24 Nurturing Soil Life through Agroforestry

The Roles of Trees in the Ecological Intensification of Agriculture

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Soil resources constitute the very foundation of agriculture, so sustainable agriculture is inherently dependent on soil health (Brown et al., 1994). Soil health reflects the capacity of soil to respond beneficially to agricultural management, maintaining both agricultural production and the provision of varying ecosystem services, nutrient cycling, and biodiversity conservation in the long term (Kibblewhite et al., 2008). Soil health depends on the physical, chemical, and biological conditions of the soil that are required for plant growth and development. These conditions are inherently linked to the capacity of natural and agricultural ecosystems to produce biomass (Barrios et al., 2015; Bünemann et al., 2018).

By its nature, soil health is a "slow variable", with changes taking place at a slower pace (e.g., years) than occurs with some other system variables. However, it has a controlling influence on how "faster variables" like crop production respond to some external drivers like rainfall during the growing season (Walker et al., 2012). This slow-changing nature of soil health allows for pervasive interactions with a wide range of biophysical and socioeconomic constraints that affect sustainable agroecosystem management. The management of soil health requires a holistic approach and a long-term perspective that aims to promote greater functional resilience and reduce risk by diversifying kinds of production and by reducing dependence on

external inputs (Swift et al., 2004; Tittonell, 2014; FAO, 2018; Barrios et al., 2020).

Agricultural intensification undertaken with greater reliance on exogenous inputs, particularly over the past 50 years, has contributed to net gains in human well-being and to economic development, but at the cost of degradation of natural resources (Steffen et al., 2004; Millennium Ecosystem Assessment, 2005). A key challenge for global sustainability is feeding the 9.6 billion people expected by 2050 (Caron et al., 2018; FAO, 2019).

Ecological intensification differs from current strategies for agricultural intensification by embracing agroecological transitions to more sustainable agriculture and food systems (Barrios et al., 2020; Wezel et al., 2020). This may involve the strategic and tactical use of external inputs, but it encourages the recovery and optimization of biological regulation in agroecosystems, relying mostly on ecological processes and functions that are sustained by biodiversity. This lowers producers' risks by reducing their dependence on external inputs, with few or no negative externalities for the natural environment (Dore et al., 2011; Bonmarco et al., 2013; Tittonell and Giller, 2013).

Agroforestry has been increasingly recognized and practiced as a multifunctional land management option that can simultaneously contribute to income, food security, and the conservation of biodiversity and ecosystem

services (Steffan-Dewenter et al., 2007; Akinnifesi et al., 2010; Tscharntke et al., 2011; Barrios et al., 2018; Kuyah et al., 2019). It is also a means for climate change adaptation and mitigation (Mutuo et al., 2005; Verchot et al., 2007; Schoeneberger et al., 2012). This has led to the recognition of agroforestry as a desirable natural resource management intervention with growing demand for scaling it up along with other land management options, capitalizing on their potential synergies to deal with the challenges of global change (Pretty et al., 2006; Jackson et al., 2012; Vanlauwe et al., 2014; Prabhu et al., 2015; Barrios et al., 2020).

Agroforestry practices have been shown to enhance soil health (Buresh and Tian, 1998; Clough et al., 2011; Muchane et al., 2020). The contribution of trees to building soil health and functional resilience is attributed at least in part to their perennial nature, which profoundly affects microclimates and soil properties and influences the abundance, diversity, and activity of the soil biota required to sustain critical biological functions that underpin soil-mediated ecosystem services (Barrios et al., 2012a).

The high variability in soil system responses to soil management interventions that is often encountered has been attributed to limited or little consideration of the underlying fine-scale variation in ecological and social contexts when making assessments. This reduces the utility of supporting decisions that are based on mean effects or average conditions (Coe et al., 2014). It is now well-recognized that the success or failure of management interventions is usually context-specific and that no particular intervention can be a panacea (Carpenter et al., 2009; Díaz et al., 2011; Giller et al., 2011). Therefore, successful scaling up of agroforestry systems requires fostering co-learning processes among the key stakeholders and institutions in order to match agroforestry options to sites and circumstances (Coe et al., 2014).

This chapter discusses the pivotal role that trees play in building and maintaining the soil health and functional resilience that are required for the ecological intensification of agriculture. First, current knowledge about functions and impacts of trees on soil health is summarized, and then the tree/soil biodiversity interactions that drive these functions are highlighted. Key socioeconomic factors that affect agroforestry adoption and the heterogeneous impacts of trees in specific farmer contexts and circumstances are then reviewed as potential limits on the fullest attainment of agroforestry contributions to soil health. We conclude with a summary of knowledge gaps that should be addressed.

