17 Managing Below-ground Interactions in Agroecosystems

Meka R. Rao, Goetz Schroth, Sandy E. Williams, Sara Namirembe, Michaela Schaller and Julia Wilson

Key questions:

1. Can plant species with complementary root characteristics be used to optimize the exploitation of below-ground resources and limit competition?
2. Under what conditions will farmers invest labour and resources in the management of below-ground interactions?
3. What practical options are available for manipulating below-ground interactions in agroforestry systems?

17.1 Introduction

Below-ground interactions (BGI) among component species in mixed agroecosystems encompass the temporal and spatial exploitation of growth resources (water and nutrients), soilborne pests and diseases, and modification of the rhizosphere environment. Interactions can be either direct or indirect, depending largely on whether the system is simultaneous or rotational. Previous chapters of this book (Chapters 1 and 4) have provided clear evidence of the importance of BGI for the functioning of agroforestry and other land-use systems. Of the different BGI, interactions involving growth resources are by far the most important, as they have the greatest effect on productivity (which is where farmers' primary interests lie). Whereas competition for water is the dominant interaction in semiarid environments and during dry seasons or dry spells in humid climates, competition for nutrients is important in many soils across a wide range of environments. Mixed or simultaneous systems in which two or more species are grown together on the same piece of land are most common in the tropics, and traditional agroforestry systems often involve many species. The BGI in such systems are much more complex than in mixed annual systems due to the combination of perennial and short-lived crops, which are of very different sizes, and which occupy overlapping niches below ground. The interactions among these components change over both time and space as trees grow larger and crops are planted, harvested and replanted. A certain degree of competition is inevitable among species in mixed systems when sharing the often fixed and limited below-ground resources (BGR).

To some extent, BGI can be manipulated through choice of plant species, and through soil and plant management. Such manipulation aims to minimize the negative of BGI whilst maximizing their positive effects. For this, a thorough understanding of what happens at the interfaces of the component species is necessary. Unlike above-ground interactions, BGI are difficult to manipulate as they take place unobserved and interventions can be laborious and expensive. Recently available models incorporate soil–plant processes and provide powerful tools for understanding and predicting cause–effect relationships in simple tree–crop agroforestry but not in traditional complex systems. Because of the importance of mixed systems for tropical farmers (in terms of greater yields, the minimization of risks associated with climatic variability and pests and diseases, and better protection of the environment compared with monocrops) ways and means have to be found for improving the productivity of both the traditional and new systems. Although the importance of BGI in agroforestry associations has long been recognized, progress in our understanding of them has been hampered by methodological difficulties. Nevertheless, considerable information is now available from the empirical research of the past decade which can help both with our understanding of BGI and with the development of practical tools for their management. In this chapter we discuss the scope and limitations of different practices for managing BGI in agroforestry land-use systems. Although we confine this discussion to the practices relevant at the plot or field scale, readers are referred to Chapter 18 for those appropriate at the landscape scale.

17.2 When and Where are BGI Important?

Use of below-ground resources can be optimized, and BGI minimized, through the combination of species that exploit different niches. Most annual crops do not efficiently utilize below-ground resources, because of their shallow root systems and short growth season. This is particularly so in fertile soils under irrigation or high rainfall, and in areas where acidic or compacted subsoils limit rooting depth. Similarly, perennial crops grown on their own do not fully exploit the inter-row spaces during the early years, because of slow growth and wide spacing. In these situations, total root activity over depth and/or space and time may be increased by: (i) integrating deeper rooting trees of economic value into plots of annual crops to exploit resources at depth and over a longer period of time; and (ii) adding herbaceous cover crops or intercrops between rows of perennial crops for greater exploitation of below-ground resources that otherwise remain unused or are lost to the system (e.g. through leaching or erosion). Some examples of the introduction of trees to annual crops are: planting of trees in rice fields in South India and Bangladesh, poplars in wheat in northern India and *Grevillea robusta* and *Markhamia lutea* in East Africa. In the case of sole systems of perennial tree crops, such as oil palm (*Elaeis guineensis*) and rubber (*Hevea brasiliensis*), patchy occupation of the soil space by the tree root systems and nutrient leaching in the inter-tree spaces may still occur in mature plantations under certain conditions, indicating that associations with shade-tolerant understorey species (intercrops and cover crops) could increase the efficiency of water and nutrient use within the system and increase per-area yields (Schroth *et al.*, 2000a). The exploitation of resources by the perennial component in agroforestry systems can be further enhanced by associating several species of varying growth cycles, so that some species produce early and are then thinned out as others grow and occupy more soil volume.

It is important to consider the conditions under which farmers may, or may not, take below-ground processes into account when designing and managing their land-use systems. Four types of situations may be distinguished, which depend on the abundance of soil resources, the value of the crop (and the relative value of different components), labour availability, and the objectives of the land-use system.

1. One situation in which farmers apparently ignore BGI is when soil resources are abundant, i.e. under conditions of high rainfall and soil fertility or the application of sufficient fertilizers. For example, on sites with sufficient water and with adequate fertilization in Costa Rica, coffee growers preferred to use the very fast growing *Eucalyptus deglupta* as a shade tree for coffee, because of its light and homogeneous shade and low pruning requirements (Tavares *et al.*, 1999). Recent research has confirmed that below-ground competition is in fact no problem under these conditions (Schaller *et al.*, 2003). Similarly, coffee growers in eastern Java, where soils are fertile and rainfall is sufficient, prefer to use the very fast-growing *Paraserianthes falcataria*, planted at a high density, as a shade tree for coffee rather than the slower-growing *Pinus merkusii*.

2. In other cases farmers may deliberately choose to ignore negative BGI even if they are biophysically relevant, because of socioeconomic considerations. Then, the decision whether to invest in manipulating BGI depends on the opportunity costs of the labour necessary for the purpose and the present or future value of the affected crop. An example is the Sumatran 'jungle rubber' system, where rubber planters allow the secondary vegetation to regrow between young rubber trees that have not yet reached the size required for tapping, instead of weeding the trees and establishing a leguminous cover crop as is the recommended practice. Delayed weeding in the early stages can actually protect the rubber seedlings from damage by wild animals, so reducing risk. Of course, tree development is reduced by the competition from the secondary vegetation, so that the planters have to wait 10 years until the first tapping as compared with 5 years in an 'optimally' managed system. Similarly, central Amazonian farmers often abandon their young tree-crop plantations after an initial phase of 1–2 years of intercropping with annual crops. The management of the plantation recommences only when the trees enter the productive phase, which is of course also considerably delayed by such 'poor' early management (Sousa *et al.*, 1999). Still, the decision not to manage competition processes may be rational as long as farmers are more constrained by labour than by the availability of land, and if farmers plant trees as part of a strategy to acquire land, as is the case in Indonesia.

3. In rotational systems, and for the rehabilitation of problem sites, maximization of tree root functions can be the objective of management. For the amelioration of compacted, waterlogged or saline soils, the suppression of weeds and the recycling of subsoil nutrients during fallow phases, farmers may use trees with large and competitive root systems at a high planting density and may not be concerned about interactions with crops (Schroth *et al.*, 1996; Mekonnen *et al.*, 1997).

4. The management of BGI is most needed and most complex where trees and crops are grown in close association, with the objective of producing multiple products, but where soil resources are limiting, at least during some part of the year. Examples are windbreaks or shade trees in seasonally dry climates, and combinations of trees and crops in the semiarid tropics and on infertile soils. The objective of maximizing the exploitation of soil resources whilst minimizing below-ground competition has to be achieved through complementarity of the associated species in terms of root distribution, phenology and function (e.g. use of different nutrient pools). Such complementarity can be achieved through the selection of species combinations, in conjunction with the management of the component species and the soils. Under these conditions, farmers may invest considerable amounts of time and resources in the management of BGI (e.g. through weeding, shoot and root pruning). The discussion in the following section mainly concentrates on this situation, in which optimization of the use of below-ground resources is the objective. It is assumed that farmers are mainly constrained by land availability and that their primary objective is to increase yields of crops and trees per unit area. This situation is representative of increasingly large areas in the tropics.

