CHAPTER 5.2

Agroforestry and Soil Health: Linking Trees, Soil Biota, and Ecosystem Services

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5.2.1 Introduction

A significant and increasing proportion of the Earth's land area is covered by crop and range lands. Agricultural landscapes hold a large proportion of the world's biodiversity but the relative contribution of each land management type to conservation of biodiversity and the maintenance of ecosystem service delivery is poorly understood (Jackson *et al.* 2005). Ecosystem services can be classified into those associated with the provision of goods (e.g. food, fibers, and fresh water), those that support and regulate ecosystem function (e.g. climate regulation, disease control, soil formation, and nutrient cycling), and those cultural services that are not associated with material benefits (e.g. recreation, spiritual, and aesthetic value) (MEA 2005). Agricultural ecosystems both require and generate ecosystem services and may enhance or degrade natural capital through time depending on how they are managed. Soil health is a key indicator of the state of natural capital, and is considered here as an integrative property that reflects the capacity of soil to respond to agricultural management by maintaining both the agricultural production and the provision of other ecosystem services (Kibblewhite *et al.* 2008).

Soil organisms contribute to a wide range of ecosystem services that are essential to the functioning of natural and managed ecosystems (Wall 2004). Evidence has shown that there is a strong link between organisms above- and belowground (Wardle *et al.* 2004), highlighting the impact that land use and management can have on the provision of soil-based ecosystem services. Little research has been conducted on the role of soil biota in high input agriculture because natural processes regulating soil structure, nutrient supply, and pests and diseases have been largely replaced by soil tillage, artificial fertilizers, and biocides (Barrios 2007). Recent concern about sustaining soil function in intensive agriculture has created a new demand for agricultural practices that are less dependent on external inputs, tighten nutrient cycles, and are productive while enhancing rather than degrading natural capital (Swift *et al.* 2004).

Agroforestry is now broadly defined, in scale-neutral terms, as the interaction of agriculture and trees (Sinclair 2004). The field and landscape scales that are a focus here, involve land use practices that combine trees with crops and/or animals in some form of spatial arrangement or temporal sequence that results in significant ecological and economic interactions among trees and agricultural components (Sinclair 1999; Fig. 5.2.1). Recent global estimates indicate that nearly half of all agricultural land has >10% tree cover, an area of about 1 billion ha that is home to more than 500 million people (Zomer *et al.* 2009). The perennial nature of most trees has a profound impact on soil properties, and hence on the abundance, diversity, and function of the soil biota, underpinning soil health.

Figure 5.2.1 Trees in agricultural fields: a) bean crop growing under diverse naturally regenerating trees (pruned and free-growing) in the Quesungual slash-and-mulch agroforestry system (Honduras); b) Shaded coffee system including *Erythrina poepiggiana* (pruned) that is often combined with naturally generated *Cordia alliadora* grown for timber (Costa Rica); c) cassava intercropped with beans growing in combination with pruned *Gliricida sepium* trees (foreground) and pigeonpea growing under *Schizolobium amazonicum* timber trees (background) (Brazil); d) maize crop under *Faidherbia albida* that is known for shedding their leaves in the wet season when the crop is growing, reducing competition while contributing to nutrient cycling (Tanzania). (Photo credits: a), c) Edmundo Barrios; b) Philippe Vaast; d) World Agroforestry Centre image database.)

This chapter first discusses the potential of trees to modify the soil and its impact on soil biota. The exploration of the linkages between the biological activity of soil organisms in agroforestry systems and their impact on soil-based ecosystem services and soil health follows next. Then recent advances in soil health monitoring systems and approaches to harnessing the complementary nature of local and scientific knowledge are discussed. We conclude by highlighting the role of agroforestry practices in adaptive and multifunctional land management with a view to enhancing soil health and agricultural sustaina-bility, as well as recommendations for future research.

5.2.2 How trees influence soil properties and biota

The integration of trees into agricultural landscapes has the potential to generate a number of improvements in the soil as a habitat for soil organisms and also for crop growth. Trees modify the soil environment in many ways: leaves intercept rainfall, transpire water taken up by roots from the soil, and provide shade to the understory and soil, and dead

or pruned leaves and branches provide soil cover and nutrient inputs to soils. These processes affect the temperature, moisture, erosion, and nutrient content of the soil as well as influencing soil biota. Martius *et al.* (2004) showed that soil macrofauna biomass in Amazonian forests strongly correlated with canopy closure, consistent with the tree canopy protecting the soil macrofauna from high temperature variation and drought stress. Similarly, research in coffee agroforestry systems of Southern Mexico demonstrated the impact of shading on lowering soil temperature, resulting in reduced water losses through evapotranspiration and maintenance of suitable soil moisture for crop growth (Lin 2010). Soil cover by tree litter and pruning biomass in Quesungual slash and mulch agroforestry practices in sub-humid Western Honduras has also been related to increased duration of soil moisture availability during critical periods resulting in sustained crop yield increases (Castro *et al.* 2009). Furthermore, studies by Pauli *et al.* (2010) which determined the spatial relationships among tree

distribution, mulch cover, and earthworm casts in the same agroforestry context showed that production and distribution of earthworm casts (an indicator of biological activity) was closely related to the spatial arrangement of trees as shown (Fig. 5.2.2). These results emphasize the role of trees in fostering conditions for increased biological activity.