24.1 SOIL HEALTH BENEFITS FROM THE FUNCTIONING OF TREES

The magnitude and timing of soil health benefits from agroforestry are largely dependent on three main factors, namely, the proportion of area that is under agroforestry, the characteristics and context of the agroforestry system introduced, and the functions satisfied by the agroforestry trees (Figure 24.1).
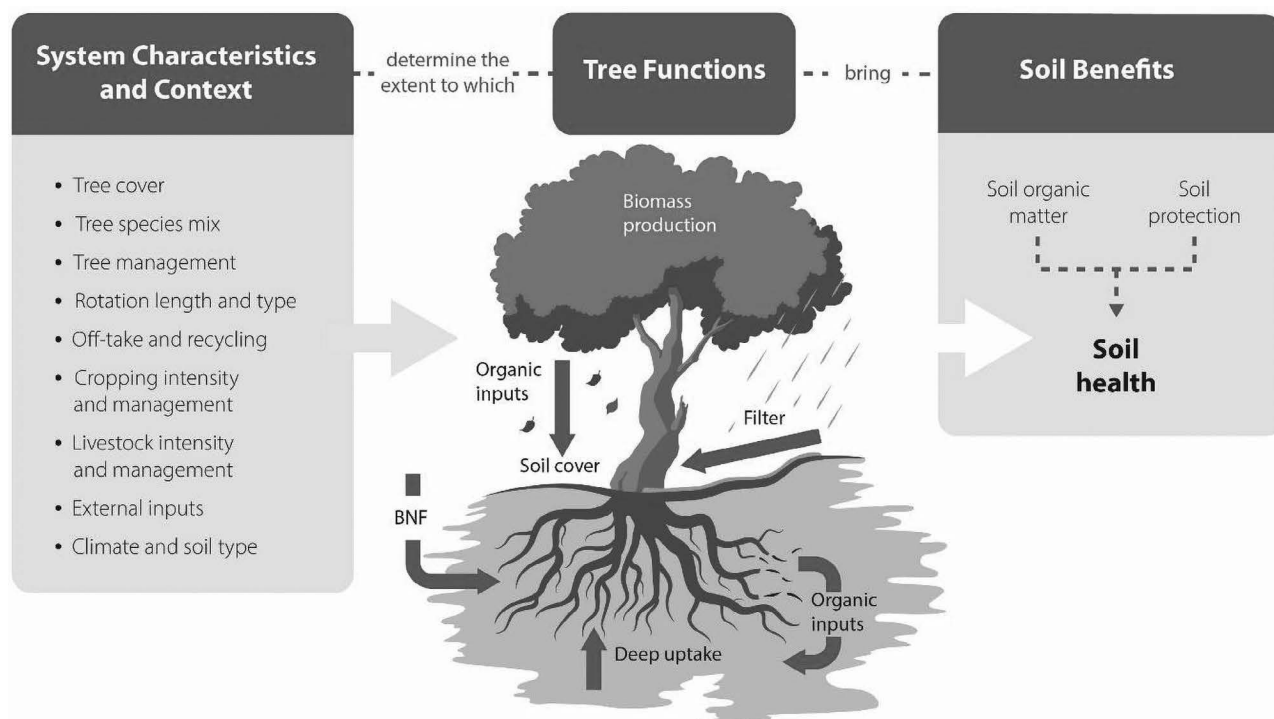

FIGURE 24.1 The influence of system characteristics on key soil functions and soil health benefits provided by agroforestry trees.

The impacts that agroforestry has on soil health derive from five major sources or functions (Young, 1997; Van Noordwijk et al., 2004):

1. *Organic inputs above- and belowground.* Agroforestry trees can contribute up to 20 t of dry matter ha^{-1} yr^{-1} just from prunings, which can contain as much as 358 kg nitrogen (N), 28 kg phosphorus (P), 232 kg potassium (K), 144 kg calcium (Ca), and 60 kg magnesium (Mg) (Palm, 1995). Tree roots also contribute significant organic matter to soil through rhizodeposition.

2. *Biological nitrogen fixation (BNF).* Agroforestry trees, particularly leguminous ones, can contribute N inputs through their BNF, which has been found to range from 56 to 675 kg N ha^{-1} yr^{-1} depending on climate, tree species, and management system (Nygren et al., 2012).

3. *Deep uptake and recycling of nutrients from below the crop root zone.* During the dry season, some agroforestry tree species, e.g., *Vitellaria paradoxa*, have been found to take up as much as 50% of their water from below the rooting zone of crops, which means they are not competing so much with crops (Bayala and Prieto, 2020). Trade-offs due to competition for nutrients and water with crops can be found, however, with certain trees, e.g., fast-growing species, in particular contexts such as drylands (Bayala et al., 2012).

4. *Water filter and accumulation functions* of agroforestry trees, which create water infiltration sinks that absorb water and also barriers to overland flows of water and sediment. This can reduce soil erosion rates by as much as 50% (Muchane et al., 2020) and can increase infiltration rates by up to 2.8 times (Ilstedt et al., 2007).

5. *Protection of the soil surface* by tree litter cover, up to 68% during the cropping season (Pauli et al., 2010).

Soil organisms are major drivers of key ecosystem processes that underpin crop productivity and the provision of ecosystem services (Wardle et al., 2004; De Vries et al., 2013; Wagg et al., 2014; Balvanera et al., 2016). Nevertheless, soil biodiversity has largely remained hidden in the dark until recently, when molecular techniques have begun to reveal the unseen (Whitman et al., 1998; Wall et al., 2010; Orgiazzi et al., 2016; FAO/ITPS/GSBI/CBD/EC, 2020).

Further, the soil biota has been largely absent from efforts to construct models for soil management, with the soil system commonly treated as a "black box", particularly in high-input agriculture (Tiedje et al., 1999; Smith et al., 2015). This may be because in this kind of agriculture, the soil biota and the biologically mediated processes that regulate soil structure, nutrient supply, and pest and disease control have been largely replaced by external inputs such as soil tillage, inorganic fertilizer, and pesticide applications (Swift and Anderson, 1993; Barrios, 2007).

