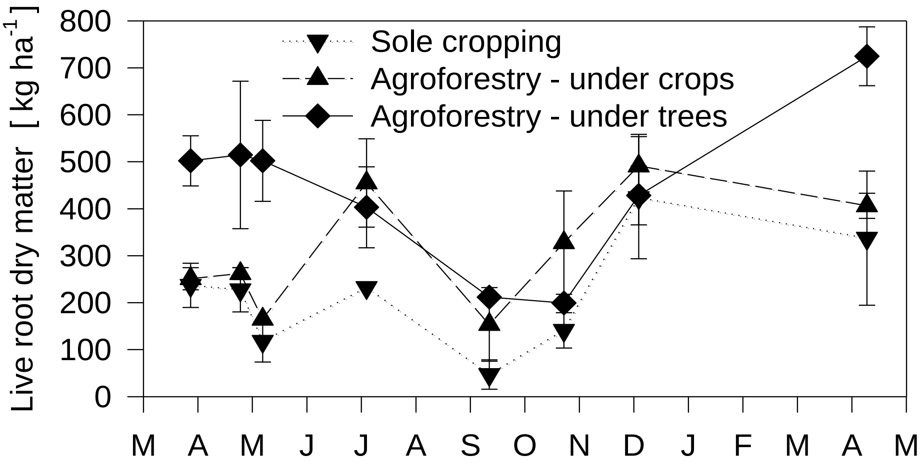

Figure 1: Changes in live fine root mass (< 2 mm) in sole cropping and alley cropping in Côte d'Ivoire between March 1992 and April 1993 as obtained by sequential soil coring (means and S.E., n=2). Crops are maize (May to August) and groundnut (September to December). From Schroth and Zech (1995)

Example 2: Accumulation of carbon and nutrients in tree root systems by excavation

Soil coring is a relatively time-efficient and cheap method for producing quantitative information about fine root distribution in relatively superficial soil layers. Sampling below 50 to 100 cm depth requires specialized equipment or the previous excavation of pits, which increases the sampling effort considerably. Moreover, coarse roots with a diameter exceeding 5 to 10 mm are not adequately sampled with the relatively small soil cores. For many studies, this is no problem, because the fine roots are the most active part of a root system in water and nutrient uptake and show the most rapid turnover. However, when information on carbon and nutrient accumulation in entire tree root systems is required, soil coring alone is inadequate. The only method to obtain quantitative data on coarse tree root mass is excavation, either of entire root systems or of representative sections. However, when excavating tree roots in the field, many fine roots are invariably lost, and fine root mass or length can thus not be assessed with this method. Where information on both coarse and fine roots is needed, a good solution is to excavate the root systems, collecting only the coarser roots (*e.g.*, >2 mm diameter), and to extract the fine roots from soil cores collected in the excavation pits.

This method was applied in a study of belowground carbon and nutrient accumulation in a multi-strata agroforestry system with four different tree crop species and a leguminous cover crop in central Amazonia (Haag, 1997). The tree species were peach palm (*Bactris gasipaes*) for fruit and for palmito, cupuaçu (*Theobroma grandiflorum*), Brazil nut (*Bertholletia excelsa*) and annatto (*Bixa orellana*), and the cover crop was *Pueraria phaseoloides*. Pits of 2 by 2 m with the tree in the center were excavated to 1 m depth, and soil cores were collected from each depth interval. In addition, transects were excavated between neighboring trees to obtain a full picture of the root distribution within the system.

Fig. 2 presents an idealized section through the agroforestry system, depicting the approximate distances between the trees and the root mass in the soil to 1 m depth. It gives evidence of an enormous heterogeneity in the belowground biomass within the plot already 3 years after planting, with differences of almost two orders of magnitude between the points with highest and lowest root mass. The highest root mass was found under the peach palms, whereas the lowest root mass was found under the cover crop. It is to be expected that over time, the differences in belowground carbon accumulation lead to corresponding spatial patterns of the quantity and probably the quality of soil organic matter within the system. As plant roots are an important factor in the formation and stabilization of soil structure, the development of spatial heterogeneity in soil physical properties within such an agroforestry plot would also be expected.

