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Agroforestry and organic agriculture

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Abstract Current conventional agriculture is considered unsustainable and inadequate to address great societal challenges such as climate change, environmental pollution, food security, dependence on fossil energy as well as the decline of natural resources and biodiversity. Many of these problems are related to agricultural specialization (i.e. monoculture) and the consequent simplification of the agroecosystem. In this respect, efforts aimed at improving individual agronomic techniques and at increasing the use-efficiency of external inputs (e.g. synthetic inputs, fossil fuels), without modifying the structure and functions of the whole system, appear to be insufficient to achieve sustainability in most conventional and intensive farming systems. Current organic farming systems adopting the so-called input substitution approach remain intensive and highly specialized and not necessarily able to significantly improve their sustainability. This would require system diversification and redesign of the agroecosystem to increase the spatial and temporal diversification of all its components and promote positive ecological relationships between them. Agroforestry is an agricultural approach based on the diversification of the agroecosystem production components (woody perennials, such as trees or shrubs, plus crops and/or livestock) and on the intensification of the agroecological relationships between these components. As such, it has transformative potential, providing an opportunity for increasing the sustainability of organic farming. In this article we review how the adoption of agroforestry practices could contribute to increasing sustainability in organic farming, and discuss the challenges and opportunities of this adoption.

Keywords Agroecology · Organic farming · Sustainability · Crops · Livestock

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The current crisis of specialized agricultural systems

It is widely acknowledged that the conventional agricultural model, originating from the green revolution and based on crop specialization and on massive use of external inputs and fossil energy, is facing a deep crisis (IPES-Food 2016). This agricultural model is considered unsustainable from social and environmental points of view and incapable of solving great challenges to sustainability, such as the decline of natural resources and biodiversity, climate change, food security and dependence on fossil energy (Geiger et al. 2010; Godfray et al. 2010; Tittonell 2014). Furthermore, specialized agri-food systems do not ensure a fair distribution of added value along the supply chain (HLPE 2019) and are not always perceived by consumers as systems capable of expressing quality and typicality (IPES-Food 2016).

Specialized agriculture has been identified as the source of various problems, from soil erosion and compaction to the loss of biodiversity, as a result of agroecosystem simplification (Bastian 1999; Dupraz et al. 2005; Nair et al. 2008, 2011). This loss of biodiversity has led to the disappearance of different species, varieties and breeds of farmed crops and animals, but also of spontaneous flora and fauna associated with them, resulting in the destabilization of agroecosystems and consequent increase in the need for external inputs (Tsiafouli et al. 2015) and for pest control (Stamps and Linit 1998). The absence of livestock and manure, the increase in the frequency and depth of tilling and the removal of trees led to a strong reduction in soil organic matter and therefore in the agroecosystem carbon stock (both in the soil and in the trees), with well-known negative consequences in terms of soil fertility, permeability, and water retention capacity. This exposed soils to drought and erosion, increased the need for external inputs, caused water pollution, and released carbon in the atmosphere (Caon and Vargas 2017).

In this context, efforts aimed at improving individual agronomic techniques and the use-efficiency of external inputs (e.g. synthetic inputs, fossil fuels), without modifying the structure and functions of the whole system, appear to be ineffective. Gliessman (2016) observes that even techniques such as precision agriculture act on individual inputs or techniques, and therefore cannot be considered as strong innovations towards sustainability.

Gliessman (2015) identified and described five phases that characterize the transitions towards more sustainable food systems. The first three phases operate at the agroecosystem level and consider (1) the increase in input use-efficiency, (2) the replacement of conventional inputs and practices with agroecological alternatives, and (3) the redesign of the agroecosystem, increasing the spatial and temporal diversification of all its components, promoting ecological relationships between these components. The remaining two phases operate at the level of the entire food system: (4) re-establishing a more direct connection between producers and consumers, and (5) constructing a new global food system based on participation, locality, equity and justice. While the first two phases can be defined as "incremental", the last three are of a more "transformative" nature.

Most agricultural systems in developed countries are intensive and highly specialized, including organic ones. In fact, most organic farming systems in these countries adopt the so-called input substitution approach (Darnhofer et al. 2010; USDA 2015), where, for example, synthetic fertilizers are replaced by organic ones, or weeds are controlled by tilling rather than with chemicals. Some of these changes bring partial improvements, for instance increased biodiversity (Maeder et al. 2002; Hole et al. 2005) and soil quality (Pimentel et al. 2005; Mondelaers et al. 2009; Lynch et al. 2012; Tuomisto et al. 2012; Reganold and Wachter 2016), or reduced use of energy (Pimentel et al. 2005; Tuomisto et al. 2012). Cover cropping and use of manure might be the practices with the most impact in improving the sustainability of organic farming compared to conventional agriculture (Teasdale et al. 2007; Muller and Aubert 2014), even though these practices can be adopted in conventional agriculture as well. Additionally, some organic farms adopt a more diversified crop rotation and include livestock (Watson et al. 2002). Despite this, most organic systems remain highly specialized, utilizing the same basic methodologies as in conventional farms (Wilson and Lovell 2016), especially on larger-scale farms (Dimitri 2010), thus relying heavily on yearly replanting, high inputs and weed control as in conventional systems (Davis et al. 2012). Therefore, efforts undertaken to improve the sustainability of the agri-food systems, including organic farming, are mainly of an incremental nature, and are not transformative agroecological approaches based on the redesign of the entire system and its components, including the human component and the producer/consumer relationship.