Nevertheless, recognition is growing that soil microbes can influence most functional traits of plants at levels comparable to the effects of the plant genotype. This recognition has highlighted microbes' potential to have large impacts on ecosystem processes and services through their modification of plants' adaptation to abiotic conditions and their interactions with other species, as well as their population dynamics (Friesen et al., 2011; Veen et al., 2019). The next section describes how tree-soil biota interactions bear on the five major functions through which agroforestry trees, i.e., trees grown within areas of farming operations or managed landscapes, are known to contribute to soil health.

24.2 SOIL HEALTH-RELATED FUNCTIONS OF TREES MEDIATED BY SOIL BIOTA

Understanding the roles of the soil biota and monitoring the abundance, diversity, and activity of functional assemblages, e.g., litter and nutrient transformers, ecosystem engineers, and bio-controllers, are needed to bolster or recover the self-regulation capacity of agroecosystems. Knowledge of the soil biota can guide management decisions by providing early indications of degradation and recovery processes that affect soil health taking place before visible above-ground signs can be detected (Pankhurst et al., 1997; Barrios, 2007). For example, agroforestry practices have been shown to modify the abundance of certain beneficial soil organisms and to support hotspots of soil biological activity near trees (Pauli et al., 2010; Kamau et al., 2017; Dierks et al., 2021).

Significant and consistent increases in the abundance of beneficial soil biota are associated with agroforestry practices, as seen in Table 24.1, which summarizes data found in the current literature. The response ratio (RR) is a ratio between the mean value of the indicator being evaluated in an area under agroforestry where appropriate trees are co-managed with crops compared to the mean value reported from an adjacent area where the cultivation of crops is managed without trees (Hedges et al., 1999). In practice, RR values need to be log-transformed to ensure normality and homogeneity of variance prior to analysis, and then presented in the arithmetic domain after back-transformation. Table 24.1 summarizes the back-transformed means and their 95% confidence limits (CL) estimated using 1,999 bootstrap replicates.

Substantial differences are generally observed in the mean abundance of soil organisms in proximity to agroforestry management, although some groups of organisms show greater response than others. For example, springtails (Collembola) with an RR near 5.0 appear to benefit the most from trees, followed by millipedes and mites with an RR near 4.0, and earthworms, centipedes, and nonparasitic nematodes with an RR near 2.0. Beetles, termites, ants, and parasitic nematodes with RRs near 1.0 appear largely

TABLE 24.1

Comparison of the Abundance of Different Soil Biota in Adjacent Soils under Agroforestry and Continuous Cultivation without Trees, Showing the Calculated Response Ratio (RR)*

Soil Group	Taxon	Agroforestry	Cultivation without Trees	Mean RR[a]	95% Confidence Intervals of RR	Sources[b]
Macrofauna (no. per m^{-2})	Earthworms (89)	60.0	24.5	2.3	(1.8–3.0)	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 19
	Beetles (40)	22.3	9.7	1.6	(1.2–2.3)	1, 2, 5, 7, 19
	Centipedes (38)	2.8	0.5	2.0	(1.5–2.6)	1, 2, 5, 7
	Millipedes (40)	8.7	1.5	4.4	(3.1–6.4)	1, 2, 5, 7, 19
	Termites (38)	107.5	98.2	0.8	(0.5–1.3)	1, 2, 5, 7, 19
	Ants (42)	31.9	12.4	1.5	(0.9–2.3)	1, 2, 5, 7, 19
Mesofauna (no. per m^{-2})	Collembola (9)	3,890.1	2,000.7	5.0	(2.0–12.7)	12
	Mites (27)	5,100.7	1,860.1	3.5	(2.8–4.4)	12
Microfauna (no. per 1000 cm^{-3} soil)	Nonparasitic nematodes (22)	2,678.6	1,198.1	2.1	(1.7–2.6)	13, 14, 15
	Parasitic nematodes (124)	1,198.2	1,961.8	1.1	(0.8–1.5)	13, 14, 15, 16, 17, 18

Source: Updated from Barrios et al. (2012a).

[a] The response ratio (RR) was calculated for each study under each taxon, and then RR values were log-transformed to ensure normality and homogeneity of variance prior to averaging across studies or locations. Column 5 presents the values back-transformed to the arithmetic domain. Therefore, the values in column 5 will not necessarily be equal to the ratio of column 3 and 4. The 95% confidence limits (CL) were estimated using 1,999 bootstrap replicates.

[b] 1: Sileshi and Mafongoya (2006a); 2: Sileshi and Mafongoya (2006b); 3: Tian et al. (1997); 4: Tian et al. (2000); 5: Dangerfield (1993); 6: Fonte et al. (2010); 7: Rahman et al. (2012); 8: Leon et al. (2006); 9: Aquino et al. (2008); 10: Hairiah et al. (2006); 11: Geissen et al. (2009); 12: Adejuyigbe and Tian (1999); 13: Kang et al. (1999); 14: Kandji et al. (2001); 15: Kandji et al. (2002); 16: Desaeger and Rao (2000); 17: Desaeger and Rao (2003); 18: Banful et al. (2000); 19: Musowka and Mafongoya (2021)

unaffected by the proximity of trees. Of significance for farmers is that parasitic nematodes were found to be about 64% more numerous in fields without trees.