Soil improvements by trees can also occur by increased supply and availability of nutrients for crops and soil biota (Buresh & Tian 1998). The increased supply of nutrients through a "deep capture" of subsoil nutrients by tree roots returns these nutrients to the surface soil as litter (Rowe *et al.* 1999). This mechanism can also recycle fertilizer applied by farmers, thus improving nutrient use efficiency and the returns to fertilizer application. Published values for leguminous trees in different agroforestry systems show average annual additions of dry matter biomass of up to 20 t ha^{-1} year^{-1} (Young 1997). The size of annual biomass additions is largely influenced by climate, soil fertility, tree species and tree management regime.
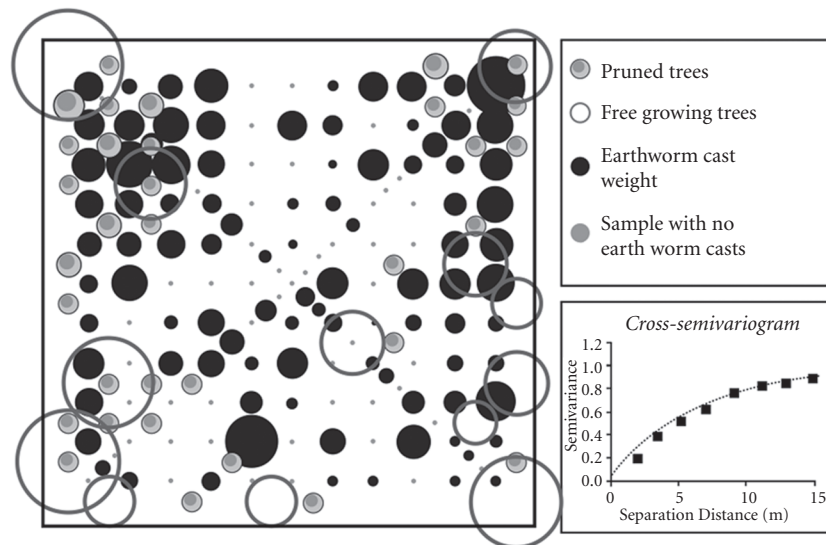

Figure 5.2.2 Comparison of earthworm casts and tree distribution in the Quesungual Slash-and-Mulch Agroforestry System. The size of the open circles represents the size of the tree canopy. The size of the light circles indicates the number of pruned trees found within each sampling cell (range of values: 1–3 pruned trees). The size of the dark circles represents the weight of earthworms casts (range of values: 0.6–10.6 g). The smaller graphics at the bottom right show the cross-semivariogram for the spatial relationship between tree distribution and earthworm cast distribution. An exponential model variogram provided the best fit to data (nugget = 0.03; sill = 1.22; range = 10.36 m). (Adapted from Pauli *et al.* 2010.)

Alley cropping in the Nigerian savanna-forest transition has reported about 5 and 7 t ha^{-1} year^{-1} of pruning biomass from *Gliricidia sepium* and *Leucaena leucocephala* respectively (Kang *et al.* 1999). In the Colombian Andes, pruning biomass contributions from *Indigofera constricta* and *Calliandra calothyrsus* planted fallows added about 9 t ha^{-1} year^{-1} to soil as mulch following pruning while *Tithonia diversifolia* contributed close to 15 t ha^{-1} year^{-1} (Barrios & Cobo 2004). In eastern Zambia, a drier environment, Sileshi and Mafongoya (2006a,b, 2007) recorded wide variations in pruning biomass contributions within the *Leucaena* genus (e.g. *L. palida*, *L. esculenta*, *L. collinsi* and *L. diversifolia* contributing 4.4, 3.4, 2.9, and 2.2 t ha^{-1} year^{-1} respectively during intercropping with maize), while *Acacia angustissima*, *G. sepium*, *Senna siamea* and *C. calothyrsus* contributed 3.3, 2.9, 2.2, and 1.4 t ha^{-1} year^{-1} respectively.

The contribution of agroforestry trees to soil nutrients through biomass additions and their utilization by intercropped plants has been reviewed by Palm (1995). One important highlight from that review is that while the nutrient concentration of pruning additions of some agroforestry trees is sufficient for most nutrients to meet crop demands, there is a general exception for phosphorus. Published values indicate that leguminous trees in alley cropping systems can contribute as much as 358 kg nitrogen (N) ha^{-1}, 28 kg phosphorus (P) ha^{-1}, 232 kg potassium (K) ha^{-1}, 144 kg calcium (Ca) ha^{-1}, and 60 kg magnesium (Mg) ha^{-1} (Palm 1995). Considerable interest in planted fallows using *T. diversifolia* has been generated because of its particular ability to accumulate nutrients, including P, in its biomass (Jama *et al.* 2000). Slash and mulch management of *T. diversifolia* in the Colombian Andes accumulated up to 417 kg N ha^{-1}, 85 kg P ha^{-1}, 928 kg K ha^{-1}, 299 kg Ca ha^{-1}, and 127.6 kg Mg ha^{-1} after 27 months (Barrios & Cobo 2004).

5.2.3 Agroforestry systems increase abundance of soil biota

Agroforestry trees have the potential to promote positive changes in the abundance, diversity, and function of soil organisms through their impact on soil as habitat for soil biota. There are few studies of tree—soil biota interactions in agroforestry systems, and most agroforestry studies reported in the literature focus on changes in the abundance of soil macrofauna with limited consideration of changes in diversity and function. For instance, studies in slash and mulch agroforestry practices in Honduras showed that total soil macrofauna densities were 52% (dry season) and 80% (wet season) higher than in the natural forest (Pauli *et al.* 2011). These figures are about five times greater than those found in the highlands of Central Honduras (271 individuals m^{-2}) (Ericksen & McSweeney 1999), close to twice the density of *Theobroma grandiflorum*, *Bactris gasipaes* (peach palm), and *Bertholetia excelsa* (Brazil nut) agroforestry (1059 individuals m^{-2}), and comparable to density values reported for coffee, *Schizolobium amazonicum* agroforestry (2054 individuals m^{-2}) and coffee, *Hevea brasiliensis* (rubber) agroforestry (2122 individuals m^{-2}) for the western Brazilian Amazon (Barros *et al.* 2002). Differences in abundance of soil organisms can be even greater when contrasting the impact of agroforestry systems to that of continuous cropping without trees (Table 5.2.1).