17.3 Scope and Options for Managing Below-ground Processes

In the surface soil horizon, water availability can fluctuate widely and nutrient availability may be high, nutrients being supplied through leaf litter, mulching or inorganic fertilizers. Plants tend to preferentially exploit these surface layers and shift to deeper ones when the surface resources become limiting. In simultaneous systems with mixtures of perennials and short-lived crops, perennials occupy both surface and deeper layers, whilst annuals often occupy only the former. Therefore, if short-lived crops are not to be outcompeted, plant and soil management that enhances the nutrient and water resources for annual crop roots in the surface horizon, and selection that encourages niche differentiation between species – particularly selection for deep rooting in trees – is desirable. In the horizontal dimension, management that restricts competitive tree roots to areas close to the tree is often preferred. Management should also aim at staggering root occupancy and activity in strategic locations for resource acquisition in the soil profile. Other agroforestry systems require different approaches to tree root architecture. For example, trees with extensive root development in terms of both vertical and lateral spread are preferable for sequential systems as they enhance nutrient capture and transfer to subsequent crops via organic pools. Trees with high root mass tend to suppress understorey weeds, which is an important function of planted tree fallows but is not desirable on sloping lands where soil protection is an issue (Schroth *et al.*, 1996). As another example, trees with high fine-root density at shallower depths are suitable for conservation hedges and filter strips.

The functions of tree roots and their interactions with the soil and the roots of associated plants can be influenced through the selection of species, their arrangement in time and space (system design), and the management of the plant–soil system through practices such as weeding, fertilizing, tillage and pruning (Table 17.1). Given the large differences in root characteristics between plant species, species selection is an important way of influencing below-ground processes, although root properties will normally only be one of several criteria used when selecting tree species and will rarely influence the decision about crop species. System design determines the coarse patterns of below-ground processes at the establishment stage of the system, whereas management can be used for fine-tuning them on a more continuous basis as the system matures. Some of the management techniques routinely applied by farmers (e.g. weeding and soil tillage) have a direct influence on roots, whereas others (e.g. shoot pruning) have indirect effects. Importantly, the more successful these measures are in manipulating below-ground processes, the more flexibility there is for choosing tree species with less-than-optimal root properties, including fast-growing, competitive species.

17.3.1 Choice of species/provenances

Species and provenance selection is a suitable way of manipulating BGI in cases where neither yield nor product quality is sacrificed. However, uncompetitive species are often also slow growing, and selecting these for use may defeat the objective of maintaining the productivity of the system. The use of species that demand less soil resources and/or are slow growing is especially important for water- and nutrient-limited sites. In the West African Sahel savannah, a wide array of useful tree species can be used in windbreaks at sites where ground water is accessible and competition with crops for soil water therefore unlikely (Smith *et al.*, 1998). By contrast, at sites where the water table is not within the reach of tree roots, the selection of trees with low water requirements and a limited lateral root spread is crucial in order to avoid competition with crops; furthermore, management measures to reduce the water consumption of the trees, such as pruning, may be required.

Table 17.1. Practices for managing below-ground competition in multispecies systems in different situations and the practicality of these practices.

Management method		Aim/effect	Where and when	Practicality
Selection of species or provenances		To maximize complementary use of BGR temporally and spatially	Anywhere, at the establishment stage and when functional niches are available	Feasible, if rooting patterns of species are known and the species possess desirable above-ground characteristics, in order to meet farmers' needs
Spacing/ design	Boundary plantings	To confine negative effects of BGI to a small area	In drier climates where tree/crop competition for BGR is high	Feasible, but other management practices need to be integrated within the system
	Scattered trees or tree clusters	To localize BGI	Relevant for croplands and pastures in all climates but especially in dry areas	Feasible
	Row (tree or hedge) intercropping	To maximize positive effects of BGI	In favourable soil and climatic conditions	Feasible
	Wider spacing of tree rows	To reduce BGI and force deeper rooting of tree roots	Appropriate for drier areas	Feasible
	Thinning of trees over time	To reduce negative effects of BGI	Where the negative effects of trees at a given density increase, and trees gain in value over the years	Feasible
	Segregation over space	To avoid BGI	Where tree/crop competition for BGR is intense and trees have to be planted at a high density. Trees and crops planted in separate blocks mostly in semiarid tropics (e.g. woodlots and crops)	Feasible. Below-ground competition still exists at the interface of tree and crop blocks
	Segregation over time	To maximize positive effects of tree–soil interactions	For reclamation of compacted soils, saline and alkali soils, nutrient replenishment and lowering the water table. Trees rotated with crops in all climates	Feasible, if land and labour (especially at the tree establishment and clearing stages) are not limited
Root pruning	Trenching	To prevent the presence of tree roots in the CRZ	Along tree lines in boundary plantings and around individual trees in croplands	Unfeasible if constrained by labour. May be relevant if combined with other interventions (e.g. fertilizer placement)

Continued

Table 17.1. *Continued.*

Management method		Aim/effect	Where and when	Practicality
Root pruning *(continued)*	Tillage	To reduce superficial tree roots at 0–15 cm depth	Applied to whole plot at the start of the crop season	Feasible. Depth of root pruning depends on degree of mechanization
	Severing of superficial structural roots	To prevent lateral extension of tree roots into CRZ, to avoid conflict with neighbours, and to train roots of young trees	Boundary plantings and individual trees, preferably executed in the dry season to older and younger trees depending on severity of competition	Feasible but constrained by labour and is relevant for only high-value crops
Shoot pruning	Pruning side branches; pollarding; lopping branches; pruning to low height	To reduce demand on BGR and root growth	Applicable in all climates depending on the system. Hedges are repeatedly pruned within a year. Shade trees in coffee are pruned at the beginning of dry season and trees in cropland are pruned before rains set in	Feasible. Primary purpose of these practices is to reduce shading of crops by trees but they simultaneously affect tree root growth
Mulching		To increase plant-available water by increasing water infiltration into soil and reducing soil evaporation To control weeds	Mulches are relevant for water conservation in dry areas and for controlling weeds in wet and dry areas	Feasible where enough organic materials are available. Certain mulches may increase termite activity
Nutrient supply through fertilizers or organics (quantity and method)	Broadcast Localized placement (~ 5 cm depth)	To decrease below-ground competition for limiting nutrients	Whenever nutrients are limiting. Localization when nutrients are for valuable species and in the case of less mobile nutrients	Feasible. However, smallholders may be constrained by lack of cash and labour. Organic residues are available in limited quantities
Barriers	Physical Chemical Biological	To reduce BGI by preventing the intermingling of tree and crop roots	Installed between tree and crop rows and at the junction of tree and crop blocks, before or together with planting of trees	Physical and chemical barriers involve prohibitive costs. Grass strips are easy to establish but may only have a temporary effect
Weed management	Manual Mechanical Chemical Biological (cover crops)	To reduce below-ground competition for water and nutrients from weeds. Cover crops also add N to soil and protect soil	Executed as part of land preparation and whenever weed competition exceeds economic thresholds	Feasible. Constraints are timely availability of labour, cover crop seed and cash for herbicides

BGI, below-ground interactions; BGR, below-ground resources; CRZ, crop root zone.