Spatial analysis of earthworm activity has repeatedly shown this to be significantly higher near to trees than away from them, although this effect is greater for some tree species than for others (Pauli et al., 2010; Kamau et al., 2017). This analysis comparing the density of soil organisms in relation to tree species makes clearer how and why trees play an important role in boosting the functional resilience of agroecosystems, providing resources and habitat that conserve soil biota, particularly during periods of environmental stress. When conditions become more favorable again, soil organisms can rapidly recolonize and recover the levels of abundance required for desirable agroecosystem functioning.

Although there is a general pattern of trees promoting increases in beneficial soil biota, some caution is advised when making generalizations regarding other soil organisms because the number of studies of soil organisms considered to date is limited. For instance, it has been found that some soil-borne diseases are more prevalent with agroforestry practices in particular contexts (Rosemeyer et al., 2000). So, simply having more soil organisms is not necessarily always better.

A meta-analysis of the effects of agroforestry on pest, disease, and weed control has shown significantly higher abundances of natural enemies of crop pests in agroforestry systems (Pumariño et al., 2015), but it found that the effects on invertebrate pests and diseases depended on the crop type. Reduction in pest and disease incidence was found to be significant in perennial crops such as coffee, cocoa, and plantain, but not so much in annual crops such as maize, rice, and beans.

24.2.1 Organic Inputs

Organic inputs into soil by agroforestry trees sustain the functional capacity of soil to accrue the soil health benefits of soil organic matter (SOM) by influencing carbon transformations, nutrient cycling, and soil structure maintenance, and indirectly, the biological regulation of pests and diseases through habitat creation (Barrios et al., 2012a). The contribution of organic inputs from above- and below-ground tree biomass to the soil is mediated by the activity of decomposer organisms (Chapter 17). The decomposition of organic materials into simpler molecules initially involves physical fragmentation of organic matter during feeding by litter-transforming invertebrates, which, by increasing the surface area of the organic matter on the ground, facilitates its colonization and breakdown by microbes. Smaller fragments are then chemically degraded by enzymes produced by bacteria, fungi, protozoa, and invertebrates, and the resulting soluble organic and inorganic compounds leach into the soil where they are consumed by both plants and soil biota (Brussaard et al., 1997; Coleman et al., 2004).

The speed of decomposition of organic inputs and the related opportunities for managing organic matter depend

on the chemical composition and quality of that matter (Palm et al., 2001). The nitrogen, lignin, and polyphenol contents of organic matter are important indicators of its quality (Vanlauwe et al., 2005). This information can be used to gain a better understanding of SOM and nutrient dynamics in agroforestry (Vanlauwe et al., 1996; Barrios et al., 1997; Cobo et al., 2002).

The contribution of arbuscular mycorrhizal fungi (AMF) (Chapter 14) to increasing plants' nutrient content influences the quality and decomposability of organic inputs and thus the benefits that the soil system derives from ensuring organic matter (Langley and Hungate, 2003; Dierks et al., 2021). For example, the outstanding ability of *Tithonia diversifolia* to accumulate P as well as other nutrients in the soil into its biomass (Barrios and Cobo, 2004) has been attributed to an effective AMF symbiosis (Sharrock et al., 2004) that increases P flows through dynamic pools that contribute to greater soil P availability (Phiri et al., 2001).

In contrast to direct biomass transfers and mulching practices, the inputs of tree litter and the year-round presence of tree rhizospheres within agroforestry systems provide the soil with continuous and diverse organic inputs. These encourage more favorable soil community structure and composition, with resemblance to soils in natural ecosystems that are characterized by higher resource-use efficiency (Ushio et al., 2010; Madritch and Lindroth, 2011; Vallejo et al., 2012).

24.2.2 BIOLOGICAL NITROGEN FIXATION

Biological nitrogen fixation (BNF) by trees plays an important role in providing N inputs in agroforestry systems and in contributing to the realization of soil benefits (Giller, 2001; Chapter 13). However, actual BNF rates under field conditions are often lower than the potential maximum due to the effects of soil and climatic conditions.

Specialized soil biota – diazotrophs or (less technically) nitrogen-fixing bacteria – are responsible for the symbiotic N fixation in which atmospheric nitrogen is transformed into ammonia or ureides within root nodules, specialized root structures from which fixed N is transferred to the host plants' vascular systems and assimilated by trees in agroforestry systems (Sprent, 2009). A review by Nygren et al. (2012) found that, on average, 60% of the total plant N in agroforestry trees is derived from BNF, with a higher proportion in young and pruned trees and a lower share when older trees were not pruned. There is high variability in the percentage of total plant N that is derived from the atmosphere among different tree provenances, e.g., *Leucaena leucocephala* (37–74%), *Faidherbia albida* (6–37%) (Sanginga et al., 1990), and *Gliricidia sepium* (40–64%) (Liyanage et al., 1994; Sanginga et al., 1994). This suggests that there are opportunities for optimizing this symbiotic tree-soil biota interaction through management decisions.

The effect of climate on BNF is clear from the higher variability and the low rates of BNF in drylands as well as from the greater N fixation with agroforestry conducted in humid and sub-humid regions. Low availability of soil P often limits the amount of BNF achieved by agroforestry trees, but some tree species are more susceptible to variation than others (Sprent, 1999). This variability could be related to attributes of the trees themselves, but it may also be affected by the potential for multiple symbioses. Limitations to BNF rates that result from low soil P availability may be reduced by enhancing the supply of P through three-way symbioses that include AMF (Gianninazi et al., 2010). Most studies reviewed by Nygren et al. (2012) showed the beneficial effects of this tripartite symbiosis are because the main function of the AMF in it is for P supply. Greater knowledge of how agricultural and agroforestry practices affect the abundance, diversity, and activity of nitrogen-fixing bacteria and AMF fungi, their capacity to tolerate and adapt to climatic stress, and how to enhance the adaptation capacity of host plants would assist in fostering greater amounts and resilience of biological nitrogen fixation within agroforestry systems.