Agroforestry systems consistently generated substantial increases in the mean abundance of all soil organisms studied compared to the continuous cropping control (Table 5.2.1). The response ratio (RR), the ratio of the mean value of the agroforestry practice to that of the control (continuous cropping) (Hedges *et al.* 1999), was used to synthesize and compare different soil biota in soils under agroforestry and continuous cultivation without trees. While agroforestry systems consistently generated substantial increases in the mean abundance of soil organisms studied, some groups of organisms showed greater response than others. For example, millipedes and centipedes with RR near six appeared to benefit most from trees, followed by earthworms, ants, and mites with RR near three, springtails and beetles with RR near two. Termites and parasitic nematodes with RR near one appeared to be largely unaffected. While these results highlight a general pattern of trees promoting an increase in beneficial soil organisms, the limited number of studies and soil organisms suggests caution with generalizations regarding other soil organisms. Further, the paucity of studies which relate increases in

Table 5.2.1   Comparison of mean densities (individuals per m^2) of different soil biota in soils under agroforestry and continuous cultivation without trees, with the calculated response ratios (RR)[a]

	Agroforestry	Monocrop	RR	References
Soil macrofauna				
Earthworms	54.4	17.6	3.1	Dangerfield 1993; Tian *et al.* 1997, 2000; Sileshi & Mafongoya 2006a, b; Fonte *et al*. 2010
Beetles	20.9	9.6	2.2	Dangerfield 1993; Sileshi & Mafongoya 2006a,b
Centipedes	2.7	0.5	5.6	Dangerfield 1993; Sileshi & Mafongoya 2006a,b
Millipedes	8.1	1.3	6.1	Dangerfield 1993; Sileshi & Mafongoya 2006a,b
Termites	90.7	81.0	1.1	Dangerfield 1993; Sileshi & Mafongoya 2006a,b
Ants	23.2	8.6	2.7	Dangerfield 1993; Sileshi & Mafongoya 2006a,b
Soil mesofauna				
Collembola	3890.1	2000.7	1.9	Adejuyigbe *et al.* 1999
Mites	5100.7	1860.1	2.7	Adejuyigbe *et al.* 1999
Soil microfauna				
Non-parasitic nematodes	2922	1288	2.3	Kang *et al.* 1999
Parasitic nematodes	203.7	211.5	1	Kang *et al.* 1999

[a] The response ratio (RR), is the ratio of the mean value of the agroforestry practice to that of the control (continuous cropping). In this table RR quantifies both the direction and magnitude of changes in soil biota abundance: if trees do not have any effect on abundance RR = 1. If agroforestry trees favour soil biota the value of RR will be larger than unity, and vice versa if trees do not favour soil biota.

abundance with diversity and functional attributes limits inferences about possible functional benefits that the trees may promote.

Studies by Sileshi and Mafongoya (2007) found that soil biota responded differently to the application of organic resources of different quality. While earthworms and beetles were more abundant under legumes producing fast decomposing "high-quality" biomass, millipedes predominated under legumes producing slow decomposing "low-quality" biomass, and spiders and centipedes were not influenced by biomass quality. Studies by Barrios *et al.* (2005) compared coppiced planted fallows which showed that earthworm abundance beneath *I. constricta* was five times that of the values beneath *T. diversifolia*. Although both species had very similar plant tissue qualities the latter generated the greatest biomass and received the greatest nutrient inputs. These results suggest that while plant tissue quality

measures provide a good prediction of nutrient release patterns, there could be additional factors influencing changes in the abundance of soil biota. Further, the limited number of studies considering soil biota/plant tissue quality interactions, particularly in the tropics, has limited the development of a predictive understanding. Nevertheless, the notion that the functional characteristics of dominant plants rather than diversity, may be a key driver of soil biodiversity and function (Hooper *et al.* 2005), suggests considerable opportunities to optimize tree/soil biota interactions in agroforestry systems.

5.2.4 Soil biological processes and soil-based ecosystem services

The relationships between the soil biological community, the biological processes they generate, and the provision of ecosystem goods and services in
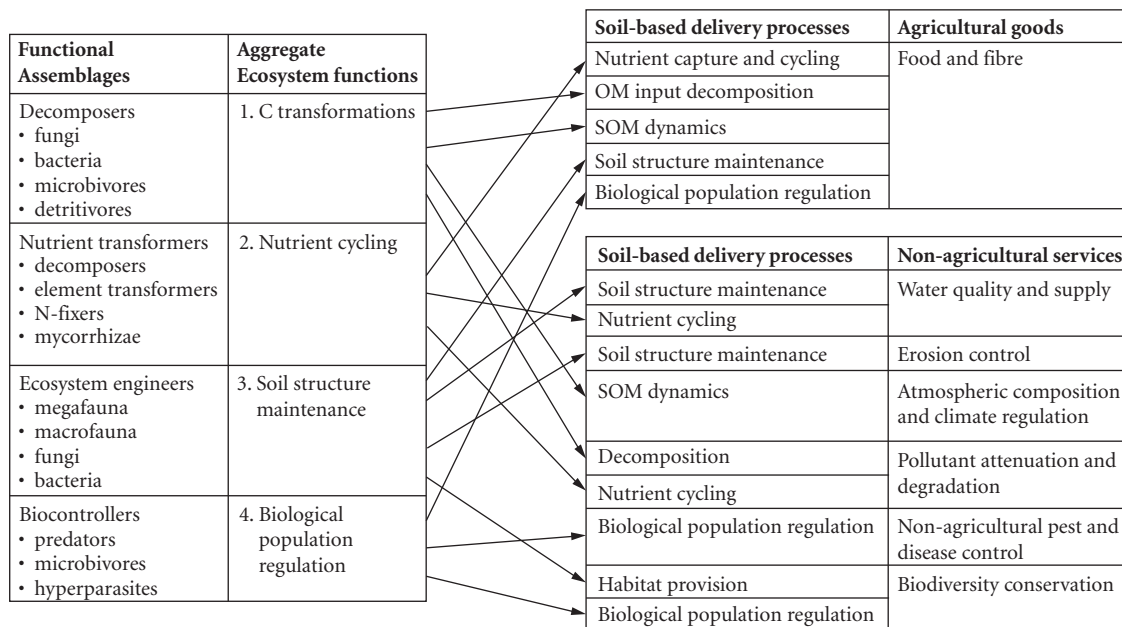
Functional Assemblages	Aggregate Ecosystem functions
Decomposers • fungi • bacteria • microbivores • detritivores	1. C transformations
Nutrient transformers • decomposers • element transformers • N-fixers • mycorrhizae	2. Nutrient cycling
Ecosystem engineers • megafauna • macrofauna • fungi • bacteria	3. Soil structure maintenance
Biocontrollers • predators • microbivores • hyperparasites	4. Biological population regulation

