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Belowground functioning of agroforestry systems: recent advances and perspectives

Rémi Cardinael · Zhun Mao · Claire Chenu ·
Philippe Hinsinger

Introduction

Growing crops or pastures in intimate combination with trees is an ancient practice that farmers have been using throughout the world. Globally, it is estimated that agroforestry systems cover about 1 billion hectare of land (Zomer et al. 2014, 2016). Agroforestry systems are often seen by farmers and practitioners as a way to diversify production, income and services (Abdulai et al. 2018). These systems are still very common in developing

countries. In developed countries where the intensification and specialization of agriculture have resulted in a massive loss of tree cover (Eichhorn et al. 2006) and in negative impacts on the environment (Tilman et al. 2001), agroforestry systems are currently being reconsidered and spreading (den Herder et al. 2017). Agroforestry systems include a diversity of practices ranging from complex associations found in homegardens, multistrata systems or agroforests, to simpler systems such as alley crops, riparian plantings, shelterbelts, windbreaks or hedgerows (Nair 1985). The association between trees and crops or pastures can be simultaneous (spatial interaction) or sequential (temporal interaction) (Somarriba 1992; Torquebiau 2000).

The management of the aboveground part of agroforestry systems to deal with the competition for light has received considerable interest (e.g. Charbonnier et al. 2013; Bouttier et al. 2014). However, trees also modify soil properties through numerous processes (Rhoades 1997), and tree-soil-crop interactions have been a research topic for decades (Szott et al. 1991; Lehmann et al. 1998; Schroth 1998; Ilstedt et al. 2016; van Noordwijk et al. 2019). Tree and crop root systems play a crucial role in these interactions (Schroth 1995; van Noordwijk et al. 1996; Smith et al. 1999; Bayala et al. 2015) and are involved in most of belowground processes (Bardgett et al. 2014), which determine soil functions and, ultimately, a large set of ecosystem services. A better understanding of these processes at the interface between soil science and agroforestry, such as soil organic carbon sequestration or water infiltration, could thus help reaching some the United Nations

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Sustainable Development Goals (Keesstra et al. 2016; van Noordwijk et al. 2018).

The aim of this special issue “Agroforestry: a below-ground perspective” was to bring together new contributions and developments about belowground processes and tree-soil-crop interactions in agroforestry systems. We received a total of 40 manuscripts of which 13 have been accepted for publication. Among these papers, nine are original research papers and four are invited reviews, including a Marschner review. Original research papers include a large diversity of agroforestry systems, such as fallows, parklands, shaded perennial-crop systems and silvoarable systems from six different countries and seven different climatic zones (Table 1; Fig. 1). The different papers cover very different aspects of belowground functioning and numerous processes are studied (Table 2). The manuscripts were grouped into three major topics: (1) water cycling in soils under agroforestry systems; (2) closing the loop: soil nutrient cycling in agroforestry systems; (3) soil organic carbon cycling in agroforestry systems. For each of these sections we provide an overview of our current knowledge, highlight the contributions of this special issue, and pinpoint key remaining challenges for future work.

Water cycling in soils under agroforestry systems

In the context of climate change that renders global terrestrial water resources more vulnerable (Vörösmarty et al. 2000; Porporato et al. 2004; Falkenmark 2013), the impact of agroforestry on water cycling processes has drawn increasing attention. Compared to intensive monoculture, agroforestry systems are expected to better promote water cycling processes (e.g. water infiltration and retention, reduced run-off) and hydrological ecosystem services due to their higher spatial complexity and biodiversity (Rowe et al. 1998; Liu et al. 2016; Pavlidis and Tsihrintzis 2018). Competition for water between trees and annual crops has often been shown (Jose et al. 2000b), but agroforestry systems also have the potential to improve the acquisition of water through complementary root distributions, trees having deeper root systems than annual crops (Jackson et al. 1996; Cardinael et al. 2015b; Germon et al. 2016), and further to promote water sharing mechanisms such as a redistribution of water in the soil profile through a process called hydraulic lift, or through shared mycorrhizal networks. Yet, to which extent such effects are significant and can be generalized remains unknown. To