24.2.3 DEEP UPTAKE OF NUTRIENTS AND WATER

Deep uptake and recycling of nutrients by tree roots located below the crops' root zone is another way in which agroforestry trees contribute to soil health. Tree roots' deep capture of subsoil nutrients returns these nutrients to the surface soil eventually as litter, thereby increasing the supply of nutrients that is available for crop plants and the soil biota (Rowe et al., 1999; Buresh et al., 2004).

There is greater nutrient acquisition capacity through the AMF, that associate with agroforestry trees (Dierks et al., 2021). Mycorrhizal tree roots display an extensive network of fungal hyphae that extend into the soil, exploring dramatically greater soil volumes than can non-mycorrhizal tree roots (Gianninazi et al., 2010). The influx and uptake of P in roots that are colonized by AMF can be three to five times greater than in non-mycorrhizal roots (Smith and Read, 2008).

Tree roots can recycle fertilizer applied by farmers that has leached to subsurface soil levels, hence improving nutrient-use efficiency and the economic returns to fertilizer use. Additionally, mycorrhizal fungi enhance the activity of phosphate-solubilizing rhizobacteria that give trees access to pools of recalcitrant P in the soil. The AMF contribute to the nutrient-capture function by taking up microbially solubilized P and moving it into tree roots from where the plants' vascular system circulates the P within the tree (Smith and Read, 2008).

In dry areas, deep-rooting trees can play a key role in making water available to crops, drawing it up from deep soil layers through what is known as *hydraulic lift* (Smith et al., 2004; Bayala et al., 2008). But some studies have shown that changes in the abundance and viability of mycorrhizal hyphae can alter the patterns of water

acquisition and redistribution by tree roots (Querejeta et al., 2012). Greater knowledge of the abundance, diversity, and activity of AMF fungi in symbiosis with agroforestry trees and of the soil volume and depth explored by AMF external hyphae would help to optimize the diversity and spatial arrangement of trees that will best sustain their deep-nutrient and water-capture functions.

24.2.4 Water Filtering and Soil Protection

Soil protection benefits include the maintenance of soil structure that is provided by tree roots through their influence on soil aggregate stability, which reduces rates of soil erosion. Earthworms and mycorrhizal hyphae also contribute to processes of soil aggregate formation and stabilization, simultaneously reducing the potential for soil erosion and increasing carbon sequestration in the soil through the physical protection of SOM (Blanchart et al., 2004; Six et al., 2004; Rillig and Mummey, 2006; Fonte et al., 2010).

The soil biota affects water infiltration rates largely through its influence on soil porosity, by generating pores and channels of different diameters and shapes. Soil macro-porosity is critical for the conductivity of water through the soil under saturated conditions and for the capacity of soils to absorb water quickly during intense rainfall so as to abate runoff and soil erosion. Soil invertebrates like soil-feeding earthworms and termites contribute substantially to soil macro-porosity (Lavelle and Spain, 2001).

Agroforestry systems that promote intermediate tree cover are reportedly able to maximize groundwater recharge in the seasonally dry tropics (Ilstedt et al., 2018). Soil micro-porosity, on the other hand, is important for the slower water flows that are required for a more effective breakdown of pollutants and to realize decontamination benefits (Loser et al., 1999). Greater knowledge of the abundance, diversity, and activity of soil ecosystem engineers such as earthworms and termites and of their interaction with perennial root systems will help to guide spatial arrangements of agroforestry trees so as to optimize and sustain the filtering and protection functions of soil.

24.2.5 Enhancing Functional Resilience in Agroecosystems

The previous sections showed how agroforestry trees enhance the functional resilience of agroecosystems in different ways, in particular providing resources and habitat to sustain the soil biota that drive key processes underpinning soil health and productivity. Enhancing functional resilience is particularly important in the context of climate change, which is expected to increase the frequency and intensity of stress periods. Greater comprehension of the roles of the soil biota in performing these several soil functions is fundamental for better understanding how best

to manage soil health through agroforestry interventions (Barrios et al., 2012a; Smith et al., 2015).

Further, greater recognition of microbially mediated plant functional traits and their impact on plant niche differentiation will illuminate the impacts of plant-soil biota feedbacks on agroecosystem diversification (Friesen et al., 2011; Sasse et al., 2018). Developing a better grasp of above- and belowground interactions will inform recommendations on the selection and diversity of tree species, desirable species traits, tree planting densities, arrangements in space and time, pruning regimes, and other management measures that are necessary for maintaining essential ecosystem functions and services.

Agroforestry systems that combine trees and crops able to coexist through positive interactions, e.g., symbiosis, will generate organic inputs of different quality that can preserve soil cover and increase the diversity and persistence of active soil biota (Pauli et al., 2011; Kamau et al., 2017; Dierks et al., 2021). Several studies have highlighted the potential of novel molecular analytical techniques to show shifts in soil-microbial community structure and distinct soil-aggregate stratification that resulted from management-induced changes in soil organic C (Davinic et al., 2012; Sul et al., 2013). Further studies are needed to assess the impact of different spatial arrangements and management that can minimize competition, favor complementarities, and facilitate interactions among trees and associated crops, and how these interactions affect the abundance, diversity, and activity of key soil biota (Veen et al., 2019).

