# Part II

## The Belowground Ecology

# 8 Belowground Interactions in Tree–Crop Agroforestry: Need for a New Approach

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## 8.1   INTRODUCTION

During the past 30 years, agroforestry has been developed and promoted as a means to combat rural poverty and increase food security while conserving the natural resource base in the tropics. Accordingly, most agroforestry research has focused on practices involving trees and staple food crops such as maize (*Zea mays*), rice (*Oryza sativa*), beans (*Phaseolus* spp., *Vigna* spp.), and cassava (*Manihot esculenta*). In a tropical climate, annual crop production faces certain difficulties, such as rapid soil organic matter loss on soil exposure and tillage with corresponding deterioration of the soil structure; nutrient leaching especially at the onset of the rainy season when crop root systems are still poorly developed; and a risk of soil erosion in mountainous areas. Agroforestry practices that specifically address these problems have been developed, including mulch-production systems, contour hedgerows, and improved fallow systems (Young, 1997). Correspondingly, the most influential concepts and theories in agroforestry research explicitly or implicitly address systems with annual crops. They include the synchrony hypothesis, according to which nutrient use is more efficient if nutrient sources are applied and managed so that temporal patterns of nutrient release and uptake coincide (Heal et al., 1997), and the safety-net hypothesis, which postulates deep-rooting trees that capture leached nutrients from the soil beneath shallow-rooted (annual) crops (van Noordwijk et al., 1996).

When studying associations of trees and annual crops, agroforestry researchers and practitioners soon noticed the crucial importance of belowground interactions. Especially in dry climates and on nutrient-poor and shallow soils, the presence of trees in crop fields implies strong trade-offs between beneficial effects of trees on soils and competition with crops for soil resources. Motivated by this insight, a considerable number of studies addressed the problem of root competition between trees and annual crops, focusing on the identification of incompetitive tree species (Schroth and Lehmann, 1995; Ong et al., 1999), effects of tillage, biomass application (Schroth et al., 1995), root pruning (Korwar and Radder, 1994), and shoot pruning (van Noordwijk and Purnomosidhi, 1995)

among other factors. Failure to identify satisfactory solutions to the soil improvement versus competition trade-off led to a certain shift in the focus of agroforestry research from tree–crop associations to improved fallow systems, where trees are grown in rotation with annual food crops, during the past 10 years (Sanchez, 1995).

While tropical farmers usually depend on annual crops for their subsistence, they often depend on tree crops for monetary income. Tree crops such as coffee (*Coffea* sp.), cocoa (*Theobroma cacao*), and rubber (*Hevea brasiliensis*) constitute the backbone of rural economies in large parts of the humid tropics. These crops are often grown by tropical smallholders together with other planted and spontaneous trees in highly diversified systems, which have recently drawn much research attention for their potential to provide environmental benefits such as biodiversity conservation, watershed protection, and maintenance of carbon stocks (Michon and de Foresta, 1999). However, attempts to conserve, promote, and intensify such diversified tree crop-based systems because of their desirable environmental and socioeconomic properties are facing a critical lack of knowledge of above- and especially belowground interactions within such systems. Researchers are confronted with questions such as: How will cocoa interact with shade trees in a drier climate? Can cloned rubber trees, if introduced into rubber agroforests, support the same level of competition from spontaneous forest regrowth as the traditional seedling rubber? Will fruit trees when introduced into extensively managed rubber or cocoa agroforests for their diversification, tolerate these conditions and be productive? How will the substitution of traditional legume shade trees by fast-growing timber trees impact on coffee production under different pedoclimatic situations (Beer et al., 1998)? There is presently only a small amount of information from research in tree crop agroforestry systems on which answers to such questions could be based (Schroth et al., 2001; Ong et al., 2003). It is therefore tempting to rely on the much broader knowledge base from agroforestry systems with annual crops when addressing such problems. But is it justified?

In this chapter, we review some aspects of the belowground ecology of agroforestry systems with tree crops. We start by pointing out the fundamental differences between agroforestry systems based on annual crops and those based on tree crops. We then introduce a classification of tree crop agroforestry depending on planned and spontaneous diversity and point out its relevance for the management of belowground interactions. Subsequently, we review root interactions in systems with fast-growing timber trees and introduce the concept of self-organization of interacting root systems. Finally, we present some recent results about the possibility to manipulate tree root distribution with biological means and show potential applications in tree crop agroforestry.