Farmers can substitute one tree species for another based on tree root competitiveness, if the trees are grown for low-value products such as green manure, firewood, soil conservation, etc. However, if a tree species is grown for specific, valuable products (such as fruits, nuts, resins or timber) the choice has to be made from among provenances of the particular species. Considerable variability exists among tree species in root system architecture, but the extent of variability among provenances of a species is not known for many agroforestry trees. Selection must not be based solely on root architecture, as root function is also important, and the basis of comparison between species or provenances must be clear (for instance, comparing trees of the same age or size). Lack of a simple and reliable method to evaluate species or provenances for differences in root morphology and function is a major constraint. Recently, the use of competition indices has been explored as a short-cut method for evaluating the competitiveness of the root architecture of different species, with mixed results (Ong *et al.*, 1999; Mulatya, 2000). Substantial differences among provenances in terms of above-ground growth are often reported (e.g. for *Gliricidia sepium*) (Dundson and Simons, 1996), which may be indicative of differences in root system growth and architecture, but there is little evidence available to support this proposition. However, significant differences were observed in the rooting characteristics of *Faidherbia albida* from different seed sources: at Niamey (Niger), material originating from East and southern Africa performed poorly, compared with that from West Africa, due to poor root system development (Vandenbeldt, 1991). The type of planting stock is also important. In Kenya, *Melia volkensii* plants raised from cuttings were more shallow-rooted than those raised from seed of the same provenance (Mulatya *et al.*, 2002).

Contrary to the general belief, most trees have a substantial proportion of their fine roots confined to the same soil horizon as crops (see Chapter 4, this volume), which inevitably leads to competition for below-ground growth resources between trees and adjacent crops. Distribution of the fine root mass of 2-year-old *Senna siamea*, *Eucalyptus tereticornis*, *Prosopis chilensis* and *Leucaena leucocephala* trees was similar to that of maize in the 0–100 cm profile. Only *Eucalyptus camaldulensis* had its roots evenly distributed up to 100 cm (Jonsson *et al.*, 1988). Similarly, roots of 3-year-old *Grevillea robusta* and *G. sepium* possessed a very similar distribution to those of maize in the 0–120 cm profile (Odhiambo *et al.*, 1999), although these trees also possessed roots that penetrated more deeply. As trees age, their root densities increase and their roots spread over ever-increasing distances. Tree root densities often exceed crop root densities and, concomitantly, competition with crops increases. Although the absorption centres of tree roots may tend to become increasingly distant from the tree trunk with increasing tree age (Morales and Beer, 1998), tree–crop competition is often characterized by diminished crop yield close to the tree, correlated with high tree root length densities and reduced soil water (Odhiambo *et al.*, 1999, 2001).

Notwithstanding these features of root distribution, zones of high or low root density are not necessarily indicative of levels of root activity. Tree roots at different depths can adjust their function according to water availability. In the dry season, water uptake by *G. robusta* at a semiarid site in Kenya was predominantly through deep tap roots; but, after rewetting of the topsoil layers with the start of the rains, existing lateral roots became immediately active, competing with the associated crop (Ong *et al.*, 1999). Thus, even if a tree species with desirable root architecture (fewer roots in surface layers) is selected, competition will ultimately depend on the activity of the roots in the surface layers during the cropping season, and not simply on their abundance.

To meet their demands for resources, fast-growing trees tend to have more aggressive roots than slow-growing trees (Jama *et al.*, 1998a), although exceptions to this rule have been reported (Schroth *et al.*, 1996). In western Himalayan valleys, the fast-growing exotic species *E. tereticornis* and *L. leucocephala* were found to have greater root biomass and fine root length density than the slower-growing indigenous trees *Grewia optiva* and *Bauhinia purpurea* (Singh *et al.*, 2000). Cherry (*Prunus cerasoides*) and mandarin (*Citrus reticulata*) extended their fine roots up to 1.5 m from the trunk and had a large number of woody roots close to the surface, which both hindered cultivation under agroforestry, and made the trees more liable to be attacked by pests and diseases when intercropped. In contrast, *Albizia* (*Paraserianthes falcataria*) and alder (*Alnus nepalensis*), which were also classed as faster growing, had the most desirable roots for tree–crop intercrop systems, as their fine roots were confined to within 1 m of the trunk, and they had fewer woody roots (Dhyani and Tripathi, 2000). In Uganda, *Ficus natalensis* is preferred to *Eucalyptus deglupta* as shade for coffee, because below-ground competition with the coffee crop is less (B.L. Oriikiriza, personal communication). In the semiarid northeast of Nigeria, per unit root length, *Acacia nilotica* had a greater negative effect on sorghum above and below ground than did *Prosopis juliflora*, a finding correlated with *A. nilotica*'s higher rates of water extraction from soil layers shared with crop roots (Jones *et al.*, 1998). Species selection for root architecture is also possible for systems in which trees are managed intensively, such as hedgerow intercropping (HI) and conservation hedges. Under a regular pruning regime, *Acioa barteri* and *Peltophorum dasyrrachis* had their fine roots distributed deeply (van Noordwijk *et al.*, 1991b; Ruhigwa *et al.*, 1992) compared with *L. leucocephala*, *Alchornea cordifolia* and *Gmelina arborea*, the fine roots of which were found at a shallow depth (Ruhigwa *et al.*, 1992) and *Erythrina poeppigiana*, the fine roots of which were found at intermediate depths (Nygren and Campos, 1995). Of the 13 woody species screened for HI in subhumid south-western Nigeria, *Lonchocarpus sericeus* had the most desirable root architecture, with only 21% of its fine roots colonizing the 0–30 cm soil layer (as compared with 84% in the case of *Tetrapleura tetraptera*). Although *Enterolobium cyclocarpum* and *Nauclea latifolia* had superior tap root systems and fine root form, they also exhibited extensive root distributions and very large lateral woody root volumes, which may interfere with tillage (Akinnifesi *et al.*, 1999b). As already indicated, there can be seasonal variation in tree root activity in different soil layers, according to the availability of soil water. Root activity may also vary according to species, a fact that could be exploited when selecting tree species for certain agroforestry applications (Broadhead *et al.*, 2003). Some variations are on a short temporal scale, e.g. *Faidherbia albida* has a 'reversed' above-ground phenology (with leaf fall during the rainy season), which implies that the seasonal pattern of root activity in this tree is different from that of other tree species. *P. juliflora* is a conservative water user and does not greatly vary its rate of water uptake in dry and wet conditions (Jones *et al.*, 1998). Use of this species in agroforestry systems may be less risky than that of other species with more variable resource demands, because of its greater predictability. Changes in competitiveness also occur on longer timescales, which must be taken into account when selecting species. For example, *Grevillea robusta* is least competitive as a young tree but depresses crop yields at the pole stage (Lott *et al.*, 2000, 2003). Conversely, trees that are initially competitive may become less competitive when they become older in certain situations. For example, certain parkland trees, despite developing very deep and laterally extensive root systems, have little effect on crop growth and are therefore tolerated by farmers in their fields because the improved soil fertility and microclimate in their vicinity outweigh their negative effects (Rao *et al.*, 1998).

Overall, spatial and temporal separation of tree and crop fine roots and their functions is not easily obtainable unless alternative sources of resources (such as subsoil water and nutrients at depth) are available to trees. Even where there is a certain amount of separation, it is likely that species choice will have to be supplemented with tree management, to improve complementary use of below-ground resources. Plus, management strategies to minimize competition will have to be changed over time, as the tree component ages.

17.3.2 Tree spacing and planting arrangement

Tree spacing and planting arrangements are among the most powerful means of managing root (and shoot) interactions in agroforestry systems. Biophysically, the optimum spacing and arrangement of trees in a crop field depends on a somewhat elusive balance between two conflicting objectives: the maximization of favourable tree root effects on soils and nutrient cycles on one hand and the minimization of competition with the crops for soil resources (and light) on the other. If trees are planted at a high density in the whole plot, their root systems intensively exploit the soil, add organic matter, improve the soil structure and reduce nutrient leaching. High tree planting densities also lead to deep tree root systems, as a consequence of competition in the topsoil, and this increases the recycling of subsoil nutrients. Such effects are successfully exploited in planted fallows (Jama *et al.*, 1998a) and also in high-density plantings of coffee (Barros *et al.*, 1995). However, in tree–crop associations the potential for increasing the planting density of the trees to maximize these beneficial effects is limited by simultaneously increasing competition with the crops for soil resources and light.