Example 3: Root system architecture with the profile wall method

The advantage of soil coring and excavation is that they produce quantitative root data. Their disadvantage is that only mean values of root length or mass for a certain soil volume (depth, distance interval from a tree etc.) are obtained. Both methods give little information about the small-scale, spatial arrangement of the roots in the soil, which is of great value for the analysis of interactions between different root systems (*e.g.*, those of trees and associated crops) or between root systems and their soil environment (*e.g.*, macroporosity, compact horizons, nutrient-enriched patches). Such information can be obtained by studying the root systems on the carefully prepared walls of soil pits or trenches with the profile wall method. Like excavation (but unlike soil coring), the profile wall method is relatively destructive, especially when deep profiles are required.

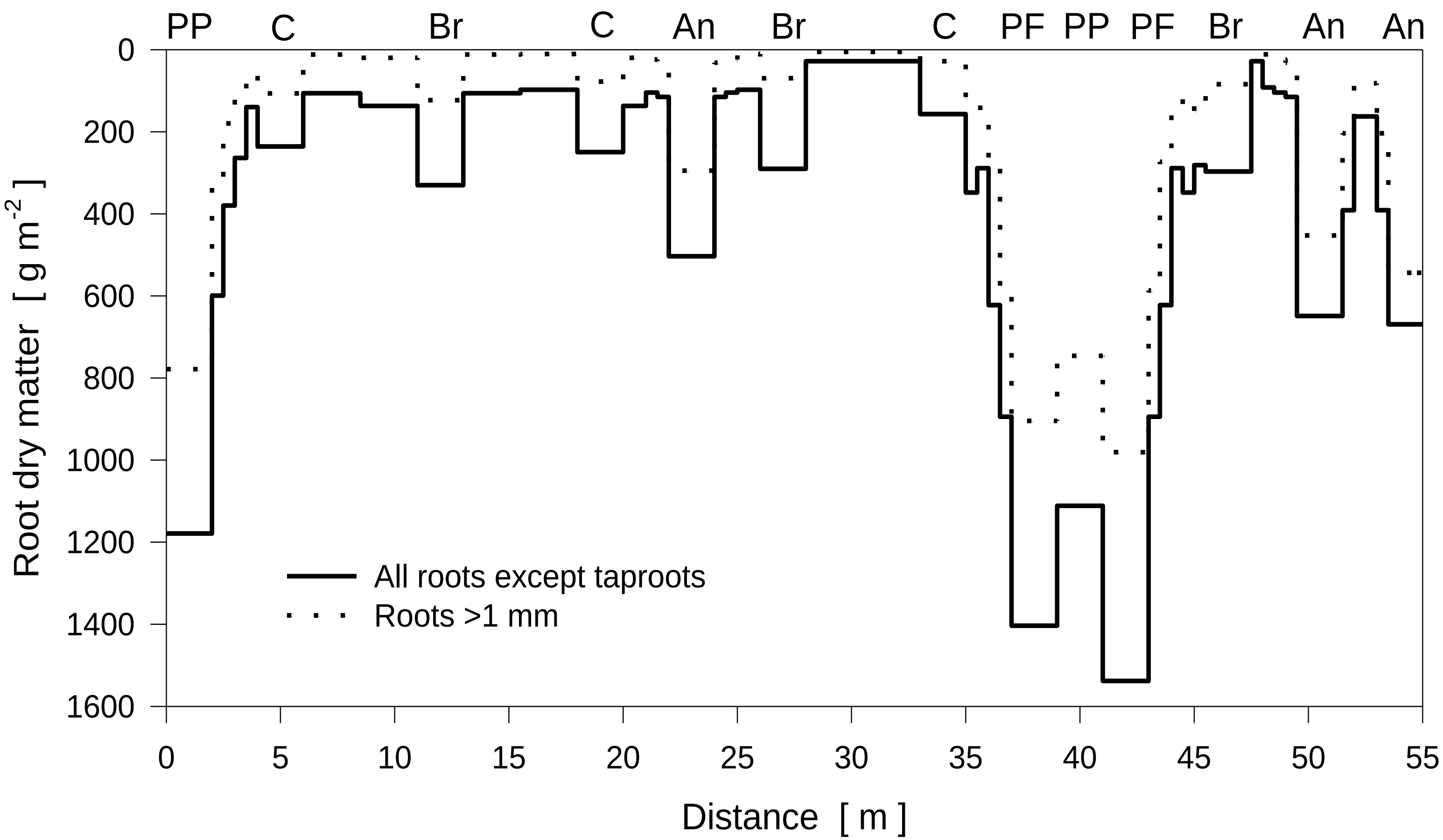

Figure 2: Schematic transect through a multi-strata agroforestry plot in central Amazonia, showing the root mass of excavated trees, cover crops and spontaneous vegetation to 1 m depth. The positions of the trees are indicated on the upper x axis. PF= peach palm for fruit, PP= peach palm for palmito, C= cupuaçu, Br= Brazil nut, An= annatto. From Haag (1997)

In addition to the description of the root systems in the profile wall, their distribution can also be analyzed by counting, drawing or image analysis. However, the obtained data are quantitative only for relatively coarse roots. Fine and fragile roots are partly lost when preparing the profile wall, especially in clayey soils. For agroforestry studies, the loss of fine roots when preparing the wall may introduce bias, because the roots of annual crops are usually finer and more fragile than tree roots, which may thus be relatively over-represented in the profile. To avoid such problems, the descriptive analysis of root distribution and architecture in the profile wall may be complemented by the collection of volumetric samples from the wall at different depths, from which the roots are then extracted and quantified as described for the soil coring method.

The profile wall method has been used for the analysis of root distribution patterns in a 14 year old oil palm (*Elaeis guineensis*) plantation near Manaus, Amazonia. Previous studies had produced evidence for a very inhomogeneous exploitation of the soil by the roots of the palms, which were planted at a 9 by 9 m triangular spacing (Schroth et al., 1999): At 1 m distance from the palms, nitrate was hardly detectable