Agroforestry and organic agriculture

Agroforestry, a word coined in 1977 (Bene et al. 1977), defines a suite of agricultural practices where trees or other woody species are cultivated together with other crops and/or livestock (Lundgren 1982). Depending on the combination of the tree and the other elements, agroforestry systems can be classified into different types (Mosquera-Losada et al. 2009): silvopastoral systems (trees plus pasture), silvoarable systems (trees plus agricultural crops) and agrosilvopastoral systems (trees plus crops and livestock). Trees in agroforestry can be of any kind and with any function, including wood, biomass or fruit production. Agroforestry was the main type of agricultural land use before specialized agriculture replaced it almost completely during the last century, in developed countries such as in Europe (King 1987; Herzog 1998; Eichhorn et al. 2006; Dupraz et al. 2018), where remnant systems are still present. In Europe agroforestry now covers about 15.4 million hectares (8.8% of the agricultural area) if only tree-based systems are considered (Den Herder et al. 2017), or 19.77 million hectares if all types of agroforestry practices are considered (Mosquera-Losada et al. 2018). Agroforestry is still the main agricultural land use in the tropics (Zomer et al. 2016). Considering all its forms, agroforestry is practiced today on over 1 billion ha worldwide (Nair et al. 2009), almost half of all agricultural area.

Agroforestry is an agroecological approach based on the diversification of the agroecosystem production components (trees/shrubs, crops and/or livestock) and on the intensification of the agroecological relationships that exist between these components in space and time. As such, it has potential for transformative scope (see phases "3" to "5" of Gliessman's theory) and the integration of agroforestry practices in organic farming can represent a pathway for further development of organic agriculture, towards increased sustainability.

In countries with a tropical climate, some crops typically grown in agroforestry like coffee and cocoa for instance, are extensively grown organically (Willer and Lernoud 2019). Several projects have specifically aimed at developing organic agroforestry practices in tropical climates (e.g. YMTM, YAFA and TWN 2007; AFSA 2015). In developed countries with a temperate climate, on the other hand, organic farming rarely adopts agroforestry practices. The Organic Research Centres Alliance states that "the integration of agroforestry in organic production is uncommon, creating a significant opportunity for research to assist farmers in this underdeveloped strategy" (ORCA 2010). Indeed, despite diversification being a key strategy in the original concept of organic farming, current organic agriculture is not required to implement diversification practices (Seufert et al. 2019). Consequently, organic agriculture in developed countries is now often practiced as large-scale monocultures that may do little to foster biodiversity or sustain ecosystem services (Kremer et al. 2012). Agroforestry could allow the implementation of diversified organic systems, whose functioning is based on the principles of agroecology, making them more sustainable in environmental, social and economic terms. One of the main dilemmas that still characterize a large part of organic farming in developed countries, is the specialization of organic livestock production and the consequent separation between livestock and plant production. Canali and Speiser (2005) reported that organic farming cropping systems in the Mediterranean basin are often stockless. Similarly, Colomb et al. (2013) mentioned that in France 35–40% of organic grain crops were currently grown within stockless cropping systems. In Poland 83% organic farms were involved only in arable production (IJHARS 2017). Agroforestry could solve or mitigate this issue, reconnecting animal and plant production at cropping systems and/or farm scale.

The transformative potential of agroforestry in organic farming is increasingly recognized, stimulating interest in combining organic farming and agroforestry, with still limited but growing examples of organic agroforestry companies, for example in the United Kingdom, Hungary, Poland, Ukraine and Italy among other countries (see for instance featured farms in the EURAF website: http://www.eurafagroforestry.eu/resources/featured-farm or see the AFINET project website: https://euraf.isa.utl.pt/afinet/rains/agroforestry-action).

However, while research in agroforestry has increased exponentially since its beginning in the 70s, there is surprisingly very little scientific information on the possible contribution of agroforestry to organic agriculture. This paper reviews some of the potential benefits of integrating agroforestry and organic farming.