Increasing the spacing of trees in a crop field or pasture reduces the influence the trees have on the soil and on associated plants simply because there are fewer trees per unit area. It also increases the 'patchiness' of the trees' influence. Another way of reducing interactions between trees and crops (or soil) is to concentrate the trees in groups or rows in some part of the plot, such as the plot boundary (i.e. changing planting arrangement). Ultimately, decisions regarding spacing and arrangement will often be made on economic grounds, depending on the relative value and role of different components of the system. Low-value shade trees need to be distributed throughout coffee and cocoa plantations, and their interactions will be regulated via spacing (i.e. trees will be planted or removed as required). However, if the trees produce valuable products, then it is desirable to keep the tree density high and interactions with the crops (and soil) may be regulated via planting arrangement, with trees often being planted on plot boundaries or in contour rows on slopes. Growing trees and crops in rotation is a third form of reducing direct tree–crop interactions. Root interactions between trees and crops and the effects tree roots have on the soil depend on lateral tree root spread, which may be extensive. The root systems of savannah trees may extend several tens of metres from the trunk (Stone and Kalisz, 1991), and cropped alleys of a few metres width between contour hedgerows can be entirely permeated by tree roots (Schroth, 1995; Rowe *et al.*, 2001). Where trees are planted in rows, with a narrow within-row spacing, the lateral root spread perpendicular to the row is likely to increase further due to competition between neighbouring trees. The decrease of tree root density with increasing distance from a tree row may be roughly logarithmic, but may also show pronounced effects of local soil conditions, e.g. soil tillage, nutrient-rich patches, etc. (Schroth *et al.*, 1995). Pronounced crop yield depressions have been observed in the proximity of boundary plantings, especially on shallow soils and in regions with a pronounced dry season and a deep water table (Malik and Sharma, 1990). In such cases, other management options (such as the selection of less competitive and often slower-growing tree species) may be necessary, assisted by management measures as discussed below.

Some perennial crops including coffee and cocoa are commonly planted under the shade of larger trees, which provide microclimatic protection, assist in nutrient cycling and soil protection and reduce the incidence of certain pests and diseases. As the shade trees are scattered over the whole plot area, the root systems of trees and (tree) crops necessarily interact. Tree spacing, thinning of surplus trees over time and regular shoot pruning are the tools for regulating tree–crop–soil interactions in these systems. Although these measures focus mainly on above-ground interactions, root processes are clearly affected (see Section 17.3.4 'Shoot pruning'). Since the root systems of shade trees and perennial crops necessarily intermingle, one would expect that desirable shade trees would be non-competitive below ground. However, as mentioned above, farmers use surprisingly competitive tree species under conditions of adequate soil moisture and fertilization, apparently without negative effects on the crop. In a commercial coffee plantation near Turrialba in Costa Rica, with 4- to 5-year-old *Eucalyptus deglupta* shade trees planted at a spacing of 8 × 8 m, coffee yields were adequate with no indications of reduced growth in coffee plants in the proximity of trees, despite vigorous growth on the part of the trees (Schaller *et al.*, 2003). Beside the high resource availability in the soil, a further reason for the compatibility of coffee with this aggressive tree species was probably a pronounced small-scale partitioning of the soil space, with coffee roots concentrated near the coffee rows and the tree roots in the inter-row spaces. However, the compatibility of coffee with such fast-growing shade trees is confined to sites with adequate water, as in another region with 6 months of dry season, coffee clearly suffered from competition with *Eucalyptus* shade trees (Jiménez and Alfaro, 1999). For very dry coffee-producing sites in East Africa, it has been recommended that trees be planted on the plot boundary instead of spaced regularly within the plantation, in order to regulate root interactions via planting arrangement (Foster and Wood, 1963). This strategy may become increasingly relevant in regions producing perennial crops in the future, if the climate becomes drier due to climate change. When trees are scattered throughout fields, below-ground competition may not be recognized, as overlapping tree root systems result in competition and reduce yield throughout the cropped area, with no areas being free of tree roots for a comparison to be made.

17.3.3 Tillage and root pruning

Tillage is a standard method used by farmers to manage BGI, especially between crops and weeds. Under agroforestry conditions, it can also temporarily reduce tree root length density in the crop rooting zone at the beginning of the cropping season and stimulate tree root turnover, with a corresponding release of nutrients into the soil from decomposing roots. Zero-tillage may therefore not be a suitable practice for agroforestry systems. In dry lands, tillage also exercises a favourable effect on soil water storage. A variety of different tillage methods are practised in the tropics; in West African savannahs the soil is mostly tilled with a hand hoe, forming ridges on which the crops are sown, and the weeds covered within these ridges; where animal traction is available, the soil may also be ploughed to form ridges or a level surface, depending on the equipment.

Tillage destroys most of the tree roots in the top 10–15 cm of soil. This should give a temporary advantage to the crops, which are usually sown shortly after tillage. However, tree roots recolonize the ploughed layer within the cropping season, although the speed with which this happens is not well known. In an experiment in central Togo on a very shallow sandy soil, ridging did not alleviate competition between the crop and *Senna siamea* (as compared with that on land that was tilled to give a level surface). This was because the tree roots invaded the ridges (Schroth *et al.*, 1995).

Additional control of tree roots can be achieved through root pruning, either as part of the tillage process, or separately, which can be achieved by deep tillage and subsoiling along tree rows. This technique is practicable and relevant, especially when it is combined with and incorporates other interventions, such as deep placement of fertilizer for trees, water conservation in dry areas and the improvement of drainage. Korwar and Radder (1994) obtained positive results in south India by ploughing several times per year between hedgerows and adjacent crops, thereby removing tree roots. Soil water contents under the crops and yields were increased, suggesting that tree root competition was reduced. Another option is to cut the superficial lateral coarse roots of trees close to the trunk with an axe, which eliminates large quantities of subtended coarse and fine tree roots in the crop rooting zone. This is often practised when competition from roots of trees in boundary plantings causes conflicts with a neighbours' crops. Farmers in Bangladesh were observed to prune tree roots in the first year after planting; root pruning to plough depth became a routine during cultivation. Intensive and deliberate pruning of tree roots as a separate operation tended to be neglected after the second and third year (Hocking and Islam, 1998). Root pruning combined with top pruning may reduce the overall growth of trees depending on the intensity of pruning. In the case of trees planted in rice fields, combined root and top pruning reduced stem diameter at breast height (dbh) and total volume growth of trees by up to 19% and 41%, respectively (Hocking and Islam, 1998). Root pruning is also being tested as a management option in eastern Africa. At the start of the rainy season, lateral roots were severed with a machete or axe to a depth of 30 cm, about 50 cm away from the trunk. The yields of beans and maize within 5 m of the trees increased in the first season by between 0% and 300%, depending on site and tree species (Raussen and Wilson, 2001). Rapid regrowth of roots indicates that root pruning should probably be repeated every 1–2 years. Two years after the pruning treatment, the dbh of root-pruned trees was 12% less than that of trees that had not been pruned. Although the first root pruning of mature trees was hard work, farmers have found that repeated pruning became much easier, and that it could be easily done at the time of site preparation (J. Wilson, personal communication). Digging trenches along the tree rows or around the trees, severing roots and refilling the spaces with soil is a sure way of avoiding tree root competition for a period of time. In semiarid India, root pruning to 0.5 m depth virtually eliminated below-ground competition between trees and crops (Singh *et al.*, 1989). However, severing tree roots up to such depth could, in many situations, be laborious and uneconomical.