Soil-based delivery processes	Agricultural goods
Nutrient capture and cycling	Food and fibre
OM input decomposition	
SOM dynamics	
Soil structure maintenance	
Biological population regulation	

Soil-based delivery processes	Non-agricultural services
Soil structure maintenance	Water quality and supply
Nutrient cycling	
Soil structure maintenance	Erosion control
SOM dynamics	Atmospheric composition and climate regulation
Decomposition	Pollutant attenuation and degradation
Nutrient cycling	
Biological population regulation	Non-agricultural pest and disease control
Habitat provision	Biodiversity conservation
Biological population regulation	

Figure 5.2.3 Conceptual framework of linkages between soil biota, biologically-mediated processes and the provision of soil-based ecosystem goods and services. (Adapted from Kibblewhite *et al.* 2008.)

agricultural soils have been recently synthesized (Fig. 5.2.3).

Soil organisms can be grouped into four functional assemblages (Kibblewhite *et al.* 2008): 1) decomposers, 2) nutrient transformers, 3) ecosystem engineers, and 4) biocontrollers, each composed of several functional groups. Functional attributes of these assemblages can be similarly grouped into four aggregated ecosystem functions that include carbon (C) transformations, nutrient cycling, soil structure maintenance, and population regulation. The decomposition of organic matter, where organic C in litter and other organic inputs are transformed through the consecutive fragmentation and enzymatic activity of a diverse suit of decomposer organisms, results in the release of CO_2 and the synthesis of soil organic matter (SOM) (Barrios 2007). While strongly linked to decomposition, the cycling of nutrients is largely mediated by soil microorganisms whose activity levels are regulated by food web interactions within the soil community (Susilo *et al.* 2004). The maintenance of soil structure is fostered by the combined action of plant roots and soil organisms known as "soil ecosystem engineers"

that continuously modify the soil by forming "biological" aggregates, pores, and channels, thus altering soil physical properties and creating microhabitats for other soil organisms (Six *et al.* 2002). The biological control of pest and diseases takes place through the action of a wide range of soil organisms that regulate the populations of soil-borne diseases and pests largely through competition, predation, and parasitism (Susilo *et al.* 2004). These aggregated ecosystem functions participate in more than one soil-based delivery process. One or several soil-based delivery processes in turn are needed for the provision of ecosystem goods and services in agricultural landscapes. This framework is used to examine soil-based ecosystem services in agroforestry systems.

5.2.5 Tree–soil biota interactions foster the provision of soil-based ecosystem services

Trees and soil biota interact in a number of positive ways through facilitation and synergies. Facilitation is simply understood as diverse benefits provided

by one species to other species (e.g. what trees provide to soil organisms and crop plants). Synergies occur when interacting species perform better together than individually (e.g. symbiosis between nitrogen fixing bacteria and leguminous trees). The enhancement of agricultural production has been the focus of attention for many decades; however, agricultural sustainability concerns have increasingly shifted attention to ecosystem services responsible for life support (i.e. C transformations and nutrient cycling) and regulation of ecosystem processes (i.e. soil structure maintenance and biological population regulation) (Swift *et al.* 2004; Barrios 2007). This section highlights tree–soil biota interactions in agroforestry systems that contribute to the provision of soil-based ecosystem services of life support and regulation.

5.2.5.1 Carbon transformations and nutrient cycling

A major contribution of agroforestry trees to soil-based ecosystem services occurs as a result of aboveground and belowground organic inputs that provide C-substrates and nutrients needed for the soil organisms involved in C transformations and nutrient cycling. C transformations occur during the decomposition of organic inputs as a result of the collective action of decomposer organisms that fragment organic inputs (e.g. earthworms, millipedes, termites and mites). This transformation in turn facilitates the enzymatic action by fungi and bacteria that results in the release of nutrients to the soil matrix, loss of C to the atmosphere, largely as CO_2, and the synthesis of SOM (Barrios 2007). C transformations and nutrient cycling take place through coordinated interaction of decomposers and nutrient transformers (Kibblewhite *et al.* 2008) and are treated here as a functional continuum.

Increased nutrient availability in agroforestry systems is often associated with higher levels of SOM under trees than away from trees (Buresh & Tian 1998). Nevertheless, while increases in total SOM are closely related with increases in soil water availability, this is not the case for soil nutrient availability because nutrient release is dependent on the biologically active portion of SOM (i.e.

microbial biomass, light fraction SOM). The addition of biomass to soil from tree legumes such as *G. sepium* biomass through prunings (Barrios *et al.* 1996a,b), and also through litter and root turnover in *L. leucocephala* alley cropping (Vanlauwe *et al.* 1996) and planted tree fallows (Barrios *et al.* 1997), significantly contribute to increased light fraction SOM. Nevertheless, the relative contribution to light fraction SOM varies significantly amongst tree species. For example, the contribution of *Sesbania sesban* to the light fraction SOM was five times greater than species such as *C. calothrysus*, *Flemingia macrophylla*, *G. sepium*, *L. leucocephala*, and *S. siamea* (Barrios *et al.* 1997). The amount of N in the light fraction SOM was significantly correlated with N mineralization in the whole soil and with the yield of maize grown after the fallow phase (Barrios *et al.* 1998). Similarly, P in the light fraction SOM has been correlated with the amount of readily available P in the soil (Phiri *et al.* 2001).