## 8.2   ANNUAL CROP AND TREE CROP AGROFORESTRY—TWO DIFFERENT STORIES

Since much more research has been carried out on the belowground ecology of agroforestry systems with annual crops than those with tree crops (van Noordwijk et al., 1996; Schroth, 1999), it is logical to ask whether insights gained in such research can be transferred from one type of system to the other. However, there are profound differences between these types of systems, which would have to be taken into account in such an approach (Table 8.1):

1. While temporal dynamics of the soil occupation by root systems are important in systems both with annual and with tree crops, they occur on different temporal scales and require different management interventions. Systems with annual crops are characterized by a pronounced *seasonal variability* of root development (Schroth and Zech, 1995a), hence the importance of synchronizing nutrient supply with demand. In tree crop-based systems, in contrast, this variability and thus the importance of synchrony are much lower and may even be negligible in climates with no pronounced seasonality (Schaller et al., 2003). Seasonal differences in root growth and activity may, however, also occur in tree crops as a consequence of weather and phenological rhythms and may provide opportunities for

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## TABLE 8.1

## Important Differences Between the Root Ecologies of Annual Crop (ac) and Tree Crop (tc) Based Land Use Systems

| Characteristic | Tree Crop-Based Practices | Annual Crop-Based Practices | Consequences for Belowground Interactions and Management |
|---|---|---|---|
| Temporal variability of soil occupation by roots | Over several years | Seasonal | Synchrony of resource availability and demand important for ac but less so for tc; successional sequence of crops with different growth rates important strategy for establishing tc |
| Spatial variability of soil occupation by roots | High | Low | Synlocation of resource availability and demand important in tc but less so in ac; intercropping important strategy for ensuring soil occupation during early tc development |
| Soil disturbance by tillage | No | Usually yes | Disturbance of root systems of weeds and other vegetation creates competition-free space for ac at the beginning of the cropping season; root systems of tc develop undisturbed over many years |
| Shade tolerance | Yes for some important species | No | Shade trees usually intimately mixed with tc such as coffee, cocoa, and tea so that root interactions are intensive; intimate mixtures of ac with trees usually unfavorable and spatially zoned or rotational designs more common |
| Nutrient and water uptake | Gradual, distributed over large part of the year and large soil volume | Temporally fast, spatially concentrated | Once established, tc probably less affected by root competition than ac; wide spacing necessary for tc if no access to deep water reserves during dry season |
| Rooting depth | Often deep | Often shallow | Tc often not dependent on other trees for deep nutrient uptake and less sensitive to competition in the topsoil than ac |

targeted fertilizer application if peaks of root activity of one species coincide with troughs of root activity of another species (Muñoz and Beer, 2001). In contrast to systems based on annual crops, tree crop-based agroforestry systems are characterized by a pronounced *successional dynamic* of soil occupation by root systems. This results from the progressive establishment of young tree crops over several years; these are therefore commonly associated initially with annual and short-living perennial crops to make use of the space and soil resources not yet exploited by tree roots (e.g., Budelman and Zander, 1990; Gouyon et al., 1993).

2. Whereas the short-term *temporal variability* of the soil occupation by root systems is much smaller in systems based on tree crops than in those based on annual crops, its *spatial variability* is much greater. Annual crops may colonize the whole topsoil with a dense network of roots within weeks or months of their germination, whereas tree crops may need several years for a more or less homogeneous occupation of the available soil volume, or may not reach this situation at all. For example, in a 15 year old oil palm (*Elaeis guineensis*) plantation in Amazonia, the palms, which were planted at 9 m by 9 m triangular spacing (143 trees ha$^{-1}$) as recommended for monocultures, had not developed sufficiently extensive root systems to prevent nitrate leaching halfway between neighboring palms, whereas the nitrate in the soil close to the palms was effectively taken up

(Schroth et al., 2000). This pronounced spatial variability of root activity makes *synlocation* of nutrient sources with zones of high root activity a much more important strategy in agroforestry systems with tree crops than it is in systems with annual crops (i.e., placement of mulch and fertilizer close to the trees). This spatial variability also stresses again the interest of associating crop species with different growth and production cycles during the establishment phase of tree crop systems to make optimum use of available soil resources, minimize nutrient losses, and generate early returns to investments (Schroth et al., 2001).