17.3.4 Shoot pruning

Pruning the shoots of trees offers a convenient way of managing below-ground competition in simultaneous agroforestry systems, provided that the trees are not being grown for their fruits, in which case further considerations concerning the impacts of management on the development of flowering shoots are important. In addition to reducing competition with crops, farmers also benefit from the products of pruning (fuelwood, poles, etc.), and the process also provides opportunities to improve timber quality. Shoot pruning: (i) controls the water demand by reducing leaf area; (ii) reduces fine roots by changing the functional equilibrium between above- and below-ground components; and (iii) alters fine root distribution within the soil profile. Shoot pruning also affects the timing of root growth and tree demand for below-ground resources. The young leaves formed after shoot pruning may also be more susceptible to drought than the old leaves of unpruned trees, and a resulting midday depression in their transpiration may further reduce competition with crops for water (Namirembe, 1999). Smith *et al.* (1998) recommended strategic shoot pruning of windbreak trees in the Sahel savannah, in order to reduce tree water use and competition with crops under dry conditions.

The severity of tree pruning varies considerably with systems, from the side pruning of trees in boundary tree plantings, to the lopping of branches in the case of dispersed trees, to severe and frequent pruning (to 0.3–1.0 m in height) in hedgerow intercropping. Few studies have been made of the extent of changes in root morphology and function as a consequence of above-ground pruning. However, studies of several species in Indonesia showed that a low pruning height induced a shallow root system with more fine and adventitious roots, probably due to reduced carbohydrate reserves in the short stems and/or a hormonal imbalance (van Noordwijk and Purnomosidhi, 1995). This suggests, first, that it may be appropriate to initiate some types of pruning only after a deep taproot has developed and, secondly, that trees should not be pruned too low; early and severe shoot pruning may induce excessive root branching in the topsoil and consequently increase competition in the topsoil and reduce tree root interception of nutrients in the subsoil.

Moderate pruning of tree branches may not make much difference to the tree's water demand, and hence may affect competition between trees and crops only slightly. Only the removal of a substantial amount of tree canopy reduces the water demand of trees and allows recharge of the soil profile for use by the associated crop (Jackson *et al.*, 2000). Severe pruning or pollarding of trees to a height of 1.5 m caused a decline in the fine root mass of *Erythrina poeppigiana* (Nygren and Campos, 1995). The effects of shoot pruning on fine roots depend on the soil water conditions. Under water stress, pruning caused an immediate increase in the fine roots of *L. leucocephala* and *S. siamea* in the 20–40 cm soil layer (which was followed by the death of those roots). However, when water was not limiting, pruning caused a significant reduction in fine root density and root biomass (Govindarajan *et al.*, 1996; Namirembe, 1999). Natural senescence and leaf fall in deciduous trees may have an effect on fine roots similar to that had by pruning. Intensive shoot pruning of *Gliricidia sepium* hedges in alley cropping during the rainy season also displaced the root maximum of the trees into the dry season, indicating increased temporal complementarity with the crops in the exploitation of soil resources (Schroth and Zech, 1995a).

The impact of pruning on competition may vary with species. In semiarid Nigeria, crown pruning substantially reduced the competitive effect that *P. juliflora* had on crop yield, but it did not reduce the competition of *A. nilotica* on intercropped sorghum (Jones *et al.*, 1998). In Kenya and Uganda, pollarding was found to be an effective means of reducing competition by five tree species. In the first season after pruning, competition was virtually removed, but the effects diminished as crowns regrew, so that pruning needed to be repeated every 2–3 seasons for the beneficial effects on crop yield to be reliably maintained; also, the magnitude of the interactions was sensitive to rainfall. Pruning of crown and root, separately and in combination, were beneficial and had different effects over time (Fig. 17.1). Although farmers benefited from an improved crop yield and tree products, there were trade-offs in terms of the long-term impacts on tree growth, which pollarding reduced by about 15% in terms of dbh. Acceptability of this to farmers will depend on their short- and long-term objectives and on the relative value of different farm products. In many instances, farmers may not resort to above-ground pruning for the sole purpose of reducing below-ground competition. But, provided it is severe enough, above-ground pruning done for other purposes (such as to remove shade, harvest firewood, remove pest- and disease-affected parts, etc.) simultaneously benefits the associated crop by reducing below-ground competition.

17.3.5 Mulching

Mulching is a common practice in multistrata, perennial tree-crop and banana-based agroforestry systems and may influence BGI in various ways. Its effects on root processes have, however, been little studied. Mulching can reduce the formation of surface crusts and thereby increase water infiltration into the soil, especially when the mulch is applied before the onset of the rainy season. It also reduces soil water evaporation. The consequent increase in soil water availability should reduce competition for water between the associated species in dry areas. On the other hand, a mulch layer is known to promote the formation of superficial fine roots because of increased water status in the topsoil layers, potentially leading to increased competition (as there are more roots in the superficial soil layers) after the mulch has decomposed. It may therefore be important to provide mulch on a continuous basis, in order to avoid increasing root interactions. However, experimental evidence for

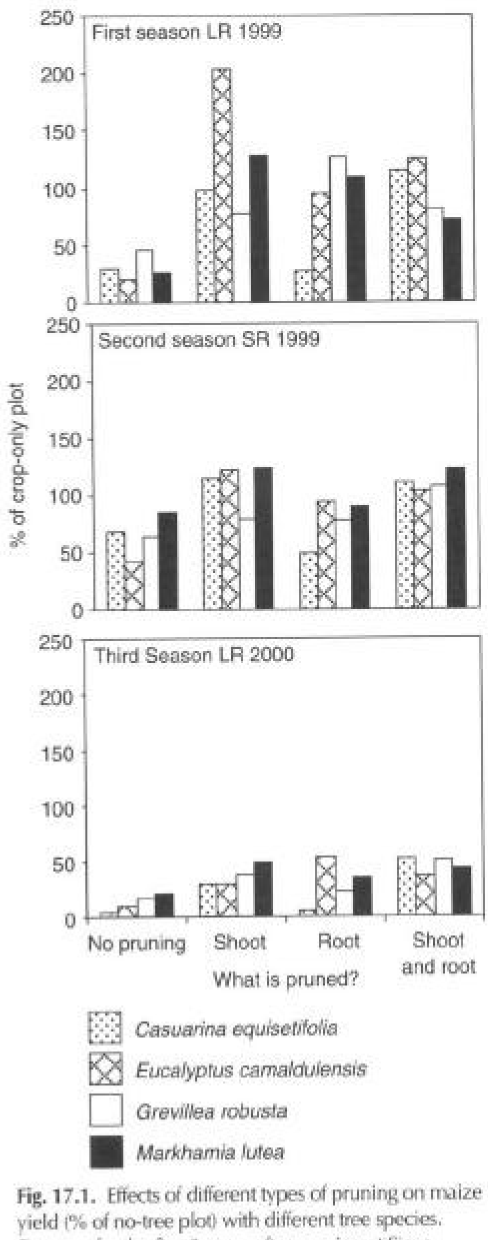

Fig. 17.1. Effects of different types of pruning on maize yield (% of no-tree plot) with different tree species. Data are for the first 3 years after pruning at Siaya, western Kenya. LR and SR are long and short rains, respectively. A. Tefera *et al.* (unpublished results).

increased root competition in (discontinuously) mulched systems is not available. In a study in Togo, biomass application either as mulch or as green manure (i.e. ploughed in) had no effect on competition (Schroth *et al.*, 1995). Organic materials used as mulches add nutrients to soil in the course of their decomposition and increase soil biological activity, and thus favourably affect BGI (see Chapter 15, this volume).