The relative contribution of organic inputs to nutrient and CO_2 release through mineralization processes and SOM synthesis is strongly regulated by plant-soil biota interactions. The quality of organic inputs influences the decomposer biota composition and thus regulates the magnitude and rate of nutrient release (Wardle *et al.* 2004). Organic resource quality is an indicator of chemical composition and has been operationally defined by the concentrations of total N, lignin, and soluble polyphenols (Palm *et al.* 2001). Organic inputs of "high quality" (e.g. low lignin + polyphenol/N ratio) will decompose faster than those of "low quality" (e.g. high lignin + polyphenol/N ratio) and thus contribute relatively more to soil nutrient availability than to SOM formation and effects on microclimate. Studies comparing the effects of different agroforestry trees as planted fallows have concluded that high litter quality, and the ability of symbiotic microorganisms to fix N_2, characterize trees with the highest potential for increasing soil N availability (Barrios *et al.* 1997). However, if increased nutrient availability following organic inputs is not synchronized with crop demand, nutrient use efficiency can be low and lead to higher nutrient losses to the environment. Early increases in soil N availability after the addition of high qual-

ity residues of *I. constricta* and *T. diversifolia* resulted in 20% and 17% N recovery by crop plants, respectively, whereas slower N release by the low quality residues of *C. calothyrsus* considerably increased plant N recovery to over 47% (Cobo *et al.* 2002).

Tree biomass also serves as a substrate for the synthesis of SOM. Regular organic inputs through leaf litter, tree prunings, and root turnover will have long term impacts on soil carbon and nutrient stocks and thus agroecosystem sustainability. While low quality organic resources are often associated with larger relative contributions to SOM (Palm *et al.* 2001), repeated applications of pruning of high quality biomass, such as those in the *Gliricidia*-maize intercropping systems in Malawi and Zambia also build SOM (Beedy *et al.* 2010). Root turnover is likely to be an important source of organic matter that significantly contributes to SOM synthesis and soil carbon storage in these contexts (Makumba *et al.* 2007). The physical protection of SOM during soil aggregation ensures sustained increases in SOM because soil aggregates generated by ecosystem engineers prevent rapid loss of SOM potentially reducing greenhouse gas emissions (Six *et al.* 2002). According to Castro *et al.* (2009) the Quesungual slash and mulch agroforestry practice was a net CH_4 sink (-102 mg CH_4 m^{-2} $year^{-1}$) compared to slash and burn agriculture that was a net source of 150 mg CH_4 m^{-2} $year^{-1}$. While both land uses were net sources of N_2O and CO_2, the overall global warming potential for slash and burn was nearly four times higher than that of slash and mulch. These results are consistent with other studies at the same location showing increased earthworm activity and reduced C loss with mulching rather than burning (Fonte *et al.* 2010; Pauli *et al.* 2010). Davidson *et al.* (2008) in the Brazilian Amazon also showed that burning generated five times higher CO_2-equivalent emissions than mulching, which contributes to global warming mitigation efforts. These results highlight important opportunities to design and manage agroforestry practices to include mixtures of trees that generate residues of different qualities, promoting SOM synthesis, nutrient release, and reduction of greenhouse gas emissions in ways that optimize the ecosystem services from organic matter decomposition, including nutrient supply, water quality and supply, as well as climate regulation.

5.2.5.2 Symbiotic interactions and nutrient cycling

Biological nitrogen fixation (BNF) constitutes a key nutrient input to agroecosystems (Giller 2001). The contribution of leguminous trees to building up N in degraded soils through BNF is well recognized as an important component of the ecosystem service of nutrient cycling (Barrios 2007). There are significant differences in estimates of BNF in trees, ranging from high rates up to 472 kg N_2 ha^{-1} $year^{-1}$ in *L. leucocephala*, *G. sepium*, *C. calothyrsus* to low rates <50 kg N_2 $year^{-1}$ in *Acacia melanoxylon* and *A. holoserica* (Giller 2001). However, actual BNF rates under field conditions are often lower than the potential maximum as they are considerably affected by soil and climatic conditions. The high variability in percentage of total plant N derived from the atmosphere among tree provenances of *L. leucocephala* (37–74%) and *Faidherbia albida* (6–37%) found by Sanginga *et al.* (1990), and *G. sepium* (Sanginga *et al.* 1994), suggest opportunities for optimizing this symbiotic tree–soil biota interaction. Nevertheless, the precise quantification of the amount of N_2 fixed in trees continues to be limited by methodological constraints (Giller 2001).

Arbuscular mycorrhizal fungi (AMF) associated with trees can complement the nutrient capture function of deep roots by increasing the recovery of nutrients from the subsoil when allowing exploration of a larger soil volume. They may also reduce nutrient loss through leaching and associated pollution, while also increasing uptake of less mobile nutrients like phosphorus. For example, the remarkable ability of *T. diversifolia* to accumulate large quantities of P in its biomass, as well as all other nutrients, seems to be related to the unusual specificity of its mycorrhizal associations (Sharrock *et al.* 2004). The lack of adequate P nutrition is usually a key limiting factor to BNF and therefore the combined action of both symbionts should be encouraged. However, legumes known to be able to fix N_2 under low soil P availability should also be targeted for agroforestry (Sprent 1999). Improved nutrition

of trees hosting AMF and nitrogen fixing bacteria would encourage greater nutrient input and greater quantities of nutrients being recycled. The optimization of these interactions is of particular significance for resource poor farmers with limited access to fertilizers and in most tropical soils where N and/or P are limited.