3. Regular soil disturbance through tillage is a characteristic of most annual cropping systems. In agroforestry systems, it temporally creates a competition-free space for the germinating crops in the topsoil by destroying tree roots. Although it is not known for how long this effect lasts, it certainly gives a temporary advantage to the crop roots (Schroth et al., 1995). In agroforestry systems with tree crops, soil disturbance is neither possible (because of the damage to the tree crop roots) nor desirable. Root interactions between system components therefore develop more under conditions of a dynamic equilibrium, which may, however, be periodically disturbed by the dieback of root systems induced by shoot pruning of certain trees (Nygren and Campos, 1995; Schroth and Zech, 1995b).

4. Annual crops are generally shade sensitive, and systems where annual crops are intimately associated with trees are therefore usually less desirable than systems characterized by a certain degree of spatial zoning, such as the planting of trees and crops in alternating strips, or even the temporal separation of trees and crops, as in fallow rotations. These designs also limit the intensity of belowground interactions. In contrast, in systems with shade-tolerant crops such as coffee, cocoa, and tea (*Camellia sinensis*), the creation of a certain degree of shade and a pest- and disease-suppressive, protected microclimate are often the very reasons for the presence of trees, which are therefore intimately intermingled with the crops (Beer et al., 1998; Guharay et al., 1999). Alternative designs such as box plots, where the trees are planted on the boundary of blocks of tree crop plants have, however, also been tested and may be an option under conditions where more intimate mixtures would lead to root competition during the dry season (Foster and Wood, 1963).

5. Nutrient uptake by annual crops occurs relatively rapidly during a short time interval, whereas that of tree crops is more evenly distributed over a longer interval and occurs from a larger soil volume. It is therefore likely that tree crops, once they are established, are less sensitive to root competition for nutrients and water than annual crops, although tree crop seedlings are usually very sensitive to competition. Tree crops which have no access to deep water sources may be sensitive to competition for water in the topsoil and require wide spacing to avoid drought stress during the dry season. Annual crops can then be interspersed with the tree crops during the rainy season to make use of surplus water (Daniel et al., 1996).

6. Although the root systems of annual crops often remain relatively shallow during the limited time available for their development, tree crops can have very deep root systems. For example, tea bushes in deep soils in East Africa may have roots to 5–6 m depth and may wilt later than associated shade trees, suggesting that the tea plants have access to deeper water resources than the trees (Willey, 1975). Similarly, arabica coffee can root more than 4.5 m deep (Webster and Wilson, 1980) and have a more homogeneous vertical root distribution in the top 40 cm of an Andisol in Costa Rica than *Eucalyptus deglupta* trees which are associated with them (Schaller et al., 2003). This suggests that tree crops may often not depend on trees for intercepting leached nutrients and recycling nutrients from the subsoil, and may also be less sensitive to competition from other species in the topsoil than annual crops.

In summary, the possibility of transferring research results on belowground interactions from agroforestry systems with annual crops to systems with tree crops is limited due to a number of fundamental differences between these system types. Furthermore, even the application of well-established principles and basic hypotheses from annual crop agroforestry, such as the synchrony and safety-net hypotheses, have only restricted applicability in tree crop-based agroforestry systems.

## 8.3   BELOWGROUND INTERACTIONS IN DIFFERENT TYPES OF TREE CROP AGROFORESTRY

There are many different types of agroforestry systems with tree crops. Some are very simple systems, consisting of one tree crop species such as coffee and one shade tree species, whereas others may contain a variety of planted tree crops and spontaneously grown trees. In addition, the intensity of management, including weeding and fertilization, differs widely between different tree crop-based systems. Species composition and management are likely to be important factors determining belowground interactions in a system and how they are perceived and managed by farmers.