Table 1 Summary details of articles published within the special issue

Study	Paper type	Agroforestry system	Association	Study site	Köppen climate
Battie-Laclau et al. (2020)	Original research	Silvoarable system	<i>Juglans nigra</i> / cereals	France	Cfb
Bayala and Prieto (2020)	Review	Diverse	Diverse	Worldwide	Diverse
Borden et al. (2020)	Original research	Shaded perennial-crop system	Shade trees / <i>Theobroma cacao</i>	Ghana	Aw
Clivot et al. (2020)	Original research	Silvoarable system	<i>Populus deltoides</i> × <i>P. nigra</i> / alfafa <i>Alnus glutinosa</i> / wheat / triticale / ryegrass	France	Cfb
Huo et al. (2020)	Original research	Silvoarable system	<i>Ziziphus jujube</i> / canola / daylily	China	Dwa
Isaac and Borden (2020)	Marschner Review	Diverse	Diverse	Worldwide	Diverse
Ling et al. (2020)	Original research	Silvoarable system	<i>Ziziphus jujube</i> / canola / daylily	China	Dwa
Marsden et al. (2020)	Review	Diverse	Diverse	Worldwide	Diverse
Rigal et al. (2020)	Original research	Shaded perennial-crop system	Shade trees / <i>Coffea arabica</i>	China	Cwa
Sida et al. (2020)	Original research	Parkland	<i>Faidherbia albida</i> / <i>Acacia tortilis</i> / <i>Grevillea robusta</i> × cereals	Ethiopia Rwanda	BSh
Terefe and Kim (2020)	Original research	Fallows	Multiple tree species × cereals	Ethiopia	Cwb
Wartenberg et al. (2020)	Original research	Shaded perennial-crop system	<i>Theobroma cacao</i> × shade trees	Sulawesi, Indonesia	Af
Zhu et al. (2020)	Review	Diverse	Diverse	Worldwide	Diverse