5.2.5.3 Soil structure maintenance

Soil aggregates resulting from the arrangement of soil primary particles and SOM bound by organic and inorganic agents constitute the structural units within the soil. Soil structure is thus a dynamic property reflecting the balance between aggregate forming factors and those that disrupt them (Six *et al.* 1998). The formation of "biological aggregates" and their stabilization is the result of the activity of fungi, bacteria, plant roots, and macrofauna (Six *et al.* 2002). Studies by Kang *et al.* (1994) reported that surface casting by *Hyperiodrilus africanus* was higher under trees including *Dactilenia (Acioa) barteri*, *Alchornea cordifolia*, *G. sepium,* and *L. leucocephala* than in a control plot without trees. In that study, while casting activities under *D. barteri* and *G. sepium* were of similar magnitude (26.4 and 24.4 Mg ha^{-1} year^{-1} respectively) the content of water-stable aggregates in worm casts varied with tree species, being highest under *D. barteri* and lowest under *G. sepium*. Recent studies in the Quesungual slash and mulch agroforestry practice (Fig. 5.2.2) show that the spatial distribution of casts was closely related to the spatial arrangement of trees and mulch (Pauli *et al.* 2010). This highlights the role of trees in promoting biological activity that contributes to soil structure maintenance. Another study in the same locality which compared the impact of slash and mulch with slash and burn showed that the mean soil erosion rate after three years was about six times higher with burning than mulching (Castro *et al.* 2009). Additionally, higher soil mesoporosity (30%) and macroporosity (19%) for mulching versus burning are consistent with increases in biological activity of various soil organisms that generate pores and channels of different sizes and shapes. These porosity differences significantly influence the plant available soil water

storage capacity, water infiltration, surface runoff, and soil erosion.

Arbuscular mycorrhizal fungi have received considerable attention because of their contribution to the formation and maintenance of soil structure through hyphal enmeshment of soil aggregates and deposition of glomalin, an AMF-specific glycoprotein strongly linked to water stable aggregation (Rillig 2004). The dynamics of physical protection of SOM in soil aggregates has received considerable attention because of its importance for soil carbon sequestration. When soil aggregates break into smaller pieces upon wetting, erosion rates increase, and SOM is readily exposed to microbial action that results in C loss to the atmosphere (Barrios 2007). Therefore, the overall potential effect of agroforestry on soil erosion control and soil C sequestration are clearly underpinned by tree–soil biota interactions that foster increases in the proportion of soil aggregates that are stable upon wetting during rainfall events, and in the magnitude and diversity of soil porosity that allows a balance between infiltration and soil water storage for plants and soil organisms. These results highlight important opportunities for the design of agroforestry practices that incorporate tree species diversity and mulch management, to promote soil biological diversity and activity that optimize the aggregate dynamics required for soil erosion control, C sequestration, and the supply of good quality water.

5.2.5.4 Control of pests and diseases

The control of soil-borne pest and diseases through biological regulation is an ecosystem service of great economic, human health, and environmental importance because global annual crop losses are near 30% and commonly controlled with application of biocides toxic for humans and the environment (Oerke & Dehne 2004). The relationship between the soil biota, soil fertility, and plant health is strengthened in agroforestry systems as trees improve soil fertility, foster above- and belowground biodiversity, and support the development of complex food webs that keep pests and diseases under control through a combination of predation, parasitism, and competition. Several soil organisms

such as collembolans, ants, beetles, centipedes, spiders, and predatory mites and nematodes act as biocontrol agents (Sileshi *et al.* 2001). Termite damage to maize in eastern Zambia was reported to be consistently lower in maize-tree (*L. leucocephala*, *G. sepium*, and *S. sesban*) associations compared to monoculture maize (Sileshi *et al.* 2005). The increased damage in monoculture maize was attributed to low soil organic matter, low soil fertility and, water stress. Fungus-growing termites preferentially feed on crop residues, mulches, and soil organic matter; however, if these are not available, they will eat live plants. The addition of large quantities of leaf litter or pruning biomass in maize-tree associations could increase labile pools of soil organic matter and water availability, and improve soil fertility, which could increase crop vigour and reduce termite damage (Sileshi *et al.* 2005). According to studies in the same area where the soils are heavily infested with *Striga asiatica* under conventional management, maize infestation was negligible following planted tree fallows of *S. sesban* and *S. siamea* that increase soil N availability (Barrios *et al.* 1998). Nevertheless, it is important to highlight that single species agroforestry systems (e.g. planted fallows) also have a high potential to face similar pest and disease problems found in crop monocultures as shown in some *S. sesban* planted fallows (Sileshi *et al.* 2008). Therefore, agroforestry systems that include different tree species, especially if they represent different plant functional types, are likely to increase the diversity of niches suitable for biological control agents. Current understanding about factors affecting plant-soil biodiversity interactions that could influence the effectiveness of biological control agents is particularly limited for agroforestry systems and suggest opportunities for future agroforestry system design to ensure adequate plant and soil biodiversity levels that would allow the tree–soil biota interactions required for biological control of soil-borne pests and diseases.

5.2.6 Soil health monitoring systems

Evidence on the benefits of trees on soil biota and ecosystem services is fragmented and strongly biased towards small-scale plot experiments. How-

ever, new advances in remote sensing, georeferenced field surveys, and proximal soil sensing (e.g. Sanchez *et al.* 2009) are providing new opportunities for vegetation and soil measurement and monitoring at multiple scales referred to here as land health surveillance. Developments in information and communication technology are also providing unprecedented opportunities for engaging local communities in systematic data collection (Ballantyne *et al.* 2010).