Benefits of integrating agroforestry and organic farming

One of the greatest criticisms of organic farming is its lower productivity compared to conventional farming (Kirchmann and Thorvaldsson 2000; Connor and Mínguez 2012). Several reviews and meta-analyses of published literature show that productivity tends to be lower than for conventional agriculture (Maeder et al. 2002; Kirchmann et al. 2009; Reganold and Wachter 2016; Wilson and Lovell 2016) even though this is not always the case. For instance, in drought years organic yields may be more resilient, probably due to higher soil organic matter and water-holding capacity (Siegrist et al. 1998; Letter et al. 2003). Additionally, in the tropics organic farming is often found to outperform conventional agriculture in yield, gross margins and soil organic matter, especially in less developed countries, in arid regions and on coarse soils (Te Pas and Rees 2014). In most situations in developed countries, however, organic farming is usually less productive. Lower productivity implies that, although organic farming is often considered more sustainable than conventional farming per unit area, it is often not per unit of product (Tuomisto et al. 2012; Muller and Aubert 2014; Meemken and Qaim 2018). With lower productivity, more land is needed to produce the same yields, possibly resulting in greater environmental impact than with conventional farming (Kirchmann et al. 2009; Emsley 2001; Trewavas 2001). By increasing overall productivity per unit of land, more diverse and multifunctional agroecosystems could strike a better balance between productivity and sustainability (Tilman 1999; Tuomisto et al. 2012; Lovell et al. 2010, 2018). Amongst these systems, agroforestry is one of the most promising possibilities to reduce the environmental impact without losing productivity (Wilson and Lovell 2016). The adoption of agroforestry in organic farming represents therefore one of the most promising improvements, as it could help reduce the yield gap with conventional agriculture, while further improving sustainability. In fact, one of the most important goals of modern agroforestry is to produce more per unit area and more sustainably, known as sustainable intensification or ecointensification (Santiago-Freijanes et al. 2018). The productivity of agroforestry systems is higher, compared to the sum of the respective monocultures, when the system is designed to optimize the use of natural resources like water, light, minerals, flora and fauna (Smith et al. 2012; Cannel et al. 1996). This means maximizing complementarity and synergisms and minimizing competition for resource use by the different system components. In other words, the tree (or shrub) exploits resources that the crop or animal would not use and vice versa. This results in higher productivity per hectare than separate cultivation of the same elements (Garrett and McGraw 2000; McNeely 2004; Smith et al. 2013). A typical example is the cultivation of winter crops under deciduous trees, which optimizes the use of light throughout the year. Many studies report higher productivity of agroforestry systems compared to the respective monocultures, the review of which is out of the scope of this paper. Very few studies report productivity data in organic agroforestry compared to just organic or just agroforestry. For instance, farmers in Nigeria reported that using plant residues from agroforestry trees to enrich the soil and feed livestock improved crop and animal productivity respectively in organic agriculture (Anyoha et al. 2018). Huber et al. (2014) found that woody biomass production did not differ between organic and integrated productions systems, indicating that organic and integrated agroforestry systems can have a comparable tree biomass production. Schneider et al. (2017) found that cocoa yields were 47% lower in the organic compared to the conventional monoculture. However, in the agroforestry system, the organic–conventional yield gap was less pronounced (− 16%) and statistically insignificant. These authors also found that, considering all products, agroforestry was more than twice as productive as monocultures, both in organic and conventional managements. Armengot et al. (2020) obtained lower cocoa yields in the organic monoculture than in the conventional one, but no differences were detected between organic and conventional agroforestry systems. The authors concluded that "promoting cultural management practices and organic agroforestry systems is crucial to achieve two of the main goals of the cacao industry and the consumers: reducing deforestation and sourcing from sustainable cacao plantations.

In addition to possible increases in yield, the diversity of products in agroforestry increases farm resilience and food security (Ashley et al. 2006; Jama et al. 2006; Leakey et al. 2006). Diversification is also an important element in sustainable bioeconomy

(Kovacs 2015). Compared to conventional agriculture, the greater diversification in organic agriculture contributes to greater food security (Parrot et al. 2006). Diversification and enhanced biodiversity are well in line with the principles of certified organic farming (Mader et al. 2002). Further diversifying the organic systems, by adding trees and their products, is therefore a step forward.

Some agroforestry systems have been shown to be economically more profitable than conventional monocultures, but others need to rely on compensation for their ecosystem services in order to be profitable (Grado and Husak 2004; Winans et al. 2015). The profitability of organic farming is often equal or superior to conventional farming, and this is based on the premium price of organic produce and/or subsidies, without which the profitability would be lower (Crowder and Reganold 2015). Agroforestry products grown in organic farms would benefit from the organic certification, obtaining premium prices. This would help make agroforestry products more profitable and improve the overall system profitability, as was shown with organic yerba mate (Montagnini et al. 2011) or organic cocoa (Andreas et al. 2016). Currently, there are some standards for agroforestry or non-timber forest products, harmonized within the IFOAM family of standards, e.g. Forest Garden Products certification (IAFN-RIFA 2020) or standards developed by the Soil Association in the UK, complying with the Forest Stewardship Council (FSC: https://fsc.org/en) standard (SA 2020). Guidelines that go beyond good organic standards have been proposed, one of them being the Framework for Regenerative Organic Certification (FROC), including agroforestry standards (Elevitch et al. 2018). A review of organic certification programs in the context of potential agroforestry inclusion can be found in Elevitch et al. (2018).