17.3.6 Fertilizer use and placement

The addition of fertilizer is an intuitive solution to the problem of below-ground competition for nutrients between different components of diverse tropical agroecosystems. Fertilization of intercrops in a system often results in increased growth of the associated tree crops (see Williams, 2000, for a review regarding rubber) and Schroth *et al.* (2001) for other tree crops. However, fertilization may have unexpected effects, or even no effect (Schroth, 1998). Also, many management-related questions arise: Where should farmers place fertilizer in a mixed species system? When would be the best time/season to apply fertilizer? How should the fertilizer be applied (broadcast uniformly or with localized point placement or injected at depth or spread on the surface)? Which species respond to patches or pulses of added nutrients? In a multispecies system, will all components benefit equally, or will some species take a disproportionate share? What other effects will fertilization have on the system?

Fertilizer should be placed in the zones where there is greatest demand for nutrients by the target component species of the system. These locations can be identified either by systematically measuring nutrient and water distributions in the soil within the agroecosystem (in order to identify areas of depletion) or by studying the root distribution patterns in the system. Knowledge of the location of fine roots and of the occurrence of active root uptake for different species will help target fertilizer application, especially for relatively immobile nutrients such as P. For example, in the coffee–*Eucalyptus* system (Section 17.3.2) coffee plants would benefit most from fertilizer applied around their bases, as is common farming practice.

If roots in a tree–crop system extend across the area between tree rows (inter-row area), then it may be best to fertilize within this area of associated crops/vegetation (where interactions are likely to occur at the level of individual roots). Wycherley and Chandapillai (1969) found, when studying 5-year-old rubber in Malaysia, that tree girths were significantly greater when P fertilizer was placed in the inter-row area dominated by secondary vegetation than when the P was applied to the clean-weeded rubber tree rows. In a study in Jambi, Indonesia, growth of rubber trees in three different situations was compared: (i) 'low weeding, no N'; (ii) 'low weeding, plus N' wherein N fertilizer was placed around rubber trees, directly within a weedy inter-row area at 3-month intervals; and (iii) 'high weeding, no N' treatments (Williams, 2000). At 21 months after planting, the mean rubber tree height and trunk volume in the low weeding plus N treatment was significantly greater than in the low weeding, no N treatment ($LSD_{0.05}$), but not significantly different from the high weeding treatment (Fig. 17.2). Thus, addition of nitrogen appeared to partly compensate for the higher below-ground competition in the low-weeding plots, so that tree growth reached levels comparable with high-weeded trees. However, addition of fertilizer to plots of early-successional vegetation in Costa Rica decreased the dominance of woody shrubs and trees and increased the dominance of herbaceous species, relative to unfertilized plots. Therefore, increasing the below-ground resource of mineral nutrients gave a competitive advantage to the herbs, over the first year of colonization (Harcombe, 1977). This may have important implications for the fertilization of tropical agroecosystems – the desirable tree-crops/woody species may be outcompeted by herbs or aggressive grasses if the system is fertilized too early or too intensively.

The degree of competition for added nutrients exerted by different species in an agroecosystem may also change with season, and this could be exploited by careful timing of fertilization. Seasonal change in the uptake of ^{15}N was observed in a mixed fruit tree plantation of *Theobroma grandiflorum* (cupuaçu) and *Bactris gasipaes* (peach palm) with a legume cover crop (*Pueraria phaseoloides*) (Lehmann *et al.*, 2000). In the dry season, the highest N uptake by all three components occurred within the area underneath their own canopies. Yet in the wet season, *Pueraria* took up a greater proportion of N from under the trees, and the trees increased their N uptake from the area under *Pueraria* (although to a lesser extent). Seasonal differences in uptake by different components of mixed systems, related to periods of active root growth, could thus be exploited by fertilizing the specific components at strategic times. For

Fig. 17.2. Size of rubber trees 21 months after planting in response to weeding and fertilization treatments in Jambi, Indonesia. 'Low weeding', strip-weeding 1 m either side of the rubber trees at 3 and 6 months after planting then no subsequent weeding; 'Low weeding + N', as above, but with 50 g urea per tree applied in a circle every 3 months (equivalent to 55 kg N/ha/year); 'High weeding', clean weeding of the entire plot, nine times per year. Error bars represent one standard error of the mean. Data from Williams (2000).

example, Munoz and Beer (2001) found that fine root productivity of shade trees was greatest at the end of the rainy season, whereas that of underplanted cacao was greatest at the start of the rains, so they suggested early fertilization during the beginning of the rains immediately after pruning the shade trees.

Fertilizer intended for one species within an agroecosystem may actually be taken up by the other associated species. For example, Woods *et al.* (1992) found that weeds took up 68% of the N applied in one experimental treatment in an Australian *Pinus radiata* plantation. Increased biomass production by associated species in response to fertilization may in turn lead to increased competition with the target species. In an association of hazel trees (*Corylus avellana* L.) and a grass (*Dactylis glomerata* L.) in France, for instance, surface application of N mainly benefited the shallow-rooted grass, which increased in biomass and thus competitive strength. This caused severe competition with the trees for water as well as for N (de Montard *et al.*, 1999). However, applying N locally to the area around the tree stem (in addition to surface N application) alleviated the effect of competition for N by the grass, in terms of tree girth increment. In this case, placement of N fertilizer in deep soil horizons, close to the tree stems, was recommended.

If fertilizer is added to a system in order to alleviate below-ground competition, and roots proliferate in response to it, then once the nutrient patch is depleted, intra- or interspecific competition is likely to be even greater than before, so fertilizer application should be repeated regularly (Schroth, 1998). However, if other nutrients or water then become limiting, the situation becomes more complex. Furthermore, if roots proliferate in surface soil layers in response to surface application of fertilizers, then it is possible that during dry periods these plants may become more susceptible to drought.

The physiological characteristics that dictate the response to added nutrients of many of the tree species used in tropical agroecosystems are, at present, incompletely understood and the species' response to this in diverse systems is even less so.

17.3.7 Root barriers

As mentioned above, in most agroforestry situations it is desirable that tree roots have access to the soil under the associated crops (because these roots are expected to have soil-improving and nutrient-conserving effects). However, there are situations in which partitioning the soil into tree and crop root compartments can be expected to improve the performance of the system. For example, when trees are planted as windbreaks or shelterbelts in crop fields in dry areas, water uptake from the cropped area by lateral tree roots may counteract the positive microclimatic effects of the trees on the crops. In such a situation, reduced root interactions between trees and crops would lead to higher crop yields. Another example is offered by the invasion of crop fields by lateral tree roots from adjacent tree-fallow plots. It has been shown that fast-growing fallow trees, such as *Sesbania sesban*, can extend their lateral roots to several metres within a few months (Torquebiau and Kwesiga, 1997). Through these roots, the fallow trees may redistribute nutrients from the cropped plot into the tree-fallow plot, instead of recycling nutrients from the subsoil of the fallow plot itself (van Noordwijk, 1999). A certain separation of tree and crop root zones in the crop/planted-fallow interface may be beneficial in two ways: (i) by increasing crop yields by reducing root competition between trees and crops; and (ii) by allowing tree roots to penetrate more deeply into the soil through lateral restriction of the available soil volume, thereby increasing the potential for nutrient recycling and physical subsoil improvement.

Barriers to the lateral development of tree root systems can be chemical, physical or biological. Chemical root barriers can be created inadvertently when trees are planted in very acid and infertile soil and are only locally supplied with fertilizer and lime. The infertile soil surrounding the fertilized planting hole can then impede lateral tree root development. This configuration can be observed in tree–crop plantations on acid soils (Schroth *et al.*, 2000a), but is not a feasible option for managing tree roots in tree–crop associations as the soil under the crops is generally fertilized to a greater degree than that under the trees. The potential for using chemicals other than fertilizers to restrict lateral extension of tree roots at the field scale without causing any detrimental effects is not known.

Physical root barriers such as polyethylene or galvanized iron sheets have often been used in experimental studies to separate the rooting zones of tree rows and adjacent crop rows. Open trenches can be dug along the tree line or around the trees. They are effective only for a short period as, after some time, tree roots tend to pass under the barriers and then grow upwards again, so that the barrier's effect is decreased.