The interactions of trees and soil biota both respond to and influence ecosystem properties, so more understanding of the feedbacks involved is necessary to link experimental results at smaller scales with use at larger scales (Bardgett and Wardle, 2010). The use of molecular analytical tools, analysis of stable isotopes, and spectroscopic techniques will increase our ability to identify and characterize "hotspots" of biological activity associated with agroforestry trees; these analytical advances could also facilitate the study of links between key soil biota and ecosystem functions at different temporal and spatial scales (Barrios, 2007). Furthermore, spatial information about tree components of agroforestry obtained through remote sensing and geographic information system (GIS) technologies could lead to some fruitful inferences about the contributions and management of the soil biota (Barrios et al., 2012a).

Integrating local knowledge about plants as indicators of soil health could help by focusing attention on trees that are known to promote beneficial soil biological activity in agricultural landscapes (Barrios and Trejo, 2003; Barrios et al., 2006; Kuria et al., 2018). This is consistent with the idea that it is important to know the identity and characteristics of plant species, rather than simply promote plant diversity alone, to better integrate trees into regenerative and resilient soil management systems (Hooper et al., 2005; Wardle, 2006; Kamau et al., 2020).

24.3 THE FEASIBILITY OF OBTAINING SOIL HEALTH BENEFITS FROM TREES

24.3.1 ACCOMMODATING THE HETEROGENEITY OF RESPONSES TO MANAGEMENT

While an understanding of the biological and physical interactions reviewed above justifies having broad expectations of beneficial impacts from agroforestry practices on soil health, the empirical evidence from direct observations gives a less clear picture. If a simple indicator of the effects of soil health management is considered, such as change in crop yield when practicing agroforestry, it should be expected that some variability would occur at all spatial scales. Indeed, some meta-analyses have highlighted considerable variation in results.

- When 97 cases across four Sahelian countries in Africa were evaluated, where cereals were intercropped with trees that were coppiced regularly (i.e., cut to ground level at the beginning of the cropping season and allowed to regrow), there was overall an increase in grain yield averaging 0.34 t ha^{-1}, compared to having no trees growing with the grain crop. But almost half of the cases (44%) showed some decrease in yield, while 6% showed large increases of at least 2 t ha^{-1}. Half of the cases were in between these two extremes (Bayala et al., 2012).
- In 262 cases where maize was alternated with a fallow using the fast-growing leguminous tree *Sesbania sesban*, there was an average increase in maize grain yield of 2.9 t ha^{-1}. However, individual results ranged from a decrease of 0.5 t ha^{-1} to increases of over 6 t ha^{-1} (Sileshi et al., 2010), again showing a huge variation in crop response to agroforestry practices. This should not be surprising given the many interactive causal factors that are operating.

While these meta-analyses necessarily combined data from quite different environments and some variation in management methods, even controlling as much as possible for variations in the regional and local evaluations did not make the data less variable (Coe et al., 2014). With such wide variation in results as reported earlier, it is difficult to draw simple conclusions and make agroforestry recommendations.

The heterogeneity observed in cropping responses to agroforestry measures is largely driven by variation in the agroforestry options themselves and by differences in the context in which these practices are utilized. There can be large variations in the tree component and in the ways that trees are managed within a given cropping system (Nyaga et al., 2015). ICRAF's Agroforestry Database lists 226 trees that are now being used in soil fertility management, and this list is not exhaustive (https://www.worldagroforestry.org/output/agroforestree-database).

Because many of the tree species in the database are undomesticated, there will be much intraspecific genetic variation, and some of this variation will affect the interactions among trees, crops, and soil health management. For example, there are marked differences in leguminous trees' ability to form root nodules (Sprent, 2009) and to fix nitrogen from the atmosphere (Nygren et al., 2012). Variation in trees' capacity for BNF has been linked to soil P availability, as noted already (Sprent, 1999), or to intrapopulation variations in the root architecture of trees, in the specific case of *Faidherbia albida* (Vandenbeldt, 1991).

Certain shrubby perennials from other botanical families (e.g., *Tithonia diversifolia* – Asteraceae) have been identified as important agents for enhancing soil fertility because many are effective phosphorus scavengers and bioaccumulators of other nutrients (Sanchez, 1999; Barrios and Cobo, 2004). Some effects may be rather subtle, such as the intraspecific variation in trees that leads to differences in the associated microbial communities in their respective rhizospheres (Madritch and Lindroth, 2011).

Agroforestry options must also take account of the management costs and local capabilities involved in each, in addition to determining which tree species and genotypes to be utilized. A wide range of management practices has been developed to deal with these variances (Sanchez, 1995; Schroth and Sinclair, 2003; Akinnifesi et al., 2010). Variation can occur in how the trees are established; the timing of their establishment relative to the crops; tree density and spatial pattern; association with fertilizer or other inputs; management practices such as pruning and coppicing; the way that prunings and litter are used, e.g., as mulch or incorporated into the soil; the degree of integration of livestock and tillage with other operations; and the long-term rotations employed, e.g., sequence and timing of tree removal and replanting.

The environmental context in which agroforestry options are used, driven most notably by climate, is probably the most important variable. More humid environments generally can support higher tree densities along with greater crop density (Smith et al., 2004). Local variations in water availability will influence the viability of a particular agroforestry interventions. For example, *Faidherbia albida*, valued and widely recommended for enhancing soil fertility, requires some access to water during the dry season to survive (Roupsard et al., 1999).