1. *Shaded tree crop systems* usually consist of only one shade-tolerant tree crop species, such as coffee, cocoa, or tea, which dominates the system economically and forms most of its understory (Beer et al., 1998). The diversity of the shade canopy may vary from very low, in the case of a single planted-tree species, to high, if the canopy is formed by trees retained from the previous forest canopy, a traditional practice in cocoa systems in West Africa and Brazil (de Rouw, 1987; Johns, 1999). The shade canopy may contain economically valuable tree species, which may be either planted or spontaneous. As the understory tree crops are the economic backbone of the system, the other species are selected, thinned, pruned, and otherwise managed to their benefit. This is most obvious for leguminous service trees with little or no economic value, such as *Erythrina* spp. and *Inga* spp., which are widely used as coffee and cocoa shade in Latin America, but can also be observed with timber trees. A farm survey in San Isidro, Costa Rica, showed that, despite a poorly developed market and low value of its wood, farmers preferred *E. deglupta* as shade tree compared to other timber trees because of its fast growth (and thus shade establishment), the light shade cast by the small leaves which is considered ideal for coffee, and the reduced pruning requirements compared with the traditional leguminous shade tree species (Tavares et al., 1999). The shade cast by other timber species such as *Terminalia* spp. and *Gmelina arborea* was considered by farmers as too dense for coffee. This suggests that the selection of timber tree species as coffee shade by the farmers was more influenced by considerations related to the production of coffee than to the production of timber. To which extent belowground interactions are taken into consideration in the selection of shade tree species by farmers is less clear but they are most likely to influence farmers' decisions on whether and which shade trees to retain in dry regions (Jiménez and Alfaro, 1999; see below). Although farmers will generally tend to design and manage their shade canopy in a way considered most beneficial for the understory tree crop, certain very valuable shade species may be tolerated in a plantation even if they are severe competitors with the understory crop, as is the case with oil palm as cocoa shade in West Africa (de Rouw, 1987). This situation leads over to the following type of tree crop agroforestry system.

2. *Homegardens* are composed of a number of valuable tree species of different size and growth form (Fernandes and Nair, 1986; Torquebiau, 1992). The different species are arranged according to their respective needs within a mosaic of niches which they both create and to which they respond. As these are intensively managed systems, it is likely

that aboveground interactions between species are closely observed and managed if required, for example, through pruning of branches if shading becomes too intensive, although this is not well documented. Almost nothing is known about the perception and management of belowground interactions in such systems. The age of a system at which belowground interactions between neighboring tree crop plants start depends on their initial spacing and lateral root development. With increasing age, root interactions should become more intensive and may complicate the management of a system. Kummerow and Ribeiro (1982) found that in a mixed plantation of cocoa and rubber in Bahia, Brazil, the fine root mass of rubber in the top 15 cm of soil directly under the cocoa trees was twice as high as that of cocoa, and suggested that this strong intermingling of root systems made targeted fertilizer application to the cocoa trees difficult. If negative belowground interactions occur and are perceived as such in homegardens, their mitigation is much more complicated than in shaded tree crop systems, because instead of manipulating or even removing all other species at the benefit of a single, economically dominant tree crop, the requirements of several species have to be balanced against each other, taking their respective present and future economic value into account. Although we have virtually no information about root interactions and their management in homegardens, it is likely that the application of manure, household refuse, and other nutrient sources plays an important role in the mitigation of nutrient competition between species.

3. *Agroforests* are composed of a single or several planted tree crop species and a large amount of spontaneous forest regrowth, which is a consequence of extensive management. Agroforests are essentially economically enriched secondary forests (Michon and de Foresta, 1999). To which degree they are ecologically impoverished compared with spontaneous secondary forests is not well known and is likely to depend on the specific site and management history. In Indonesian rubber agroforests, rubber trees may reach a sufficient size for tapping with a delay of several years compared to clean-weeded plantations (Gouyon et al., 1993), suggesting competition between young rubber trees and forest regrowth. Similar practices exist in the Amazon (Schroth et al., 2003). Similarly, tree crops such as cupuaçu (*Theobroma grandiflorum*) may start to produce fruit with a delay of several years if they are planted into an annual crop but are then not further weeded after the annual crop has been harvested until the trees start flowering, which is a common practice in the Amazon (Sousa et al., 1999). In these cases, negative interactions between tree crops and forest regrowth are tolerated because, within the planning horizon of the farmer, the effort for reducing them by more intensive weeding is not justified by the expected gain from earlier maturing of the tree crops. Also, tree shade may reduce the growth of more noxious species such as *Imperata* grass (Williams et al., 2001). Agroforests have obviously developed under conditions where agricultural activities were more limited by the availability of labor than by that of land, and this has important consequences for the conservation of these relatively diverse systems under conditions of increased population pressure.