Biological root barriers consist of narrow strips of vegetation with competitive root systems planted alongside tree rows to impede the lateral spread of tree roots. Research into the potential of biological barriers for manipulating tree root distribution is based on reports that the roots of certain trees could be laterally confined and forced to go deeper if herbaceous intercrops or cover crops with competitive root systems are planted at a short distance from trees. Schaller *et al.* (1999) hypothesized that a similar effect could be achieved by planting perennial grasses, with their typically dense root systems, in narrow strips, in order to manipulate the root systems of recently planted trees. The success of this technique depends on the degree of competitiveness of the barrier strips with respect to trees and crops: it could theoretically be used to minimize the competition exerted on adjacent crops by trees in boundary plantings, contour strips or planted fallows.

In a series of experiments in Costa Rica, it was found that the effect of grass barriers depends on both the tree and the grass species. Whereas grass strips induced drastic alterations in the root architecture of *Cordia alliodora* seedlings (Fig. 17.3), the roots of the faster growing, more aggressive *Eucalyptus deglupta* trees were much less affected and generally passed through the barriers. Guinea grass (*Panicum maximum*) and *Brachiaria brizantha* formed more effective barriers than sugarcane (*Saccharum* sp.), vetiver (*Vetiveria zizanioides*) and lemon grass (*Citronella* sp.). Increasing the barrier width from one to three grass rows did not increase the barrier effect of the most competitive species (guinea grass) but tended to increase the effectiveness of the *Brachiaria* barriers (Schaller, 2001). The sugarcane barriers were ineffective against the aggressive *Eucalyptus* roots at all the tested widths. Contrary to expectation, and inexplicably, the grass barriers led to shallower and not deeper root systems in the case of *Eucalyptus* trees.

These early results indicate that the technique may have most potential when it is used with tree species such as *Cordia alliodora*, whose root architecture can be strongly modified at an early stage of development by the presence of grasses. To what extent changes in the root architecture of tree seedlings translate into a more desirable root distribution in older trees remains to be seen.

With regard to physical root barriers, farmers may not be expected to plant grass strips solely for the purpose of tree root management. However, in sloping areas, grass strips also aid soil and water conservation, and the fodder value of the grasses may provide additional benefits. Thus, the root management effect is only one of several functions biological barriers have. However, many more long-term experiments are necessary before it is possible to draw a final conclusion as to their potential.

17.3.8 Managing interactions with weeds

Weeds affect BGI by appropriating resources that would otherwise be utilized by the main crop(s) in an agroecosystem, and so limit their growth. For example, in Sumatra (Indonesia), the stem diameter and trunk volume of rubber associated with a mixture of woody and non-woody weeds at 21 months after planting were 17% and 37% lower, respectively, than those of clean-weeded rubber (Williams, 2000). This significant retardation of rubber tree growth was mediated entirely by below-ground interference, as the weeds were low-growing and did not shade the rubber. This was borne out

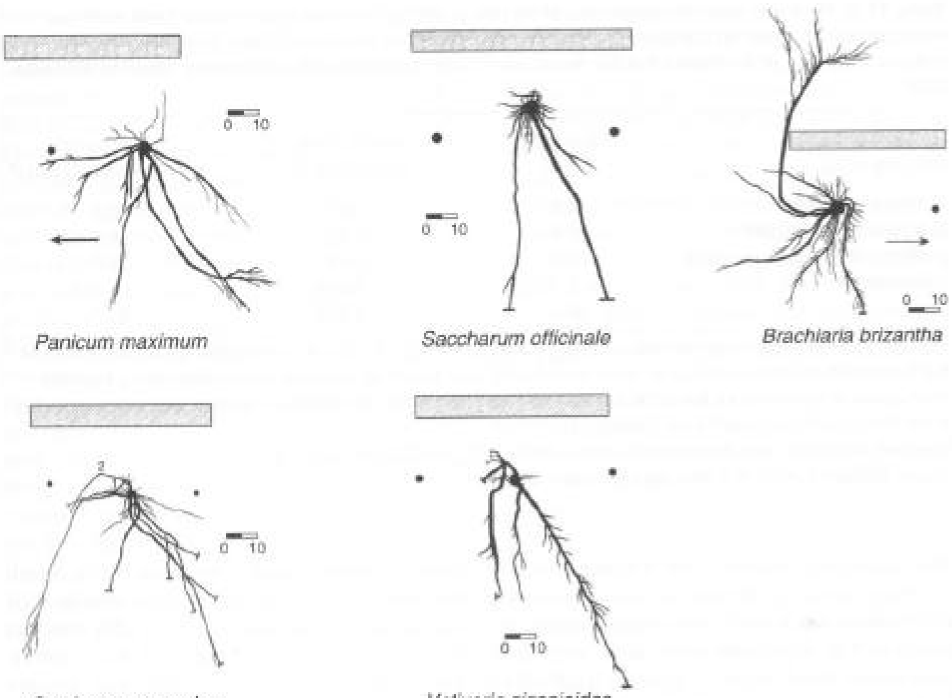

Fig. 17.3. Avoidance reaction of the root systems of 8-month-old *Cordia alliodora* saplings in response to strips of different grass species, seen from above, at Turrialba, Costa Rica. The grey bars symbolize the grass strips that were planted at 30 cm from the trees; dots indicate the position of trees whose root systems are not depicted. The scale shown in each figure corresponds to 10 cm. In the case of *Brachiaria brizantha*, a border tree is shown whose roots grew around the end of the grass strip. Modified from Schaller (2001).

by the fact that soil nitrate-nitrogen in the unweeded rubber was 2.83 mg/kg compared with 7.37 mg/kg under weeded rubber.

Biomass allocation within trees may change in response to below-ground competition. For example, rubber trees that experienced competition, either from the noxious weed *Imperata cylindrica* or from a pineapple intercrop, were found to be significantly smaller above ground (in terms of squared stem diameter, Dsq) than were clean-weeded trees (Table 17.2). They were also found to have allocated a greater proportion of biomass to their roots than clean-weeded trees. Competition, especially from the weed *Imperata*, also led to a shift from horizontally to vertically oriented root cross-sectional area (Table 17.2). Implications for management are that regular weeding will favour above-ground tree growth relative to below-ground growth and may also result in a greater concentration of roots in the upper soil layers. This in turn may decrease the severity of future weed infestations due to increased shading and the presence of already well-established tree roots in the surface soil.

Parasitic weeds should be considered as a specific case in below-ground interactions. *Striga hermonthica* and *Striga asiatica* are two major biological constraints to the production of staple cereals (maize, sorghum and millets) in sub-Saharan Africa. The *Striga* problem in smallholders' farms is exacerbated by severe nutrient-depletion as a result of continuous cropping and limited or no use of inorganic inputs. *Striga* remains a pernicious problem as it produces millions of

Table 17.2. Root and stem characteristics of 39-month-old rubber trees grown under three inter-row management regimes: no competition (A), competition from an intercrop (B) and competition from a noxious weed (C), at Sembawa Rubber Research Station, South Sumatra, Indonesia. (Source: Williams, 2000.)

Management of inter-row area	Stem Dsq (cm^2)	Shoot : root ratio (Dsqs)[a]	% Horizontally oriented roots (Dsqs)[b]
A. Clean weeded	74.8	0.46	60.7
B. Intercrop (pineapple)	38.4	0.23	34.1
C. Weed (*Imperata cylindrica*)	13.9	0.28	23.7
F-probability	< 0.001	0.022	0.008
SED[c]	8.1	0.074	10.1

[a]Shoot : root ratio (diameter squares) = $\Sigma D_{stem}^2 / (\Sigma D_{hor}^2 + \Sigma D_{ver}^2)$. Shoot : root ratios were calculated on the basis of the cross-sectional areas of tree stems and 'proximal' roots (the roots originating from the stem collar or tap root), as the latter can be used as a surrogate for total root system size when applying a fractal branching method (see Chapter 4).