Also, water availability can vary over short distances within a landscape, with dry season water tables within the reach of tree roots in some niches but not in others. Considerations regarding short-term variation or risks in weather will also influence farmer choices by affecting the viability of certain options, e.g., some trees that cohabit beneficially with crops are hard to establish without frequent watering during their early growth.

Soils and climate interact strongly with the performance of trees expected to enhance soil health. A meta-analysis by Chivenge et al. (2011) showed that while additions of organic N led to greater absolute crop yield responses in

finer-textured soils having high mean annual precipitation (MAP), the relative increases in both crop yield and soil organic C in response to organic nutrient additions were greater with low MAP, e.g., <600 mm yr^{-1}, as well as with coarse-textured soils. The greater differences in soil organic C observed in sandy soils compared with clayey and loamy soils are likely because sandy soils have a lower baseline content of organic C, so additions of organic residues generate greater proportional increases (Chivenge et al., 2007). Moreover, if soils are quite degraded, the trees themselves will not grow very well and will not be able to serve as soil improvers in the short term (Chaer et al., 2011).

Position in the landscape has also been shown to influence the performance of an agroforestry option due to a combination of soil status and water availability (Harawa et al., 2006). When farming is done on the plains, trees will all have relatively similar exposure to solar radiation, just as crops do; conversely, there will be large differences in tree growth and functioning in hillside agriculture, where whether a field is on one side of the mountain or the other determines light interception, and this has significant effects.

Soils in which the abundance and diversity of soil organisms have been depressed because of factors like soil compaction, aridity, or acidity will require some time for the soil biota to recover and replenish itself. Over time, trees can reverse soil biological deficits, but as noted at the beginning of this chapter, soil health is a "slow" variable.

While we often think of trees as influencing the soil and of the soil as then influencing crops, there are also other interactions between trees and crops in systems where they are growing together. These relationships can be competitive, facilitative, or neutral, and the balance of influences will be different for different combinations of trees and crops. For example, one crop may benefit from reduced temperatures that tree shading gives, while the growth of another crop will be inhibited by its competition with trees for light (Ong et al., 2004).

In addition, within-farm variation in soil fertility, resulting from preceding management decisions and crop choices, will generate niches in which different agroforestry options would be more or less suitable (Tittonell et al., 2005; Vanlauwe et al., 2006). Sources of biophysical variation are also intertwined with social and economic variations. Tittonell et al. (2010) have shown how farmers' resource endowments and livelihoods influence their ability and interest to invest in different soil fertility management options.

Understanding the sources of variation in diverse socio-ecological niches requires adequate methods for defining these as well as for matching soil health management options to appropriate niches (Ojiem et al., 2006). Local knowledge of soil quality is likely to assist in the definition of socio-ecological niches (Barrios et al., 2012b; Kuria et al., 2018). Experimental designs should seek to detect variation within an area rather than be preoccupied with determining what the average or typical conditions are. Data should be analyzed in ways that can quantify risk, considering "error" or "noise" to be as important as mean values.

Given the likelihood of a high variation in on-farm experiments, trials with large sampling size (large N trials) and observational studies that cover large areas and represent their inherent heterogeneity are needed to generate reliable empirical evidence of the interaction between an agroforestry option and the niches (contexts) in which it is likely to be successful (Sinclair and Coe, 2019). Rather than be satisfied with uniform prescriptions, farmers and other stakeholders, e.g., change agents and local researchers, should be encouraged to experiment formally or informally, collectively and individually, so as to adapt practices to best meet their needs and local conditions.

Local knowledge should be part of any process, for example, for identifying well-adapted tree species and positive tree-soil biota interactions (Cerdan et al., 2012; Pauli et al., 2012; Kamau et al., 2017). Building continued experimentation and knowledge-generation into programs is part of the "co-learning" framework for agroforestry proposed by Coe et al. (2014).

24.3.2 Enabling Environments

Whether and to what extent farmers' selection of agroforestry practices for soil health is influenced by their respective social and economic characteristics will vary in space and time. At the household level, key variables that have been found to affect the adoption of agroforestry practices for soil management (as well as other soil management practices) include the size of farm, labor availability, financial resources, resource property rights, access to markets and support services, and other livelihood activities besides farming (Ajayi et al., 2007; Nyaga et al., 2015). However, a recent review of adoption studies spanning all types of agroforestry practices found that many explanatory variables can have either positive or negative effects depending on the practice involved and on the local context (Amare and Darr, 2020). Small size of landholding, for example, can in some areas be a deterrent for adopting new practices, while under other circumstances, it is an incentive.

When targeting agroforestry programs, consideration should be given to whether the practice being encouraged is traditional or introduced and whether the trees will be established through natural regeneration or active propagation. For instance, agroforestry systems relying on natural regeneration are already found in some savanna regions in semi-arid West Africa as reported in Chapter 36. A study of households in Burkina Faso, Mali, Niger, and Senegal found that almost all of the households' plots have useful trees that are contributing to soil fertility, with both mature and young trees growing in a scattered field pattern (Place and Binam, 2013). The adoption and spread of such a system will be quite different from a new system that depends on the planting of trees. This requires much more knowledge and more inputs, with new requirements for labor, land, or capital.