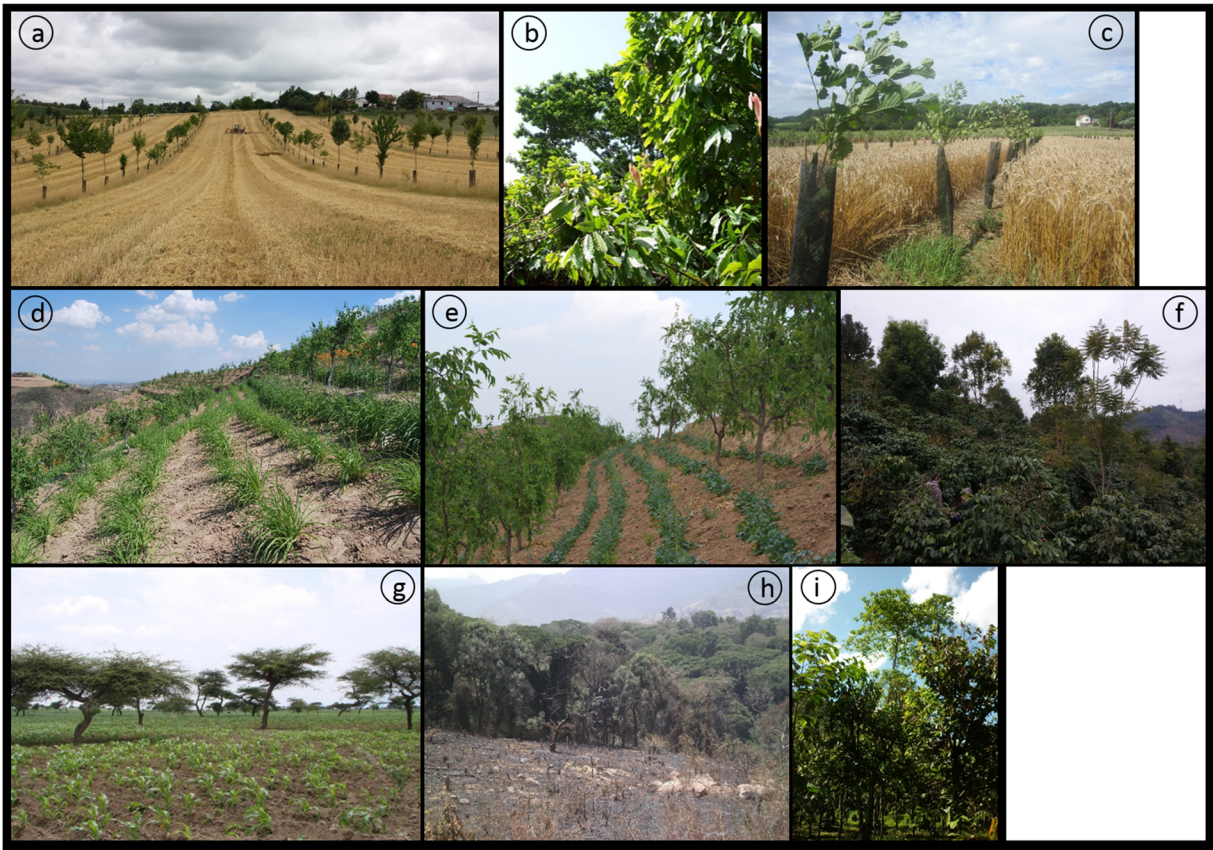


Fig. 1 Pictures illustrating the diversity of the study sites investigated in the original research papers published within this special issue. **a** Walnut trees and other high value hardwood tree species (*Fraxinus excelsior* L., *Sorbus torminalis* L., and *S. domestica* L., *Prunus avium* L., *Acer pseudoplatanus* L.) associated with soft wheat, Noilhan, France (Battie-Laclau et al. 2020) ©Patricia Battie-Laclau; **b** Cocoa trees with *Terminalia ivorensis*, Ashanti Region, Ghana (Borden et al. 2020) ©Kira Borden; **c** Alder trees and triticale, La Bouzule, France (Clivot et al. 2020) ©Nicolas Marron; **d** Jujube trees with *Brassica napus*, The Loess Plateau of China (Huo et al. 2020) ©Gaopeng Huo; **e** Jujube trees with

daylily, The Loess Plateau of China (Ling et al. 2020) ©Qiang Ling; **f** Arabica coffee trees with various shade tree species (including *Jacaranda mimosifolia*, *Cinnamomum camphora* and *Bischofia javanica*), Yunnan Province, China (Rigal et al. 2020) ©Clément Rigal; **g** *Acacia tortilis* with maize, Meki, Ethiopia (Sida et al. 2020) ©Frédéric Baudron; **h** Shifting cultivation, Gudaya Billa District, western Ethiopia (Terefe and Kim 2020) ©Dong-Gill Kim; **i** Cocoa trees with *Anthoccephalus cadamba*, Wonuahoa, Southeast Sulawesi, Indonesia (Wartenberg et al. 2020) ©Ariani Wartenberg

address these crucial points, Bayala and Prieto (2020) presented an original review on the acquisition, sharing and redistribution of water by roots in agroforestry systems. They found that root competition between crops and trees is a common phenomenon, and that farmers can use several techniques to alleviate it to some extent, such as crown reduction, tree pruning and a proper selection of trees and crops. They also highlighted that the hydraulic lift could constitute a very relevant mechanism to ensure productivity of agroforestry systems in regions with erratic rainfalls. Finally, they suggested several research perspectives, such as the clarifying the role of mycorrhizal networks

in the hydraulic lift, as well as quantifying the volume of water transferred to neighboring plants through hydraulic lift. In addition to this review paper, Huo et al. (2020) carried out a case study in a semiarid agroforestry system in the Loess Plateau in the north of China to characterize water uptake strategies and hydraulic redistribution between trees and crops, using an *in situ* approach based on stable isotopes (^2H and ^{18}O). Inter- and intra-annual dynamics of soil water content (SWC) were monitored in two systems: an agroforestry system with jujube (*Ziziphus jujuba* Mill.) trees intercropped with canola (*Brassica napus* L.) or daylily (*Hemerocallis fulva* L.), and a pure jujube tree

Table 2 Belowground processes and related ecosystem services covered in this special issue