There are, however, examples where organic agroforestry farms provided greater income than conventional agroforestry farms, independent of certification. For instance, in India Padmavathy and Poyyamoli (2013) found that adopting agroforestry increased income in organic farms, and this was correlated to greater diversity. Agroforestry has been shown to improve farm income in organic farms also in Nigeria (Anyoha et al. 2018). However, the information available is still scarce, particularly for developed countries, and more data is necessary to evaluate the profitability of organic farms adopting or not adopting agroforestry.

Agroforestry can protect crops from extreme climatic events (Sánchez and McCollin 2015), representing one of the most promising systems for climate change mitigation and adaptation (Aertsens et al. 2013). Arenas-Corraliza et al. (2018) predict that the yield of herbaceous crops in silvoarable systems could be higher than in open sites in Mediterranean environments, if the frequency of warmer and drier springs continues to increase, because drought and high temperature would limit crop productivity more than tree shade, while the latter attenuates the negative effects of drought and temperature. If so, adopting agroforestry could reduce the gap in productivity between organic and conventional production, since crop yield would be limited by water and temperature more than by nutrients (i.e. the limiting factor in organic vs. conventional agriculture). In the scenario outlined by Arenas-Corraliza et al. (2018), with spring drought and high temperature, organic alley cropping could produce as much as conventional alley cropping, and more than both organic and conventional crop monocultures, limited by temperature and water stress in the absence of some shade.

Agroforestry is often found to increase product quality, for example forage quality (Lin et al. 2001) or protein content in wheat (Dafour at al. 2013). Adopting agroforestry in organic farming could, therefore, contribute to further increase product quality in organic agriculture, which is often claimed to produce higher quality food, even though there is not always definitive evidence (Vigar et al. 2020).

In the shade of trees, not only crops but also animals are protected from the weather and, in particular, from excessive exposure to sun and extreme temperatures, with consequent improvements in livestock productivity and welfare (Payne 1990; Blackshaw and Blackshaw 1994; Gregory 1995; Mitlohner et al. 2001), nutrient recycling (Nair et al. 2007), quality of the meat or other products (Cartoni Mancinelli et al. 2019; Dal Bosco et al. 2014, 2016). Increasing livestock productivity and welfare are important goals of all livestock operations, but particularly for organic production where low productivity, ethical issues related to the animals' welfare, and limitations in the use of veterinary medicines are particularly important aspects. Integrating agroforestry with organic free-range poultry, by planting trees in the paddocks, has been increasingly investigated (O'Brian et al. 2006; Bestman et al. 2016; Moussier 2015). Use of forage from agroforestry trees has been found to improve animal productivity in organic farms in Nigeria (Anyoha et al. 2018). For a review of the many benefits of raising livestock in agroforestry systems, in light of their potential to improve organic animal farming, see Escribano et al. (2019).

If trees can benefit animals, the latter, in turn, can favor the cultivation of trees by providing fertilization and weeding, thus reducing the environmental impact of both crops and livestock (Paolotti et al. 2016; Rocchi et al. 2019). These authors used life cycle assessment (LCA) to assess the environmental benefits of the tree/livestock integration. They found that fertilization, especially with N fertilizers, and weeding were the two operations with the highest environmental impact in the orchard. Chickens provided sufficient weed control (by scratching) and fertilization (with their droppings), making weeding and fertilization with external inputs no-longer necessary, thus greatly reducing the orchard's environmental impact. Providing grazing land, the orchard reduced the impact of livestock rearing. These interactions are advantageous for both conventional and organic systems, but more so for the latter, where fertilization often relies on bulky and costly off-farm materials, and weeding is mostly mechanical (due to the ban on most weed killers of synthetic origin), requiring large amounts of fuels and/or labor, with high economic and environmental costs.