5.2.6.1 Land health surveillance

Land health is the capacity of land to sustain delivery of essential ecosystem services. Land health surveillance implies large area monitoring of land health using standardized measurement protocols that permit meta-analysis, and where appropriate, use of statistical approaches for sampling of populations to avoid sampling bias (Shepherd *et al.* 2008). The Africa Soil Information Service (AfSIS) provides an example of the application of these principles and provides opportunity for systematic study of tree–soil interactions from continental to plot (or stand) scales. AfSIS deploys a randomized set of "sentinel" sites, spatially randomized within major Köppen climatic zones in non-desert portions of sub-Saharan Africa (Fig. 5.2.4). A sentinel site is a 10×10 km block of land, within which a spatially stratified, randomized ground sampling scheme is implemented. Tree and shrub density are measured and soil samples taken in 100-m^2 sub-plots, which are nested within 1000-m^2 plots, in turn nested within 1-km^2 diameter clusters. The position of the clusters within the 2.5×2.5 km tiles is also randomized. Soil samples from each plot are characterized using infrared spectroscopy (Shepherd & Walsh 2007) as a front-line soil screening tool (Fig. 5.2.4). Conventional reference analyses of soil chemical, physical, and biological properties are done on a random subset of samples and related to infrared spectral signatures to infer values for the entire set of samples. The georeferenced soil properties are mapped through hierarchical statistical modeling of the soil data from the combined set of sentinel sites to satellite data (e.g. Landsat, Modis) and other GIS data (e.g. digital elevation models) with continental coverage.
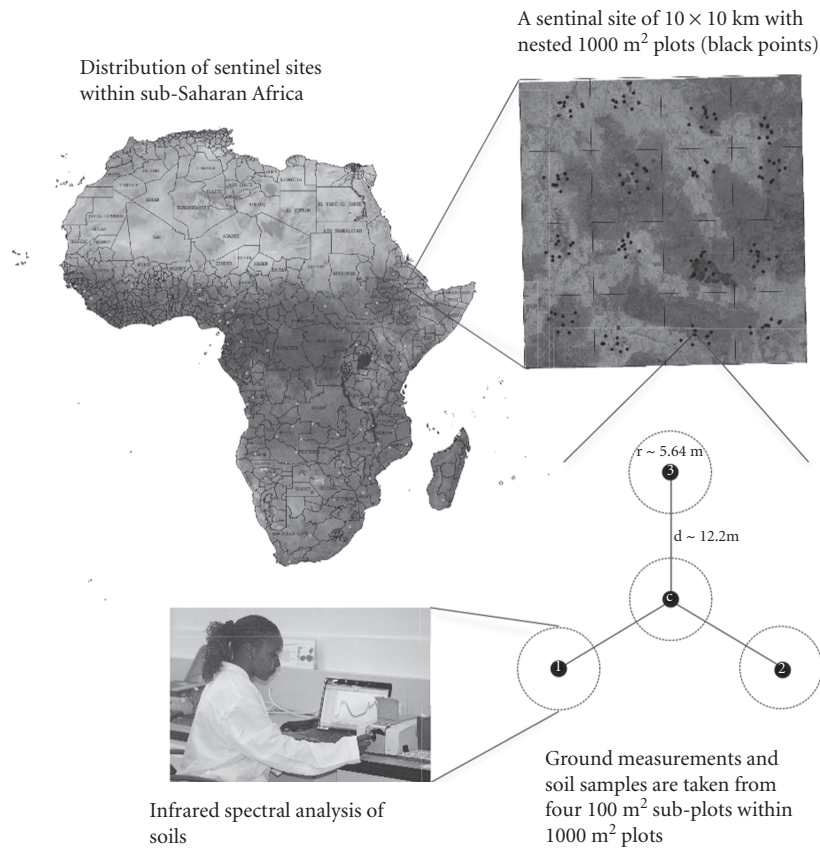
Distribution of sentinel sites within sub-Saharan Africa

A sentinal site of 10×10 km with nested 1000 m^2 plots (black points)

r ~ 5.64 m

d ~ 12.2m

Infrared spectral analysis of soils

Ground measurements and soil samples are taken from four 100 m^2 sub-plots within 1000 m^2 plots

Figure 5.2.4 Illustration of the measuring scheme used in the Africa Soil Information Service. (Graphics by Tor-Gunnar Vagen.)

The richness and consistency of the data sets provide unprecedented opportunities for exploring tree–soil interactions at different scales. For example, collection of data on soil microbial and faunal diversity is being piloted using DNA sequencing (e.g. Fierer & Jackson 2006; Wu *et al.* 2009). The soil biodiversity data can then be related to other data collected at the different scales, such as soil chemical and physical properties, soil erosion status, vegetation characteristics, woody biomass density, land form, climate, etc.

The population based sampling frame permits statistical distributions of key soil biodiversity indicators to be established, and these can be used to develop norms conditioned on factors such as climate zone, topography, land cover classification, historic land cover, geology, landscape position, and

static or slowly changing soil variables. Comparison of indicator values against norms can be used as a statistical basis for developing indicators of degradation. This represents a major advance since it is currently difficult to interpret soil biodiversity data in terms of soil functional capacity. Furthermore, risk factors associated with biodiversity loss could be quantitatively established and verified through monitoring changes in prevalence of degradation over time (i.e. incidence). The surveillance approach has potential to greatly increase the efficiency of research in terms of knowledge gained per unit research investment. For example, the combination of probability sampling, co-located measurements, and use of standardized protocols enables characterization of whole populations and the meta-analysis of results at different scales. This contrasts with
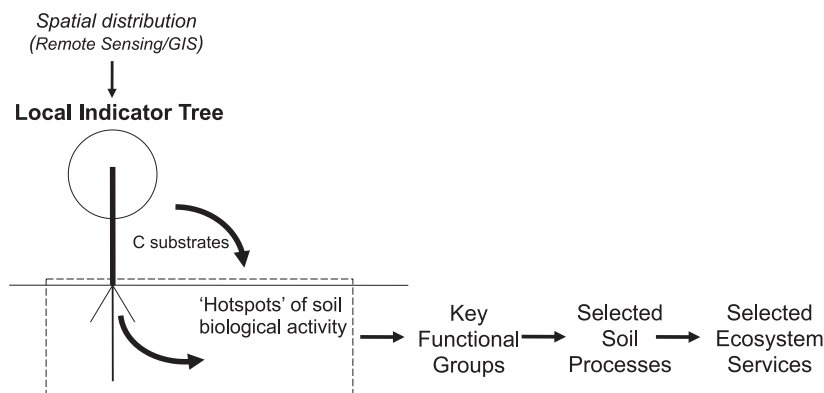
Figure 5.2.5   Integrative approach to identify hotspots of soil biological activity. (Adapted from Barrios 2007.)

existing approaches in which studies typically do not sample a known population of soil spatial units and results can rarely be combined to provide multiscale insights or generalizable conclusions. Surveillance can provide a practical, evidence-based approach for considering soil biodiversity and other land health indicators when planning and evaluating land management interventions.