Processes	Triggers	Management options	Ecosystem services	Articles
Water infiltration/run-off	Root systems, Soil fauna	Soil cover, Soil tillage, Deep-rooted trees and crops	Flood regulation, Water purification	2, 5, 7, 13
Hydraulic lift	Root systems	Deep-rooted trees	Primary production, Provisioning services	2, 5
Competition/Facilitation/ Niche complementarity	Root systems, Mycorrhizal networks	Tree density, Tree and crop species including breeding (root architecture, root plasticity, root traits), Root pruning, Soil tillage, Fertilization, Amendments	Nutrient cycling, Primary production, Provisioning services	1, 2, 3, 6, 9, 10
Litter decomposition	Microbial communities, Soil fauna	Plant species (litter quality), Fertilization, Soil tillage	Nutrient cycling, Climate regulation	8
Soil organic carbon sequestration	Root systems, Mycorrhizal networks, Soil fauna	Soil cover, Soil tillage, Deep-rooted trees and crops	Climate regulation	9, 11
Symbiotic nitrogen fixation	Bacteria	N ₂ -fixing plants, Inoculation, Fertilization	Nutrient cycling	6
Mineral weathering	Root systems, Mycorrhizal networks	Tree and crop species, Deep-rooted trees and crops	Soil formation	6
Nutrient leaching	Root systems	Deep-rooted trees and crops, Fertilization, Amendments	Nutrient cycling, Water purification	2, 13
Aggregate stabilization	Root systems, Mycorrhizal networks, Soil fauna	Soil cover, Soil tillage, Plant density, Amendments	Climate regulation, Water purification	8, 12, 13
Soil porosity formation and maintenance	Root systems, Soil fauna	Soil tillage, Deep-rooted trees and crops	Flood regulation, Water purification, Climate regulation	7, 8, 13

Cultural services (aesthetic, spiritual, educational, recreational...) have not been studied here. Ecosystem services are derived from Millennium Ecosystem Assessment (2005). Provisioning services include the provision of food, fresh water, wood, fiber, and fuel. 1: Battie-Laclau et al. (2020); 2: Bayala and Prieto (2020); 3: Borden et al. (2020); 4: Clivot et al. (2020); 5: Huo et al. (2020); 6: Isaac and Borden (2020); 7: Ling et al. (2020); 8: Marsden et al. (2020); 9: Rigal et al. (2020); 10: Sida et al. (2020); 11: Terefe and Kim (2020); 12: Wartenberg et al. (2020); 13: Zhu et al. (2020)

plantation as a control plot. This study showed the highly plastic behavior of the agroforestry system in water uptake strategy depending on soil depth and season at the early stage of land-use change from plantation to agroforestry. Within the soil layers where crop roots were largely present (0–1.2 m depth), jujube trees in the agroforestry system were able to obtain more shallow water (0–20 cm or 20–60 cm) during wet periods, but more deep water (60–120 cm) during dry periods. It shall be noted that this study includes some precious water data from very deep soil layers (down to 4 m). The authors demonstrated that, in the driest season, trees in agroforestry systems could take up very deep soil water (down to 4 m). According to the authors, while this is good for tree metabolic maintenance, it may also induce a strong desiccation of very deep soil layers as the ground water level was too deep (> 50 m) to compensate for such a water stress. However, this negative effect could be partly offset by increased soil water infiltration (Ilstedt et al. 2016; Liu et al. 2016).

Concerning water movement on soil surfaces and shallow soil layers, stratified tree canopies over crops in agroforestry systems have been found to effectively reduce water loss through runoff and soil loss due to erosion (Villatoro-Sánchez et al. 2015; Liu et al. 2016). Litterfalls from trees can further increase soil surface rugosity and soil aggregate stability, while tree roots can increase soil porosity, thus resulting in increased water infiltration and ultimately limiting water erosion (Liu et al. 2016). Yet, to which extent such effects can be generalized over a global scale and across different types of agroforestry systems remains unknown. To fill such a gap, Zhu et al. (2020) performed a systematic review to quantitatively assess the impact of agroforestry systems on erosion control and associated environmental issues, such as soil nutrient losses and pollutant dispersion, for four types of agroforestry systems in temperate and tropical regions. While this review successfully confirmed the general positive effect of agroforestry systems, it also showed large discrepancies of the performance of agroforestry systems amongst the various case studies. This suggests the necessity of optimizing soil and vegetation management depending on the context of the agroforestry systems. Zhu et al. (2020) mainly focused on water processes at the surface of soils, or at sub-surface, but also highlighted a lack of research on the role of belowground soil-root-biota interaction in the regulation of water processes in agroforestry systems, especially for deep soil layers. Water