in the soil to 2 m depth, indicating efficient uptake of the nutrient by the palms. In the middle between neighboring palms (4 m tree distance), in contrast, considerable quantities of nitrate were present in the soil profile, indicating that the palms had insufficient access to the soil resources at this distance. The nitrate accumulation at 2.5 m tree distance was intermediate. These findings were surprising, because the palms were expected to occupy the whole available soil volume at this age. We speculated that the localized fertilization of the trees, which had led to the progressive enrichment of the soil close to the palms with nutrients, had discouraged lateral root development and thus contributed to an incomplete utilization of nutrients and water in the more distant soil.

Fig. 3 shows the root profiles at three distances from a palm tree. Only the primary and secondary roots were depicted, because many finer roots were lost when preparing the profiles. The roots were marked in different colours on a transparent polyethylene sheet covering the profiles. Their coordinates were then measured manually and entered into a graphics program. After drawing the roots, soil cores for the quantitative determination of fine root length density and root mass were collected from different depths from all three profiles (data not shown).

The profiles show well the architecture of the oil palm root system, which is characterized by a dense layer of horizontal primary roots at about 15 to 20 cm soil depth, from which secondary roots branch off vertically in both upward and downward direction. The primary root system is most pronounced in the profile at 1 m distance from the oil palm, where it locally forms an almost continuous root layer, but it can still be recognized in the profile at 4 m distance. The root density in the profiles decreases substantially with increasing distance from the tree, confirming the hypothesis that the more distant soil is insufficiently accessible for the palms because of a restricted lateral root development.

With respect to the use of oil palm in agroforestry systems, these results indicate that associated trees and crops growing at a distance of about 3 m or more from the palms would probably not suffer from severe root competition, although they would certainly be shaded by the palms. For the management of oil palm in monoculture plantations, on the other hand, the question arises if broadcast fertilizer application would not lead to a more extensive lateral root development of the palms and consequently a better use of nutrients and water in the soil between them.