These brief accounts testify for the wide range of conditions under which tree crops are grown in tropical agroforestry systems. These influence the intensity with which interactions between system components are managed and the options which exist for their management. These options range from intensive management of the whole system at the benefit of a single, economically dominant species, through the balancing of requirements and tolerances of different valuable species, to a partial or sometimes even total tolerance of (negative) interactions under socioeconomic conditions that favor extensive management.

## 8.4   ROOT INTERACTIONS BETWEEN TREES: COMPETITION AND SELF-ORGANIZATION

As mentioned before, root interactions between trees and tree crops within a mixed plantation should become more intensive, but also more diffuse as trees and their root systems become larger and the youngest roots grow further away from the individual plants (Schroth, 1999). It is not possible to make efficient use of a piece of crop land without permitting a certain amount of root interaction (and competition) between the plants. However, besides being unavoidable, root competition is not a purely negative phenomenon in mixed species plantations but also has important regulatory functions with respect to the spatial and temporal exploration of the soil volume by the root systems (Schroth et al., 2001). If root systems compete with each other in the topsoil, they may grow deeper and make better use of subsoil water and nutrient resources, thereby also acquiring greater resistance to drought (Eastham et al., 1990). Where deep- and shallow-rooted plants are associated with each other, the shallow-rooted species may only profit from nutrients recycled by the deep-rooted ones if they compete effectively with them in the topsoil for nutrients released from litter, whereas this competition may be the very incentive for the other species to form deep roots (Schroth et al., 2001). In other words, nutrient uptake from the subsoil by deep-rooted trees may actually only occur and be beneficial for associated shallow-rooted crops if there is root competition in the topsoil. Similarly, nitrogen-fixing tree species may only continue fixing nitrogen over many years if the nitrogen released by them is effectively removed by nonfixing species and does not accumulate in the soil. Interactions between plant species could also accentuate differences in phenology, including temporal dynamics of root growth and activity, thus extending phases of high water and nutrient uptake over a longer time period and making more efficient use of water and nutrients in the soil (Schroth et al., 2001).

The regulatory effect of competition on the spatial exploration of the soil by root systems in mixed plantations is well illustrated by a coffee plantation shaded by *E. deglupta* trees in a farmer's field in Costa Rica, which was studied by Schaller et al. (2003) to find out what allowed such a fast-growing and competitive tree species to be associated with coffee apparently without negative effects on coffee yields. Despite the high planting density of the coffee (5000 plants ha$^{-1}$), the soil was not homogeneously occupied by the coffee roots, which were mostly concentrated in the proximity of the coffee rows, whereas the tree roots spread preferentially in the interrow spaces (Figure 8.1). Through this small-scale partitioning of the soil, which was obviously the result of root interactions, spatial overlap between the root systems was reduced. Interestingly, the total root length density was very similar in all positions (2.5–2.7 cm cm$^{-3}$), suggesting that in a self-organizing process, without any specific management intervention, root interactions between the two species had led to a homogeneous exploration of the soil by the combined root systems. Together with the high nutrient and water availability in the soil at this site, the spatial division of the soil space enforced by the relatively competitive coffee roots was seen as explanation for the successful use of very fast-growing shade trees in coffee in Costa Rica, and possibly other tropical regions such as Indonesia where coffee is shaded by the very fast-growing *Paraserianthes falcataria* (Schaller et al., 2003). The observed rooting patterns also provided a scientific justification for the farmers' practice to apply fertilizer for the coffee along the coffee rows and not broadcast between the rows, which had previously seemed questionable because of the close spacing of the coffee bushes.