processes at depth are largely mediated by those occurring in shallow and deep soil horizons, which can be susceptible to the distribution patterns of tree and crop roots, as well as their associated soil biota (e.g. macrofauna, mycorrhizal fungi etc.). Roots and soil biota can influence belowground water processes either by direct hydraulic redistribution in soil due to their water absorption and sharing strategies or by modifying soil hydrological and hydraulic properties, e.g., water storage capacity, infiltration rate and hydraulic conductivity. In addition to this global synthesis, Ling et al. (2020) proposed an original case study in a similar context as for the study of Huo et al. (2020), but on a different plot. The authors characterized soil water content, root distribution and soil physical properties related to soil water cycling processes in an agroforestry system with jujube (*Ziziphus jujuba* Mill.) trees intercropped with canola (*Brassica napus* L.) or daylily (*Heemerocalis fulva* L.), and in a pure jujube tree plantation as a control plot. They found that, compared to a monoculture of jujube tree plantation, the agroforestry system could decrease soil bulk density and increase field capacity, saturated hydraulic conductivity and soil porosity, especially in inter-rows, thus having a generally positive effect on soil water cycling and vegetation performance. In addition, the study showed a lower soil water content in the agroforestry system inter-rows, suggesting a competition for water between trees and intercropped species.

Closing the loop: soil nutrient cycling in agroforestry system

Research on nutrient cycling in agroforestry systems has been prolific for decades (Nair et al. 1999). The following questions have been largely addressed: the contribution of agroforestry trees to nutrient requirements of intercropped plants and the timing of nutrient transfer from the decomposition of the pruning residues to intercrops (Palm 1995; Zingore et al. 2003; Tully and Lawrence 2012), the competition for nitrogen (Jose et al. 2000a; Zamora et al. 2009), the use of nitrogen-fixing trees and their effect on crop production (Akinnifesi et al. 2010), the uplift of deep subsoil nutrients by trees (Vanlauwe et al. 2005) and the role of tree roots as a safety-net to reduce nutrient leaching (Rowe et al. 1998; Bergeron et al. 2011; Tully et al. 2012). Functional trait-based approach has been evidenced to

be efficient explaining plant strategies related to nutrient use (Garnier and Navas 2012). While such an approach is widely used in plant ecology, it is still poorly explored in the context of agroforestry systems where tree and crops can show intra- and interspecific facilitation or competition interactions. The Marschner review of Isaac and Borden (2020) is therefore very timely. The authors reviewed the processes underpinning nutrient acquisition in agroforestry systems, including root distribution and plasticity, biological nitrogen fixation and deep soil nutrient uplift. They also pointed that understanding these mechanisms requires consideration of the multiple scales at which trees and crops interact with each other and acquire nutrients from soil. They further explained that interspecific root overlap is often associated with nutrient competition, but several studies also evidenced facilitation for nutrient acquisition through enhanced chemically and microbially mediated processes. They finally suggested that root functional trait-based approach is promising in its ability to capture the multi-scalar nature of nutrient acquisition processes in agroforestry systems. In addition to this review paper, Borden et al. (2020) focused on a cocoa (*Theobroma cacao* L.) agroforestry system in Ghana including two shade tree species (*Terminalia ivorensis* Chev., *Entandrophragma angolense* (Welw.) C.DC.). They mapped root distribution, root functional traits and soil nutrients down to 60-cm depth. They found that the species of shade tree induced root plasticity in *T. cacao*. Cocoa root morphological traits indeed shifted towards a nutrient acquisition strategy, exhibiting higher specific root length and lower fine root tissue density, when next to a shade tree. They also showed that root traits plasticity depended on the soil nutrient (Ca^{2+} , NH_4^+ , NO_3^-).

Through their symbiotic relationship with roots, the crucial role of mycorrhizal fungi in nutrient acquisition has been generally recognized (Barea et al. 2005). However, the effect of trees on the abundance, diversity and activity of mycorrhizal communities is still poorly known (Bainard et al. 2011, 2012). The tree-crop mixed cultivation in agroforestry systems provides a valuable opportunity to investigate this. Battie-Laclau et al. (2020) studied the respective role of trees and herbaceous vegetation beneath trees in maintaining arbuscular mycorrhizal communities in temperate alley cropping agroforestry systems. They showed that roots of trees and associated herbaceous vegetation were extending several meters within the cropped alley in the topsoil,

challenging the common view of a stratification and niche separation of tree and crop roots. Such intermingled root systems are an important feature for potential plant-plant interactions in agroforestry systems, e.g. facilitation processes through sharing common mycorrhizal communities and networks. Surprisingly, they showed that the herbaceous vegetation beneath the trees was better at maintaining an active arbuscular mycorrhizal network than associated tree roots. They therefore suggested that a proper selection of plant species sown under the trees could benefit the development of the annual intercrop. In addition, their study pointed the major contribution of the herbaceous vegetation beneath the trees to plant diversity and to their associated above- and belowground biodiversity.