There is potential for land users to participate in centrally coordinated land health surveillance systems, and in doing so increase the quality of the information they are able to access. Land users could make simple georeferenced observations on land quality using a standardized protocol and submit this data through mobile phone technology to centralized databases. Ways to avoid sampling bias would have to be found, but there may be opportunity for researchers to direct sampling efforts to locally recognized degradation hot spots by using adaptive sampling schemes. Systems whereby communities take soil samples from pre-defined georeferenced locations may also be possible. Further, land users could utilize the same technology to tap into information systems that provide highly location-specific information on land and climatic conditions and access interpreted results from their observations. Local observations could be used to improve recommendations through Bayesian updating (Pearl 1988) of prior information supplied from regional environmental databases, returning the improved estimate to the user.

5.2.6.2 Integrating local knowledge about soil health

The increasing attention paid to local knowledge in recent years is recognition that the knowledge of people who have closely interacted with their environment for a long time can offer many insights about the sustainable management of natural resources (Barrios *et al.* 2006). Participatory research approaches that encourage the integration of local and scientific knowledge could be useful to reduce the uncertainty of plant–soil biota interaction studies at the landscape scale by adding relevance and legitimacy to the process. Barrios (2007) proposed an approach to integrate local knowledge for the identification of soil biota "hotspots" in the landscape that are presumably responsible for a large proportion of the provision of soil-based ecosystem services. In short, local knowledge about native plants as indicators of soil health is consistently considered a key source of information for land use decision-making across farming communities of Latin America and Africa (Barrios *et al.* 2006). The presence of native plants indicating healthy soils informs and assists farmers to make decisions during establishment of new agricultural plots. Similarly, Barrios (2007) proposed to use local indicator trees to identify healthy soils where "hotspots" of soil biological activity are likely to be concentrated (Fig. 5.2.5).

These "hot spots" include the rhizosphere, biogenic structures (i.e. soil aggregates), soil C pools

(i.e. light fraction SOM), and organic detritus (i.e. litter), where key functional assemblages can be studied to focus on soil biological processes that underpin the provision of soil-based ecosystem services. Given the difficulty of studying soil biota at the landscape scale, greater knowledge about indicator plant–soil biota interactions combined with spatial information obtained from remote sensing about indicator plants, could guide inferences about the role of soil biota and function in the provision of soil-based ecosystem services. The general consensus that soil biological processes are not randomly distributed but largely aggregated near C substrates, and that greater knowledge about tree–soil biota interactions have great potential to improve understanding of the impacts of soil biota at larger scales, are consistent with this approach (Wardle *et al.* 2004).

5.2.7 Conclusions and recommendations

Agroforestry systems have the potential to facilitate the transition to multifunctional agriculture that successfully addresses the challenge of optimizing crop productivity while maintaining the provision of other ecosystem services. In order to realize this potential, however, there is considerable need for greater understanding of how to optimize tree–soil biota interactions that improve agroecosystem function and soil health.

The promotion of agroforestry systems including multiple tree species (e.g. multistrata agroforestry systems) has been highlighted here as a strategy to enhance the sustained provision of soil-based ecosystem services. Combining trees and crops that can coexist while generating sufficient organic inputs of different quality is seen as a way to preserve soil cover and increase the diversity and persistence of active soil biota. There is a need to further study the impact of spatial arrangements and management that minimize competition and favors complementarities and facilitative interactions among trees and associated crops in terms of biomass production, nutrient and water use efficiency, and how these in turn influence the abundance, diversity, and activity of key soil biota. Tree–soil biota interactions both respond and influ-

ence ecosystem properties, and so, a greater understanding of the feedbacks involved is necessary to link experimental results at smaller scales with those at large scales. Agroforestry practices embrace manageable levels of complexity that would help address fundamental questions about the role of interacting above- and belowground biodiversity in increasing functional resilience to disturbance or climate change. The use of gradients of physical factors and agricultural intensification as the basis of landscape experimental design would be helpful to gain greater understanding of tree–soil biota interactions under different disturbance regimes and how they influence agroecosystem function and the provision of ecosystem services.

A better understanding of tree–soil biota interactions would provide opportunities to design systems that maximize complementarities, facilitation, and synergies that result in the sustained provision of ecosystem services. Major challenges to the measurement of ecosystem services and the interpretation of data include the particularly limited number of published quantitative field studies, the diversity of applied methods, the difficulty in sampling and identification of some taxa, the spatial biases created by some sampling methods, and the different spatial and temporal scales at which ecosystem services are delivered. The focus proposed by Kibblewhite *et al.* (2008) on four aggregate ecosystem functions and key functional groups or assemblages constitutes a practical approach to address the difficulty of studying all soil biodiversity as part of soil health evaluation. The application of common methodologies for sampling and characterizing soil biota (Moreira *et al.* 2008) may allow greater comparability among studies in agroforestry systems. Furthermore, the strategic use of molecular tools, analysis of stable isotopes, and spectroscopic techniques will increase the ability to identify and characterize "hotspots" of biological activity and facilitate the study of linkages between key soil biota and ecosystem functions at different temporal and spatial scales.

The Land Health Surveillance approach used in the AfSIS project, provides a robust experimental framework to systematically analyze and integrate information at different spatial and temporal scales,

and thus provide a comprehensive evaluation of how changes in tree density and diversity influences soil health in agricultural landscapes. Research efforts are also needed for the development of local soil health monitoring systems that inform land users about their land's capacity to provide ecosystem services (Barrios 2007). The empowerment of local communities, and agricultural research and extension institutions, to conduct local monitoring can generate valuable information. Such data, combined with new approaches for the economic valuation of ecosystem services, may be used during negotiations for payments of ecosystem services that reward good management practices and thus become a further incentive mechanism for sustainable land management and development.

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