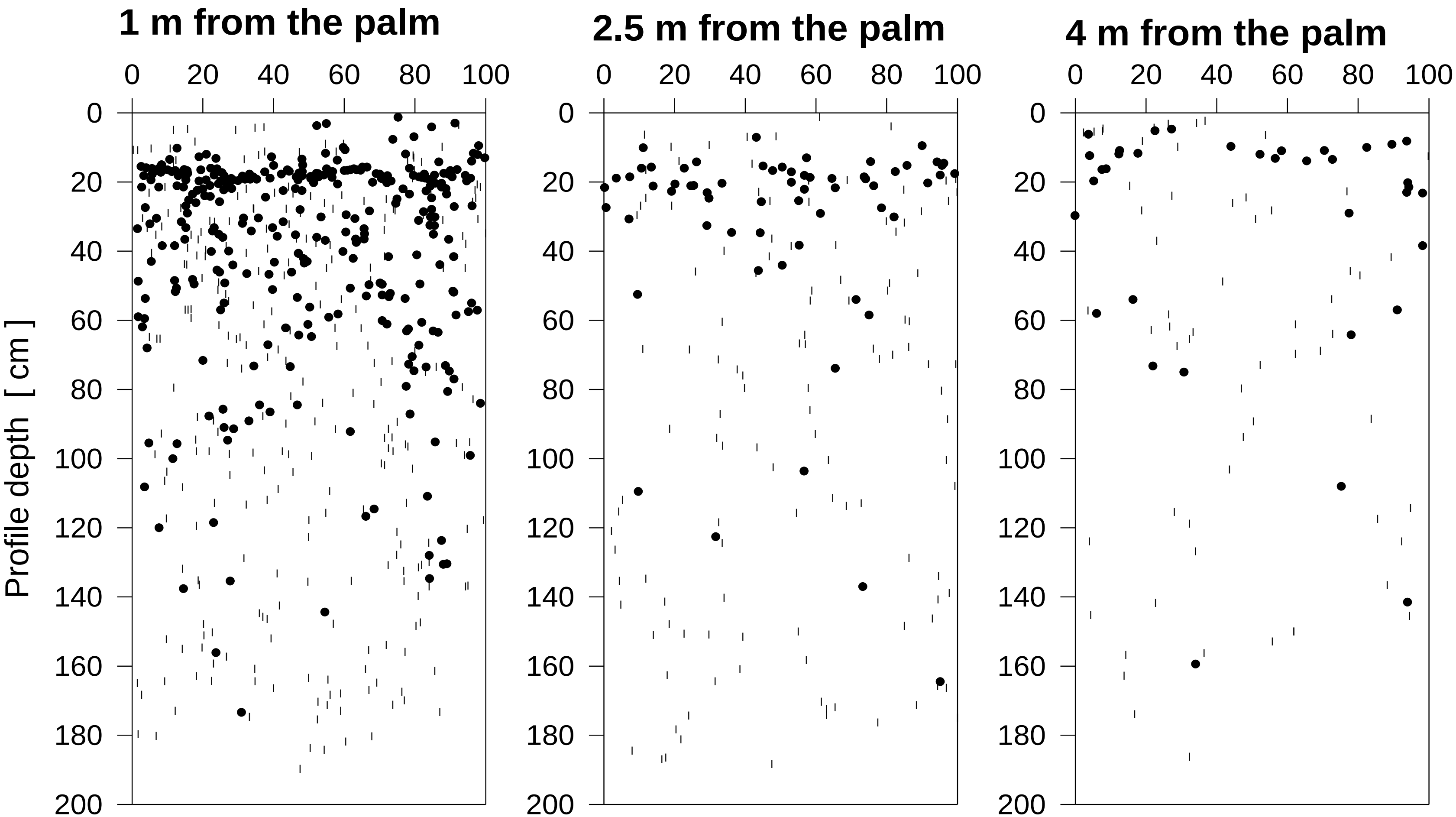

Figure 3: Root profiles of oil palm at three distances in central Amazonia as obtained by the profile wall method. The round spots indicate primary, horizontal roots, and the lines indicate secondary, vertical roots. Roots < 2 mm were not depicted.