Studies on nutrient provision in agroforestry systems have mostly focused on tree litter decomposition and release of nutrients from pruning residues, in terms of amounts and use efficiency (Palm 1995; Montagnini et al. 1999; Gnankambary et al. 2008) as well as on biological N_2 -fixation (Chikowo et al. 2004). However, studies on the nutrient use efficiency of mineral fertilization in agroforestry systems remain scanty (Cannavo et al. 2013). Sida et al. (2020) designed an original trial to disentangle tree-crop-fertilizer interactions in several agroforestry systems in Ethiopia and Rwanda. They found that in parkland with the nitrogen-fixing tree species *Faidherbia albida* (Delile) A. Chev., the addition of nitrogen only had not effect on wheat yields under the canopy compared to nitrogen addition in open field plots, while the application of phosphorus only doubled the wheat grain yields. Moreover, the phosphorus use efficiency was doubled under the canopy of *Faidherbia albida*. Phosphorus was therefore more limiting than nitrogen for wheat production under the canopy of *Faidherbia albida*, and nitrogen fertilization could be saved under tree canopies. The phenology of *Faidherbia albida* is unique as it sheds its leaves during the rainy season, and cattle usually graze under its canopy during the dry season, potentially bringing some nitrogen, but also phosphorus and potassium through their dejections. On the opposite, the yield and nutrient use efficiency were reduced for maize grown under another nitrogen-fixing tree species *Acacia tortilis* (Forssk.) Hayne and *Grevillea robusta* A.Cunn. ex R.Br. Processes of facilitation and competition are therefore site-specific and fertilizer recommendations should account for local conditions (soil type and fertility level) and the type of agroforestry systems (tree and crop species).

Soil organic carbon cycling in agroforestry systems

Early research on agroforestry systems has focused on the effect on soil organic matter and soil fertility (Young 1989; Onim et al. 1990; Chander et al. 1998). More recently, research on soil fertility in agroforestry systems was extended to the concepts of soil health and soil quality (Barrios et al. 2012; Muchane et al. 2020). In the last two decades, the burning issue of global warming induced a new research in agroforestry systems, with a huge increase in the number of articles dealing with climate change mitigation via carbon sequestration in soils (van Noordwijk et al. 2019). Despite the important diversity of agroforestry systems, recent reviews and meta-analyses suggest that the conversion of arable land to agroforestry systems leads to increased soil organic carbon (SOC) stocks (Lorenz and Lal 2014; Kim et al. 2016; Cardinael et al. 2018b; Feliciano et al. 2018; Shi et al. 2018; Corbeels et al. 2019), and these systems are now better taken into account in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Cardinael et al. 2018b; Ogle et al. 2019), which is a critical but insufficient step to gain access to finance and other support (Rosenstock et al. 2019). SOC storage at the plot scale is controlled by a balance between organic carbon inputs and losses. In agroforestry systems, higher organic carbon inputs to the soil are often observed compared to treeless croplands (Cardinael et al. 2018a), as a result of tree litterfall (Sileshi and Mafongoya 2007; Negash and Starr 2013) and pruning residues (Zingore et al. 2003; Nyamadzawo et al. 2012), but also tree root inputs (Sierra and Nygren 2005; Germon et al. 2016). Increased organic inputs under trees are also due to tree canopy throughfall inputs, nutrients and to soil particles transported by the wind and captured by tree canopy (Biielders et al. 2002), accumulation of windborne soil around trunks, as well as fecal inputs from perching bird or grazing animals (Rhoades 1997). Increased biomass production at the plot scale (Graves et al. 2010) and organic inputs might explain the enhanced SOC sequestration in agroforestry systems. Besides, other soil and soil biota related processes favored by agroforestry systems can promote higher SOC sequestration, such as enhanced aggregate stability (Udawatta et al. 2008) promoting SOC stability and reduced erosion due to increased water infiltration and reduced runoff (Anderson et al. 2009).