Organic farming is generally considered better than conventional in terms of nutrient leaching, but the problem remains and, in some cases, leaching levels are even higher than those of conventional agriculture (Bergström et al. 2009; Pimentel et al. 2005). This is even more true if leaching is considered per unit of product, considering the lower productivity in organic than in conventional farming (Mondelaers et al. 2009; Tuomisto et al. 2012). Intercropping with trees could contribute to the containment of nutrient leaching in organic farming. In fact, Nair et al. (2007) and Jose (2009) report a 40–70% reduction in nitrogen leaching with agroforestry, while Palma et al. (2007a) estimate that the conversion of 12 million ha of arable land into silvoarable agroforestry systems would lead to a 28% reduction in nitrogen leaching in Europe. Agroforestry also reduces surface water flow (runoff) and the consequent loss of soil and nutrients (Borin et al. 2005), due to both the physical barrier—due to the trees, but also to the vegetation, spontaneous or cultivated, under the tree lines—and to an improved soil permeability, enhancing water and nutrient infiltration (Schultz et al. 2009). Reducing leaching and reducing runoff both increase nutrient use efficiency. The increased nutrients' use-efficiency achieved with agroforestry has environmental benefits as well as economic benefits, considering the increasing cost of fertilization and the limited natural supplies of some fertilizers. This is true for conventional agriculture, but in particular for organic farming, where permitted fertilizers are generally more expensive. The reduction in surface flow and leaching of nutrients leads to improvements in water quality, both groundwater and fluvial. Further mechanisms for improving water quality are due to the presence of fine roots, which intercept, absorb and/or degrade nutrients and contaminants (Schultz et al. 2009; Udawatta et al. 2002, 2011), also thanks to the microbial flora associated with the rhizosphere (Ambus 1993; Mandelbaum et al. 1993, 1995; Struthers et al. 1998).

Organic farming often results in improved soil quality as reported in the previous section, but soil erosion and degradation remain problematic due to frequent soil tillage, necessary for planting annual crops, incorporating cover crops into the soil and mechanical weed control (Teasdale et al. 2007; Arnhold et al. 2014). Agroforestry reduces soil erosion (Ceballos and Schnabel 1998; McIvor et al. 2014; Palma et al. 2007a, b; Reisner et al. 2007; Muchane et al. 2020), both by reducing surface flow and through the reduction of wind speed, for example with hedges (Sánchez and McCollin 2015). The positive effect of windbreak hedges on crops is well known, and trees in silvoarable systems have similar effects (Garrett et al. 2009). Agroforestry can improve also other soil quality traits, like storage of soil organic carbon and nitrogen, availability of soil nitrogen and phosphorus to crops, and alleviation of soil acidity (Muchane et al. 2020).

Organic farming tends to increase soil organic matter (Mondelaers et al. 2009; Gattinger et al. 2012; Tuomisto et al. 2012). Agroforestry also increases the level of organic matter in the soil (López-Díaz et al. 2017; Seitz et al. 2017; Upson and Burgess 2013), probably thanks to the contribution of leaf litter and tree roots (Park et al. 1994). However, soil C does not always increase, depending on the local climate and the soil management system prior to tree establishment (Feliciano et al. 2018): the increase is much more likely and consistent in arable land, including organic arable systems, than in permanent grassland, where the carbon content is usually already high. The increase in organic matter is higher if, in addition to the tree leaf litter and roots, the chopped biomass of the tree pruning material, a woody material with a high humification coefficient, is added to the soil, as found for instance in the work of Youkhana and Idol (2016 and previous work cited therein). This biomass could strongly contribute to soil fertilization in organic production, using on-farm inputs. In particular, this would be advantageous for organic agriculture where fertilization may be based on importing large quantities of organic fertilizers and amendments, which are bulky and therefore expensive (also environmentally) to transport from outside the farm. Jordan (2004) reports that the ramial biomass (18.4 Mg ha^{-1} of dry matter), removed annually with tree pruning in an alley cropping system in the southern USA was sufficient to provide the necessary nutrients to the understory crop, without additional external fertilizers. The effectiveness of agroforestry in providing organic biomass for soil fertilization in organic production has been recognized by Nigerian farmers, who reported that biomass from agroforestry improves "soil health through which suitable environment is provided for organic plant growth" (Anyoha et al. 2018). However, while agroforestry can provide significant nitrogen (N) inputs via biological N fixation, and significant inputs of other nutrients, via deep nutrient capture (capture of nutrient from soil horizons too deep for the crop), this may not work for phosphorus, which is scarce in deep soil layers (Sanchez 1995). Therefore, while ramial mass does contain phosphorus, this represents recycling, does not constitute an input and cannot compensate for offtake (Sanchez 1995). What the trees can do in effect is to expand the volume of soil used by a considerable amount (Cahn et al. 1992). However, organic inputs have an advantage over inorganic fertilizers in the sense that, much of the 50 to 80% of the applied organic nitrogen not utilized by crops, is incorporated into active pools of soil organic matter because these mulches also provide the carbon source needed as energy for microbial immobilization (Palm 1995). Most of the N in inorganic fertilizers is instead lost via leaching and denitrification. If the ramial mass is produced on a different site than the crop, then all nutrients imported are real inputs, but this would simply entail a transfer of nutrients from one site to another, enriching the latter, but depleting the former.

In addition to act as a fertilizer, ramial biomass can be used for mulching, contributing to the control of weeds (Kang et al. 1990 and references therein), one of the most serious threats to organic crop production (Bàrberi 2002 and references therein). The incorporation of plant residues with high C:N ratio is beneficial also in terms of reducing nitrous oxide (N_2O) emissions from the field (Hansen et al. 2019), although further understanding is needed.