Improved fallows have been found to be adopted only by farmers with relatively large landholdings, for example Place et al., 2005 and Kabwe, 2010. Access to support services such as extension advice or the services and support of a government or donor project is another factor that influences whether farmers will take up an agroforestry practice for soil health (Place et al., 2005). The study by Kiptot et al. (2007) showed that the uptake of a newly introduced agroforestry practice such as improved fallows can be a reflection of inducements from a project and should not be construed as evidence of farmer adoption.

Policies and institutions shape the incentives that affect farmers' decisions about agroforestry management for soil health in several ways (FAO, 2013). First, government policies and institutions may influence overall assessments made by farmers of the benefits, costs, and risks involved, which will affect their incentives for soil health investments of any kind. Second, policies may affect farmers' incentives for making long-term vis-à-vis short-term investments of any kind in their agricultural operations. Insecure property rights, lack of long-term credit, and an unstable policy environment will increase the proportion of investments that provide short-term solutions (e.g., agrochemical inputs, precision agriculture) versus long-term benefits (e.g., agroforestry, buffer strips) (Carsan et al., 2014). Where policy and institutional conditions are not supportive, the connection between improved soil health and household benefits will be uncertain, which reduces the incentive for any investment.

Third, some policies will create particular incentives for or against the use of trees in soil health management. According to Place et al. (2012), examples of policies that distort incentives away from agroforestry include subsidies for the use of mineral fertilizer; emphasis on conventional agricultural methods in agricultural development programs; government ownership of tree resources; unclear land rights; and neglect of formal rewards for measurable ecosystem services from agricultural practices, e.g., carbon sequestration. Forest regulations often protect certain indigenous tree species, prohibiting their felling or cutting unless a fee is paid (Yatich et al., 2014). Faced with such regulations, farmers will prefer not to plant such species or to allow such species to regenerate on their farms.

While investment in soil health improvement provides private benefits to households, it also provides ecosystem-service benefits for the public, such as carbon sequestration, soil erosion control, improved water regulation (less flooding), and conservation of biodiversity. When households are not compensated for creating these benefits, one can expect that agroforestry practices will be underinvested in from a societal perspective (Jack et al., 2008).

Mapping is a powerful way for visually displaying variation that is attributable to causes that vary consistently across space. The empirical results of interventions can be mapped to show communities the viability and benefits of certain agroforestry options. This can deliver information on key principles of soil health management through agroforestry that should be communicated to local resource-users, rather than relying just on conveying the details of specific practices. Furthermore, empirical results can be fed into process-based models that assess and predict *niche × practice* combinations, also to spread an understanding of their implications over time (Burgess et al., 2019).

The effective adaptation of agroforestry options to local circumstances needs to be based on an understanding of the fine-scale variation in the biophysical, economic, social, and institutional contexts. At the same time, continual refining of such understanding through co-learning among research, development agents, the private sector, and resource-users will facilitate scaling-up processes that benefit large numbers of people (Coe et al., 2014).

24.4 KNOWLEDGE GAPS AND CHALLENGES AHEAD

Increasing our understanding of the sources of variation and reducing the level of uncertainty in tree and crop responses to agroforestry interventions are needed to increase the predictability of outcomes from given suggested practices. This includes a better understanding the ecological and social-economic determinants that define "niches" for innovation and how well agroforestry interventions can be matched to them to improve soil health.

The strong feedbacks between plants, both trees and crops, and the soil biota suggest that there is much potential to use agroforestry trees to reliably influence soil functional diversity and to provide soil-mediated ecosystem services. Furthermore, soil microbes have been shown to modify plants' functional traits so as to foster niche expansion and differentiation, as well as greater plant adaptation to abiotic stresses.

The availability of new molecular tools can greatly facilitate the characterization of soil functional diversity and the application of trait-based approaches, both for trees and for key functional groups of the soil biota, optimizing agroecosystem designs to minimize trade-offs and maximize complementarities, facilitation, and synergies. Agroforestry practices should embrace manageable levels of complexity that will help address fundamental questions about interactions between above- and belowground biodiversity, thereby enhancing agroecosystems' functional resilience to disturbance or climate change.

A considerable shift in agroforestry systems research is seen in the explicit acknowledgement of *heterogeneity* as a fundamental challenge to be embraced so as to reduce the risks associated with adopting agroforestry innovations. Embedding research in development projects as suggested by Coe et al. (2014) constitutes a strategy for covering the large areas necessary to acquire a realistic representation of context heterogeneity, where hypotheses that address fine-scale variation in the drivers of adoption of agroforestry practices can be effectively evaluated.

Developing and applying tools and approaches that combine high-end science with local knowledge to promote soil

health through tree growing and the diversification of crops and trees can facilitate the development of strategies and options that build greater resilience into agricultural farms and landscapes. Further, promoting top-down and bottom-up approaches simultaneously can build an understanding of the heterogeneity and variability of agroforestry impacts on soil health, getting a better understanding of tree-soil biota interactions over the long term, and carrying out experiments in the real world to derive lessons from large-N trials that assess planned comparisons.

Implementation of soil health management principles through agroforestry should be tailored to the needs of farmers, extension services, non-governmental organizations and other development agents, researchers, and policy makers. Before, during, and after the implementation of such principles, local soil health monitoring systems (Chapter 45) that inform land users about their land's capacity to provide ecosystem services can support greater and better-informed payments from schemes that aim to expand such services, thereby creating further incentives for sustainable agriculture.

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