Such self-organizing processes make it difficult if not impossible to predict rooting patterns in mixed-species associations from the known patterns of the individual species grown in isolation. They are not restricted to interactions between different tree species, but also occur if root systems of individuals of the same species interact. Such reactions result in reduced root overlap and increased exploration of soil parcels where rooting densities are still low, including in the subsoil (Atkinson et al., 1976; Eastham and Rose, 1990). They should increase the efficiency with which available soil
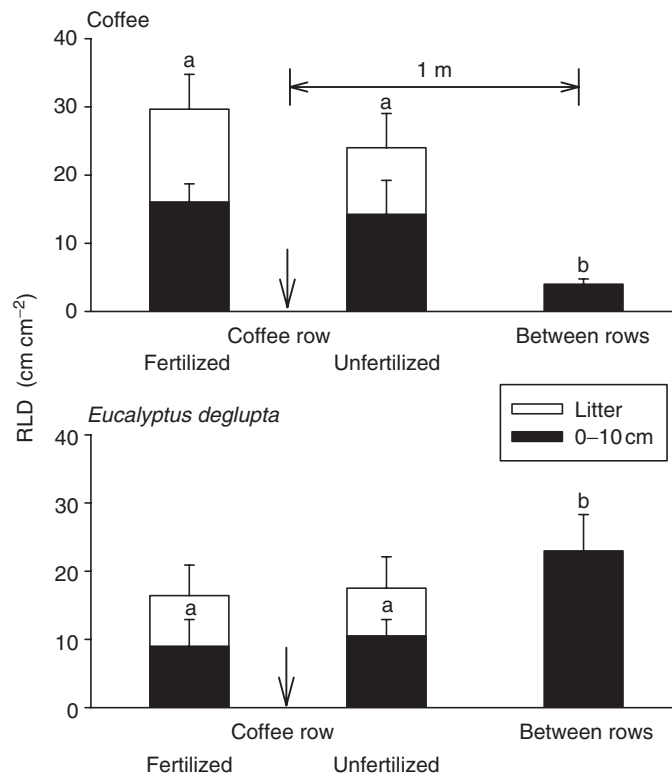
**FIGURE 8.1** Fine root length density (RLD; cm cm$^{-2}$ ground area; d $<$ 2 mm) of coffee (*Coffea arabica*) and *Eucalyptus deglupta* shade trees at different positions between rows of coffee spaced 2 m at Juan Viñas, Costa Rica (means and standard errors). Different letters indicate significant differences at $p < 0.05$. (From Schaller, M., G. Schroth, J. Beer and F. Jiménez., *For. Ecol. Manage.*, 175, 205, 2003. With permission from Elsevier.)

resources are used, reduce nutrient losses by leaching, and delay the occurrence of growth and yield losses caused by competition.

However, competition will occur if the combined requirements for water and nutrients of associated plants exceed the amounts available in the soil for prolonged periods of time. In the central valley of Costa Rica, where the dry season is longer than at the study site of Schaller et al. (2003), Jiménez and Alfaro (1999) measured lower soil water contents and observed symptoms of drought stress of coffee shaded by *E. deglupta* in comparison to unshaded coffee and coffee shaded by the traditional *Erythrina poeppigiana* trees, suggesting that the aforementioned processes of complementary exploration of the soil were no longer sufficient to protect the coffee plants from tree root competition and that other, less fast-growing and competitive, shade species were needed.

## 8.5 MANIPULATING TREE ROOT DISTRIBUTION BY BIOLOGICAL ROOT PRUNING

On sites with a pronounced dry season or infertile soils, or where very fast-growing and competitive tree species are used in association with tree crops, it may be advantageous to design systems in a way that root interactions between trees and crops are reduced. As discussed above, the options for this are fewer in systems with tree crops than in systems with annual crops, because the tree shade is often considered necessary for the tree crops and disturbance of the tree root systems through tillage is not an option. Root systems of trees may respond to the presence of competing root systems of