The possible contribution of organic farming to greenhouse gas emission and C sequestration is not clear. In fact, organic farming tends to have lower emissions per unit of land than conventional farming, but the opposite may be true per unit of yield, due to lower yield in organic farming (Mondelaers et al. 2009; Tuomisto et al. 2012; Muller and Aubert 2014). Annual cropping systems, whether conventional or organic, do not mitigate climate change because even when C is accumulated in the soil, other emissions (e.g. N_2O) offset the gains (McIsaac et al. 2001). However, N_2O emissions can be reduced by incorporating into the soil ramial biomass from the trees (Hansen et al. 2019). More importantly, planting trees in arable soils increases carbon sequestration, stocking C in the tree biomass and with the possible increase in soil organic matter (Kim et al. 2016; Kay et al. 2019). Aertsens et al. (2013), after reviewing the literature on the C sequestration in agroforestry plots (mainly with walnuts and poplars) established on pastures and arable land in temperate climates, propose an average annual sequestration of 2.75 Mg C ha^{-1}. Carbon sequestration can be maximized by increasing the duration of the rotation of the tree species (increasing the average amount of wood present in the field), and using wood to make long-lasting products (delaying the re-entry into the atmosphere of the carbon) (Jose et al. 2012). A further indirect form of carbon sequestration is related to the improved productivity and efficiency of crops and livestock, which result in emission savings per unit of product (Kort and Turnock 1999). A careful examination of the potential carbon sequestration of the different agroforestry systems is reported in several reviews (e.g. Jose et al. 2012). Overall, it is estimated that the adoption of new agroforestry systems could offset a significant part of the emissions due to the consumption of fossil fuels (Jose et al. 2012; Kay et al. 2019). Therefore, adopting agroforestry in organic farming systems without trees has a great potential to reduce net emissions in organic agriculture.

Organic farming tends to increase biodiversity (Maeder et al. 2002; Hole et al. 2005; Mondelaers et al. 2009; Lynch et al. 2012; Tuomisto et al. 2012), including the diversity of crops and livestock (Reganold and Wachter 2016). However, planting trees in arable systems can increase biodiversity much further, not only in terms of number of cultivated species but also in terms of natural flora and fauna associated with the various tree/shrub species or the environments created by them (e.g. understory herbaceous vegetation below the trees on the tree line) (Birrer et al. 2007; Bailey et al. 2010; Lecq et al. 2017; Marconi and Armengot 2020). Agroforestry increases the diversity of insects (Stamps and Linit 1998), soil arthropods (Peng et al. 1993; Peng and Sutton 1996), birds (Gillespie et al. 1995; Berges et al. 2010) and can provide habitat for pollinators (Sutter et al. 2017). Adopting agroforestry in organic farming systems could greatly increase biodiversity in organic agriculture.

The increased biodiversity in agroforestry systems can provide opportunities to implement agronomic pest management in organic farming where the use of synthetic pesticides is not allowed and agronomic or agroecological approaches to pest management are essential. In fact, the IFOAM standards state that organic farming systems apply biological and cultural means to prevent unacceptable losses from pests, diseases and weeds (IFOAM 2014). Additionally, limitations in the use of synthetic pesticides makes agroforestry adoption easier in organic than in conventional farming, where agroforestry hinders the use of such chemicals, which might be registered for the understory crop, but not for the tree and vice versa. Agroforestry can improve natural pest control (Bianchi et al. 2006; Simon et al. 2011; Civitello et al. 2015) and increase crop pollination (Hanley et al. 2015). Sileshi et al. (2008) review how different agroforestry practices affect crop pests, weeds and diseases in the tropics. Less information is available from other climates. Altieri and Nicholls (2008) review the principles of ecologically based pest management in agroforestry systems. Ecological corridors, usually made of tree and shrub species, create landscape heterogeneity and enhance populations of natural enemies or avoid crops colonization by pests/pathogens (Letourneau and van Bruggen 2006). Short rotation coppice hedges may increase diversity and activity of cereal aphids parasitoids (Langer 2001). *Eucalyptus torelliana* windbreaks provide refuge for predatory citrus mites (Landis et al. 2000). Grazing in orchards can limit the development of fungal diseases from fallen infected leaves, which are consumed by animals (Burgess et al. 2016). Finally, shelterbelts at the edge of organic fields can protect organic crops from pesticides drift (e.g. Herard 1985). Despite the general lack of specific data from organic agroforestry trials, the literature reported above suggests that agroforestry adoption could represent a viable possibility to improve weed, pest and disease control in organic agriculture, but more specific research is clearly needed.

Organic agriculture reduces the exposure of farm workers to pesticides and other synthetic chemicals (Costa et al. 2014; Reganold and Watcher 2016). Even though, in diversified systems, the amount of pesticides used is expected to be lower than in monocultural systems, in many developing countries agroforestry tends to reflect modern agricultural systems in the intensive use of fertilizers and pesticides (Ashton and Montagnini 1999). Therefore, the integration of organic farming in agroforestry, with a reduction or the elimination of chemical inputs, may prevent or mitigate workers' exposure to harmful chemicals.