Several authors found an increase abundance, biomass and diversity of earthworms in agroforestry

systems (Price and Gordon 1999; Cardinael et al. 2019b). Soil fauna is largely involved in litter and SOC decomposition (Lavelle et al. 2006) and its effect on SOC stabilization is still debated (Frouz et al. 2015; Lubbers et al. 2017). Agricultural practices largely impact soil biota (Ponge et al. 2013) but very little is known about agroforestry systems. To fill this knowledge gap, Marsden et al. (2020) performed a systematic review on the effect of agroforestry systems on soil macro, meso and microfauna and their functions. They found that most studies have so far focused on soil macrofauna community (abundance, diversity and biomass) in agroforestry compared to a reference plot. They showed that the effects on fauna abundance and diversity are mainly positive when agroforestry is compared to cropland, and neutral or negative when compared to forests. However, soil fauna functions in agroforestry systems were only studied in 17 out of the 67 retrieved papers. Interestingly, the main soil function addressed was soil structure maintenance, while very few studies investigated the role of soil fauna on carbon and nutrient cycling in agroforestry systems.

Several years, often a decade, are necessary to detect a change in SOC stocks (Smith 2004). However, early changes in SOC dynamics can be tracked using early indicators such as some soil fractions or soil enzyme activities. Rigal et al. (2020) and Clivot et al. (2020) both studied such early changes, four years after tree planting in very different contexts. In Rigal et al. (2020) studied the effect of three shade tree species (*Cinnamomum camphora* (L.) J. Presl, *Bischofia javanica* Blume, *Jacaranda mimosifolia* D. Don) on soil quality in a coffee (*Coffea arabica* L.) agroforestry system. More specifically, they characterized soil enzyme activities, soil microbial communities, including arbuscular mycorrhiza fungi (AMF) and non-AMF fungi, nematode communities, as well as soil chemical properties. They observed a significant increase in the abundance of bacterial and fungal communities in shaded areas compared to open areas, especially during the dry season, and a significant build-up of soil organic matter under shaded coffee. As the yields of shaded coffee were maintained, except under *C. camphora*, they concluded that carefully selected shade trees could rapidly contribute to restoring soil quality, while maintaining high coffee yields. In France, Clivot et al. (2020) studied the effect of two alley cropping agroforestry systems, poplar (*Populus deltoides* × *P. nigra*)-alfalfa (*Medicago sativa* L.) and alder (*Alnus glutinosa* L.)-

ryegrass (*Lolium perenne* L.) on several soil properties and microbial and enzymatic activity, compared to treeless control plots. No significant differences in SOC contents nor in labile soil organic matter fractions were found in the topsoil (0–15 cm). Microbial enzyme activity varied greatly across years, but no general trend was found. However, near-infrared and mid-infrared spectroscopy showed a differentiation in soil organic matter quality between the poplar-alfalfa agroforestry system compared to the alfalfa treeless plots. In contrast, Guillot et al. (2019) reported in an older alley cropping agroforestry system with hybrid walnut trees that there was an increased microbial biomass and activity in the alley, beyond the tree row. In such agroforestry systems, as also pointed by Battie-Laclau et al. (2020), such effects on soil microbial communities are possibly impacted by the herbaceous vegetation beneath trees, not just by the trees.

Farmers implement various agroforestry systems to restore soil fertility, such as planting nitrogen-fixing shade trees, or shifting cultivation. Wartenberg et al. (2020) and Terefe and Kim (2020) studied changes in soil fertility and SOC contents and stocks in these two systems, respectively. More specifically, Wartenberg et al. (2020) investigated the interactions between 11 commonly intercropped shade trees and cocoa trees in cocoa (*Theobroma cacao* L.) agroforests in Sulawesi, and their impact on cocoa productivity and on some soil properties, such as aggregate stability. Mean weight diameter of stable aggregates are key indicators of the fate of macro- and micro-aggregates in soils, both involved in the stabilization of SOC (Oades 1984; Six et al. 2004). While many studies have focused on soil tillage (Six et al. 2000), little is still known about the effect of agroforestry systems on soil aggregates (Udawatta et al. 2008). The authors found that SOC, soil nitrogen and aggregate mean weight diameter were increased under shade tree canopies compared to open areas. Cocoa tree growth was reduced but with no adverse effects on cocoa yields. Interestingly and similarly to Rigal et al. (2020), the authors suggested that shade trees do not always induce a direct trade-off between yield and soil fertility. In Ethiopia, Terefe and Kim (2020) studied shifting cultivation systems, an example of sequential agroforestry, with different fallowing durations compared to adjacent monocropping fields and a natural forest. The authors found that long-term shifting cultivation did not affect soil pH, soil organic carbon (SOC) and soil total

nitrogen stocks compared to the forest. However, the conversion of shifting agriculture to conventional monocropping resulted in a huge loss of SOC stocks (about –50% over 10 years). Shifting cultivation is therefore a relevant practice to maintain high SOC stocks.