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herbaceous plants with reduced lateral and increased vertical extension, as shown in a classic study by Yocum (1937) for apple trees (*Malus domestica*) associated with maize (see also Schroth, 1999). Grass strips planted on the contour are a recommended soil conservation measure in sloping areas, such as those widely used for coffee plantations in Central America. Schaller (2001) hypothesized that these strips could simultaneously be used for manipulating the lateral root spread of timber tree species planted in rows on the contour, instead of evenly distributed in a plantation, and bordered on both the upper and lower sides by strips of grasses. In a screening experiment, strips of five different grass species were planted on one side along rows of *Cordia alliodora* seedlings to identify the most promising species for subsequent field experimentation. At the age of 8 months, when the trees in the control treatment without grasses were 2.6 m high, all five grass species had caused pronounced deformations of the tree root systems, with the most pronounced reactions caused by guinea grass (*Panicum maximum*), brachiaria (*Brachiaria brizantha*), and sugar cane (*Saccharum officinarum*), and less pronounced reactions by vetiver (*Vetiveria zizanioides*) and citronella grass (*Cymbopogon nardus*, Figure 8.2). Tree roots growing in the direction of the grasses either remained much shorter and thinner than those growing in the opposite direction or they changed direction before reaching the grasses. Such abrupt changes in growth direction were rarely observed in the absence of grass strips. The avoidance reaction of the tree roots to the grass root systems resulted in their effective exclusion from the soil beyond the grass strips, suggesting an effect of ''biological root pruning.'' Such effects were only rarely observed when seedlings of *E. deglupta* were exposed to the effect of the same grasses, presumably because of the faster growth and ability of their superficial roots to respond opportunistically to weak points within the grass barriers (Schaller, 2001).
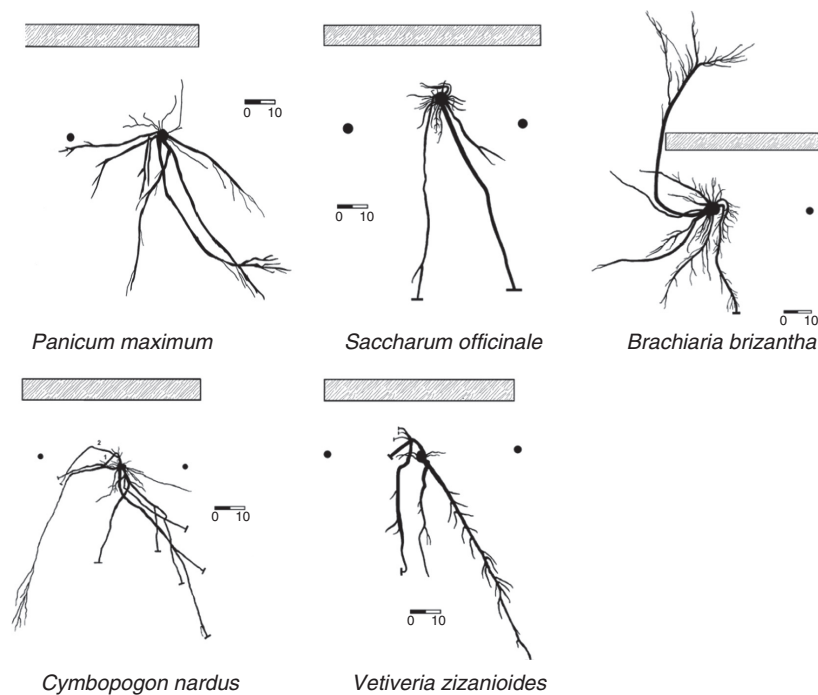


**FIGURE 8.2** Root system of 8 month old *Cordia alliodora* saplings as influenced by strips of different grass species, planted at 30 cm from the trees, in Turrialba, Costa Rica. Arrows indicate the direction of the tree line in the case of border trees. (Modified from Schaller, M., *Quantification and Management of Root Interactions Between Fast-Growing Timber Tree Species and Coffee in Plantations in Central America*. Doctoral Thesis, University of Bayreuth, Bayreuth, 2001. With permission from Island Press.)

While these results show a surprisingly strong effect of grass strips on *Co. alliodora* seedlings, indicating a potential to manipulate the root distribution of trees at an early development stage with relatively simple means, they also make clear that no generalization for other tree species is allowed. Furthermore, it is not yet clear to what extent the ''pruning'' of the seedling root systems translates into an altered root architecture of older trees, what the consequences for root interactions within a system would be, and whether the costs incurred by planting the grass strips, including competitive effects on trees and neighboring crop rows, are outweighed by benefits arising from soil conservation and reduced root interactions between trees and crops.

## 8.6 CONCLUSIONS

Much less is known about belowground interactions in agroforestry systems based on tree crops than in systems based on annual crops. Because of the numerous fundamental differences between these types of agroforestry systems, it is difficult to apply research results obtained in one system type to the other system type. Rather, a whole new set of concepts may be necessary for a deeper analysis of belowground processes of agroforestry systems involving tree crops. Based on a differentiation of tree crop agroforestry systems according to the relative importance of planned and spontaneous plant diversity, which has implications for the perception and management of above- and belowground interactions between system components, we propose the concept of self-organization of belowground interactions and offer an approach to the manipulation of tree root distribution and root interactions with simple, biological means. We see these in no way as definite results, but rather propose them as guides and inspirations for further research.

## ACKNOWLEDGMENTS

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[AQ1]  The reference "Lim (1980)" is listed but not cited. Please add in-text citation or delete from the list.

[AQ2]  Please check the edits to the page range in the reference "Nygren and Campos (1995)."