Organic farming has been often shown to increase employment, requiring additional manual work (Reganold and Watcher 2016). The same is generally applicable to agroforestry as, for instance, with reference to tropical cacao plantations. Armengot et al. (2016) observed that agroforestry systems have a higher demand for human labor compared to monocultural systems. This was mainly due to increased labor needs for tree management and harvesting of additional products, which implies not just more labor requirements, but greater labor diversification in time and skills, which is as important as an increase in the number of jobs. Instead, comparing organic and conventional agroforestry cocoa systems in Ecuador, Pérez-Neira et al. (2020) observed no differences in the demand for labor requirement. It may be concluded, therefore, that while adoption of agroforestry in organic farms increases labor requirements, adopting organic practices in agroforestry farms might not necessarily entail increased labor requirements. However, there is still limited knowledge on these aspects, and further research is needed to better understand the potential impact of organic agroforestry on employment and labor, as well as on worker welfare and gender equity.

Farmers practicing organic agriculture are often motivated also by cultural values (Hansen et al. 2006). Landowners value the esthetic and natural value of their land, both in principle and for perceived benefits (e.g. health, recreation) (Strong and Jacobson 2006). Agroforestry systems are among the preferred natural elements in this context (Sullivan et al. 2004; Valdivia et al. 2009). In general, agroforestry increases green infrastructure, improving the ecosystem services provided by agriculture (Kay et al. 2018a, b; Maes et al. 2015; Smith et al. 2017).

Challenges to agroforestry adoption in organic agriculture

Despite the many benefits of agroforestry, the adoption of modern agroforestry systems is still low (Trozzo et al. 2014; Sereke et al. 2016; Camilli et al. 2018). These authors found that the main constrains to agroforestry adoption include expense of initial establishment, higher requirements of labor and knowledge, farmers' and extension personnel's lack of experience, farmers' attitudes, lack of research and demonstration sites, inadequate policy, lack of support paying farmers for the ecosystem services that benefit society, difficulties in mechanization and logistics, requirements for creative marketing of diverse products and relative legal constraints. A detailed analysis of these challenges to agroforestry adoption is not in the scope of this review as such challenges and their perception by agroforestry stakeholders are well described in previous work (Wilson and Lovell 2016; García del Jalon et al. 2017). Some of the challenges to agroforestry adoption are very similar to those that limit the adoption of organic farming and other innovative systems (Reganold and Watchter 2016; Wilson and Lovell 2016). Therefore, organic farms, having shifted from conventional agriculture, might have already faced some of the common challenges, making the adoption of agroforestry potentially easier. Farmers that have already adopted organic farming system, are more likely motivated than conventional farmers to adopt additional practices, such as agroforestry, that can improve agriculture's sustainability.

Some of the potential benefits of agroforestry adoption in organic farming, relative to organic and conventional farming without agroforestry, are summarized in Fig. 1, where specific sustainability metrics are considered, as proposed by Reganold and Wachter (2016). Data for the organic agroforestry scenario, qualitatively based on the studies reviewed in this article, are compared to data on organic and conventional scenarios reported by Reganold and Wachter (2016) and qualitatively based on the studies discussed in their review. The figure suggests that, although all metrics considered are improved by integrating agroforestry and organic farming, compared to organic farming alone, the main benefits are likely to be in terms of enhancing biodiversity and ecosystem services as well as minimizing pollution. However, further research is necessary to provide quantitative data on the benefits of integrating agroforestry and organic agriculture. Further improvements in agroforestry design and practices, may also change the relative gains in the different metrics. For instance, designing agroforestry systems with better complementarity in resource use between trees and organic crops, and selecting crop cultivars and animal breeds especially suited for organic agroforestry systems, may improve gains in productivity.

Conclusions and future perspectives

Agri-environmental benefits make agroforestry strategic for the redesign of more sustainable agricultural systems. Modern agroforestry systems must be designed to combine environmental benefits with modern requirements like mechanization and high labor efficiency, in order to make the system economically sustainable. In the last few decades, research has greatly progressed in assessing interactions, both positive and negative, between trees, crops and/or livestock. Based on this knowledge, several innovative agroforestry systems have been proposed and studied. Examples include trees planted in rows at a distance based on the width of the combine harvester or of the other mechanical equipment, to optimize mechanization, or early pruning with specific techniques to