[b]Percent horizontal root diameter squares = $100 \times \Sigma D_{hor}^2 / (\Sigma D_{hor}^2 + \Sigma D_{ver}^2)$.

[c]SED = Standard error of differences between means.

tiny seeds each season, which remain viable for many years in the soil. As the *Striga*–host interaction starts with the establishment of haustorial connections soon after germination of the *Striga* seed, it causes considerable damage to the host crop before it emerges from the soil. Management practices appropriate for small-scale farmers should be based on the principle of depleting the *Striga* seed reserve in the soil. Therefore, rotation of *Striga*-susceptible crops with trap-crops that stimulate *Striga* seeds to germinate without being parasitized (to deplete the soil seed bank) and repeated hand removal of the weed before it sets seed (to avoid additions of seed to the soil) are recommended. However, these practices are not widely adopted for economic reasons. Obviously, an integrated approach with a suite of practices that deplete the soil seed reserve and replenish soil fertility is required to overcome the *Striga* problem and increase crop production (Parker and Riches, 1993).

Agroforestry systems that replenish soil fertility, such as biomass transfer (synonymous with green-leaf manuring) and short-rotation planted fallows, have been examined for their potential to reduce *Striga*. Of the biomass of a number of trees and shrubs tested, only the high-quality biomass of *Tithonia diversifolia* and *Sesbania sesban* (with a low C : N ratio and low concentrations of lignins and polyphenols), reduced the amount of *Striga* present on continuous application to the soil at 5 t/ha (dry weight) over four years (Gacheru and Rao, 2001). The biomass of these species was rapidly decomposed and mineralized to maintain a high level of inorganic N in the topsoil, which has a negative effect on *Striga*. There was no evidence to indicate that *in situ* decomposition of organic residues stimulated *Striga* germination due to the production of *Striga* seed stimulant. None of the organic materials reduced *Striga* as much as inorganic N fertilizers, so use of organic materials should only be considered to be complementary to other methods.

A number of leguminous tree/shrub species have been found to stimulate *Striga* germination in laboratory conditions (Oswald *et al.*, 1996). Of the promising species tested under field conditions, *Senna* spp., *Sesbania* spp. and *Desmodium distortum* depleted *Striga* seeds in the soil after being grown for 12 months, and decreased *Striga* infestation in the subsequent maize crop. However, only the planted fallows of *S. sesban* and *Desmodium* increased the yield of the following maize crop in comparison with that of monocropped maize. This is because both these fallow species produced large amounts of high-quality foliar biomass, which has a direct bearing in terms of increasing soil fertility (Gacheru *et al.*, 1999). Although *Tithonia* and *Tephrosia* also improved maize yields, the decreases they caused in *Striga* infestation were primarily due to increased soil fertility. For use in fallows, farmers will be interested in those species that fix atmospheric nitrogen, produce a high biomass that has multiple uses, and substantially improve maize yields. In this respect, 1- to 2-year-old *S. sesban* fallows are more attractive than others, as *S. sesban* produces firewood and its foliar biomass has fodder value. In soils with moderate *Striga* infestation, repeated cycles of *Sesbania* fallow–crop rotations may overcome *Striga*. However, under conditions of high infestation, fallows alone may not greatly reduce *Striga* infestation. In P-deficient soils (as, for example, in western Kenya) use of phosphorus fertilizers is essential to exploit the benefits of *Striga* reduction gained by the use of the planted-fallow and green manuring technologies.

17.4 Conclusions

Optimum use of soil resources requires that below-ground niches (vertical, horizontal, temporal and functional) be exploited by species and life forms with complementary root properties (functional diversity). Exploitation of niches is maximized, for example, by adding deep-rooted trees to shallow-rooted crops or pastures, associating annual crops with perennial trees, or adding temporary intercrops to systems with young tree crops. Whether, and to what extent, farmers attempt to control negative BGI depends on site factors and socioeconomic conditions. Where the availability of soil resources is high, farmers may associate rather fast-growing and competitive tree species with their crops without negative consequences for crop yields. Where labour is more limiting than land and tree-crops are not yet in the productive phase, farmers may also decide not to manage BGI that are having adverse effects on trees, even though technically it would be advantageous (e.g. in the case of young jungle rubber). However, when BGI are a limiting factor in the functioning of land-use systems (e.g. in dry areas) farmers need to consider BGI in their decisions about tree (and crop) species, planting designs and management.

Options for managing BGI include germplasm selection, spatiotemporal arrangement of species, planting density, tillage/root pruning, shoot pruning, fertilizer use and placement, weeding and possibly (as an added benefit of anti-erosion strips) biological root barriers (Table 17.1). The more successful planting design and management are in terms of manipulating BGI, the more flexibility farmers will have to choose tree species with less-than-optimal root characteristics for their systems.

BGI cannot be managed without affecting above-ground interactions and the growth of species, implying the need for a holistic approach to the management of interactions among species in complex systems. For example, delayed weeding and pruning of trees may promote deeper penetration of tree roots, but both operations are likely to reduce the growth of young trees and associated crops. While system design in terms of the spatiotemporal arrangement of trees and tree density radically changes BGI, tillage, weeding, mulching and light shoot pruning have relatively small and/or temporary effects on the root systems of trees and BGI. Severe crown pruning, however, can substantially reduce competition, and the benefits of harvesting tree products can be attractive, but how pruning affects overall growth needs to be considered. Although root pruning is a safe, effective and direct way of reducing below-ground competition, it may be unattractive to farmers because it involves additional work, without the benefit of an immediate tree product (unlike shoot pruning). Farmers' needs and resources and market forces dictate the design of systems, and management of BGI within the context of a given system often demands that a combination of practices be applied. There is much still to be learned about optimizing agroforestry systems: we must improve our understanding of how to optimize resource use as well as our understanding of the short- and long-term effects of such optimization; we must increase our understanding of individual species; we must improve our capacity to predict these interactions, through modelling; and, we must understand these systems within the context of the socioeconomic drivers that dictate what systems will be adopted and how they will be managed. Field experimentation with trees is time consuming, but as models have not been developed to the stage whereby they can be employed for this type of decision making in agroforestry, long-term field experiments as well as the use of indigenous knowledge are essential in order to improve our understanding.

Conclusions

1. Optimum use of BGR requires the selection of species that exploit different soil resources, or the same resource over different timeframes. Although enhanced interactions between soil and tree roots may have positive effects on subsequent annual crops in rotational systems, increased BGI among component species beyond a certain degree or stage would have negative effects in mixed systems.
2. A holistic approach is needed for managing BGI in mixed systems, as most practices will have concomitant and often conflicting effects on below- and above-ground processes, including plant growth.
3. Of the different options for managing BGI, germplasm selection, spatiotemporal arrangement of species, planting density (especially of the tree component), and fertilizer use and its placement have greater effects compared with tillage/root pruning, shoot pruning, mulching, weeding, and biological root barriers. In any given system a combination of practices may be desirable to manage BGI, as none would alone minimize the negative effects of BGI.
4. The choice of whether or not to manage BGI depends on both site factors and socioeconomic conditions. The need to manage BGI is greater in sites characterized by low rainfall and poor soils than in sites characterized by high rainfall and deep and fertile soils.

Future research needs

1. How much functional root diversity is needed for a given agroforestry system?
2. How many and which types of species are needed to provide this diversity?
3. What long-term implications does optimizing the use of below-ground resources have on the resource base and on productivity?
4. How do different tree species respond to management practices in the short and long term; and, what differences are there between species and provenances in terms of their flexibility/ability to respond to root management measures?
5. What are the costs and benefits of different strategies for managing roots and tree crowns (in terms of tree growth, yields, effects on soil properties, etc.)?
6. Can simple predictors and models for the prediction of tree root responses to environmental and management factors be developed?