Conclusion and perspectives

To better understand the belowground functioning of agroforestry systems, a considerable effort has been made over the recent years to explore the various and numerous processes in diverse types of agroforestry systems. This special issue is a perfect illustration of such an effort, gathering studies dealing with different topics and approaches related to a broad range of disciplines such as soil ecology and biology, hydrology, biochemistry, ecophysiology, ecology and agronomy. However, a comprehensive understanding of the belowground functioning of these systems is still lacking, because numerous and complex site-specific interactions and trade-offs are at play. We summarize here what we think should be further explored in the coming decade. Future works should:

- **Document temporal dynamics.** More precisely, future studies should study the processes on the long-term, and better document temporal effects (seasonal, year-to-year, short- vs. long-term effects). For instance, significant changes in SOC stocks can only be observed on the long-term while short-term transitional effects might be misleading. Maintaining long-term trials is critical in that respect.
- **Investigate spatial dynamics.** Future studies should better document lateral spatial heterogeneities generated in such systems (Battie-Laclau et al. 2020; Marsden et al. 2020), depending on the types of agroforestry systems and spatial arrangement of trees, and how these affect soil functions and related ecosystem services (Cardinael et al. 2017, 2019b; Roupsard et al. 2020). Beyond the role of trees, that of the herbaceous cover under the trees shall also be better accounted for (Cardinael et al. 2017, 2018a; Battie-Laclau et al. 2020), whenever present, or the contribution of grazing animals, when relevant, as they are likely to be additional sources of heterogeneity.

- **Dig deeper.** Several papers of this special issue were innovative in also focusing on deep soil layers (Battie-Laclau et al. 2020; Ling et al. 2020; Terefe and Kim 2020; Huo et al. 2020). Deep-rooting of trees in agroforestry systems is likely to impact the whole soil profile (Mulia and Dupraz 2006; Cardinael et al. 2015b) and better understanding of soil processes at depth is critical for water and nutrient cycling (Bayala and Prieto 2020; Isaac and Borden 2020), as well as for carbon sequestration (Cardinael et al. 2015a, 2018a, 2019a) as also summarized in recent reviews on the role of deep roots (Maeght et al. 2013; Thorup-Kristensen et al. 2020; Germon et al. 2020).
- **Be integrative.** Develop an integrative approach, linking above- and belowground processes, and also coupling the cycling of different elements, such as water, nutrients and carbon. Modelling of agroforestry systems should be particularly developed towards this aim (Luedeling et al. 2016; Dupraz et al. 2019). For instance, the complete radiative forcing of agroforestry systems should be quantified including a balance of greenhouse gases and if possible also changes in biophysical effects such as albedo. Only quantifying the carbon balance of agroforestry systems might lead to a biased understanding in their role towards climate change mitigation. Only a few studies have focused on nitrous oxide (N₂O) emissions in agroforestry (Kim et al. 2016) and on the role of nitrogen-fixing trees in such emissions (Rosenstock et al. 2014). Beyond the potential contribution of agroforestry systems to climate change mitigation, how such systems adapt to climate change compared to conventional cropping systems shall deserve further consideration.
- **Embrace diversity.** Globally, agroforestry systems are very diverse, and some are poorly studied. More data should be for instance collected in temperate agroforestry systems, as works on tropical agroforestry systems are over-represented by now. Only two studies in this special issue presented new data on temperate agroforestry systems (Battie-Laclau et al. 2020; Clivot et al. 2020) despite the growing development of such systems in temperate regions of the world.
- **Highlight the multifunctionality.** The multifunctional features of agroforestry systems should be better taken into account in management practices. This demands future studies to understand and

characterize a larger and more transdisciplinary pool of ecosystem services in the assessment of agroforestry systems, not only biophysical indicators of soil ecosystem functions and services, but also when possible, social and economic indicators. Simultaneously, future studies should analyze synergies and trade-offs among expected ecosystem functions and services. Rigal et al. (2020) and Wartenberg et al. (2020) both reported an absence of trade-off between yield and soil fertility, but this might not be the case everywhere. Synergies and trade-offs among ecosystem services could then be optimized to achieve multifunctional agroforestry systems (Andreotti et al. 2018).

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