Example 4: Interactions between different root systems by excavation and graphic representation

When interactions between the roots of associated species are the topic of a study, a more detailed and more complete graphic representation of the root systems than that obtained on profile walls may be required. In a series of experiments in the humid tropics of Costa Rica, we are studying the effect of grass roots on the root development of young timber trees, with the perspective of using barriers of competitive grasses for manipulating the root distribution of the trees (*e.g.*, development of deeper, laterally more restricted tree root systems) (Schaller et al., 1999). In one of these experiments, the different types of responses of roots of *Cordia alliodora* to the presence of grass roots were investigated by planting trees and grass strips at 30 cm distance from each other and excavating the tree root systems superficially at an age of 8 months. The distribution of the roots was recorded manually with the help of a line grid and was later reproduced in a graphics program.

Fig. 4 shows the drastic change of the root distribution of a young *Cordia alliodora* tree when grown in competition with the grass *Panicum maximum*. Such effects can explain the pronounced growth depressions of tree seedlings that are often caused by grasses and other weeds. From the excavation and graphic representation of a series of such root systems, different types of reactions of tree roots to the presence of competitive grass root systems could be identified, which ranged from slight changes in horizontal or vertical growth direction of tree roots which then passed through "weak points" in the grass barriers, to a complete reflection of the tree roots by the grasses.

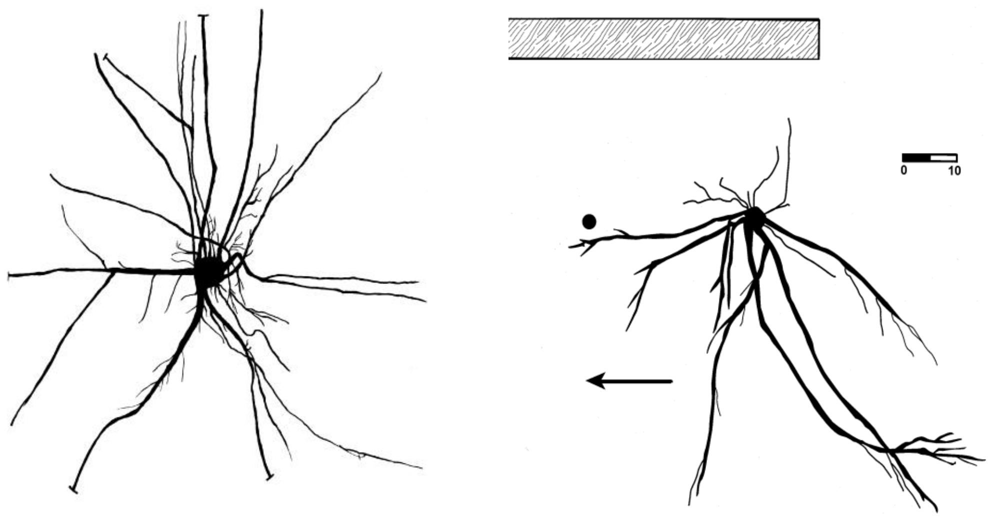

Figure 4: Root system of an 8 months old *Cordia alliodora* as influenced by a row of guinea grass (*Panicum maximum*) in Costa Rica. Left: control without grass row; right: with grass row, symbolized by the grey bar. The arrow shows the direction of the nearest tree neighbor. The small bar corresponds to 10 cm. From Schaller et al. (1999)

Conclusions

The four examples given above illustrate how variable the objectives of root research in humid tropical ecosystems can be, and that no single method would be adequate for all research questions. Root researchers have to be flexible in adapting their methodology to the objectives of their study, the site factors, and also the available means in terms of manpower and equipment. Qualitative and semi-quantitative information about root systems can often be produced in relatively little time and with simple means, *e.g.*, with the profile wall method. In other cases, however, major investments in time and money are required, especially when dynamic processes or detailed spatial patterns are under investigation. Possibly the most important factor deciding the success or failure of root studies is that the research question is clearly defined and an adequate methodology is selected accordingly. Root studies have contributed significantly to our understanding of the ecology of agroforestry and other humid tropical land use systems in the past, and they will certainly continue to do so in the future. For this, the traditional methods that were the topic of this article as well as more sophisticated, recent methodological developments, will be of use.

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