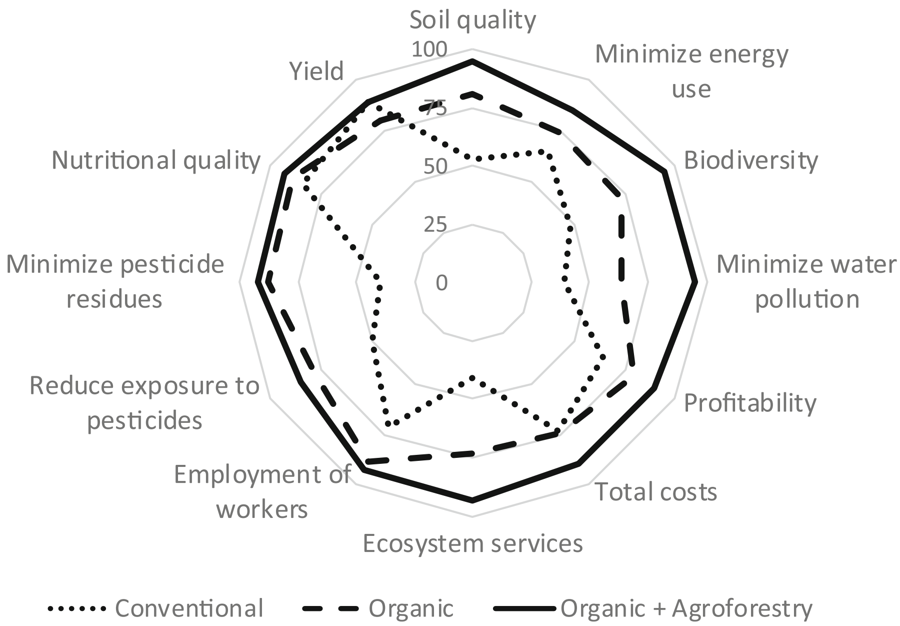

Fig. 1 Potential benefits of agroforestry adoption in organic farming, relative to organic and conventional farming without agroforestry. Data for Organic and Conventional farming are from Reganold and Wachter (2016), they are qualitatively based on the studies discussed in their review and indicate the level of performance of specific sustainability metrics relative to the four circles representing 25, 50, 75 and 100%. Data for Organic + Agroforestry are qualitatively based on the literature reviewed in this article

produce high quality wood even outside the forest (Bender et al. 2009; Morhart et al. 2010; Brix et al. 2009), and minimize shade and therefore yield reductions of the understory crops (Dupraz and Newman 1997). Although still limited, agroforestry research is increasing considerably at a global level. For example, in addition to the commitment in agroforestry research of fundamental institutions like ICRAF, FAO or ACIAR, in Europe several projects (SAFE: Silvoarable Agroforestry For Europe; AGROFE: Agroforestry education in Europe; AGFORWARD: Agroforestry that will advance rural development; AGROF MM: Agroforesterie—Formation-Méditerranée et Montagne; AFINET: Agroforestry innovation networks) have been funded by the EU. Such projects involved many stakeholder groups (farmers, consultants, policy makers, etc.). In 2011, the European Agroforestry Federation (EURAF: www.eurafagroforestry.eu/) was founded, a federation of national agroforestry associations. Since then, many new national associations were created under this umbrella-organization. Similar associations exist on other continents (e.g. the Association for Temperate Agroforestry, AFTA, in North America, https://www.aftaweb.org/about/afta.html). Despite all this interest in agroforestry, studies aimed at highlighting the many possible synergies between agroforestry and organic farming are still rare, while organic farming can find in agroforestry a promising transformative opportunity. Research efforts are needed to identify and analyze the levers that can favor the adoption of agroforestry in organic farming and the obstacles existing at the level of cropping system, farm, agri-food chain, society and policy.

In identifying methods of technical, economic and social integration, and paths of mutual recognition between agroforestry and organic farming, research and development could pursue two main strategies. The first concerns traditional agroforestry systems, where these are still present, updating them, if and where necessary, to the basic principles of organic agriculture (health, ecology, fairness and care; IFOAM 2005). This would entail the exclusion of synthetic inputs and of the most controversial technologies, and adopting certification and labeling systems for the recognition of the environmental and social qualities, as currently done in organic farming. Organic certification, among other labels such as PEFC, FSC or EU, ensures traceability of the products and guarantees the promised qualities (EIP-AGRI 2017), making the systems recognizable to consumers as sustainable agri-food models, thus providing the opportunity to obtain premium prices. The second strategy should start from modern, specialized and intensive organic farming systems, promoting the adoption of agroforestry as a structural diversification strategy to reconcile environmental, productive and mechanization requirements.

Suitable policies, increased research and demonstration activities, training of farmers and dissemination personnel, and increased awareness within the organic farming movements and organizations that transformative changes are needed, would all foster the development and adoption of agroforestry in organic farming (Stolze and Lampkin 2009; UNCTAD 2013). At least initially, until new products, markets, knowledge, social attitude and policy exist, subsidies for the ecosystem service provided by more diverse and sustainable agricultural systems will be of critical importance to encourage such adoption (Current et al. 2008; Jose et al. 2012).

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