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Abstract

The farming practices adopted since the end of the Second World War, based on large areas of monocultures and chemical use, have adversely affected the health of farmers and consumers and dramatically reduced farmland biodiversity. As a consequence, many studies over more than twenty years have stated that agriculture is facing three main challenges: (1) feeding the growing world population (2) with more environmentally friendly products (3) at a reasonable return for the producer. Increasing the efficacy of biocontrol could be one lever for agriculture to meet these expectations. In this study we propose implementation of a relatively under-researched system based on the management of landscape level crop diversity that would reduce demand for pesticide use and increase conservation biocontrol. The principle of manipulating crop diversity over space and time at a landscape scale is to optimize resource continuity, such as food and shelter for natural enemies to increase biocontrol services, reduce pest outbreaks and crop losses. The feasibility of such management options is discussed in relation to environmental, social and economic aspects. The operational and institutional inputs and conditions needed to make the system work are explored, as well as the potential added values of such a system for different stakeholders.

Key words: landscape crop diversity, natural enemies, economic feasibility, farmer acceptance, farmer training, farming practices, government subsidies, agricultural market opportunities

1. Introduction

Intensive agriculture has negative effects on the environment and on human health (Tscharntke et al., 2005; Jokanovic, 2018; Forkuoh et al., 2018; Wahlang, 2018). These negative effects are caused by habitat destruction, low crop diversity, intensive soil tillage and intensive use of agrochemicals, including pesticides and fertilizers (FAO, 2019). Pesticides have been used in agriculture for over a century to increase food production and they have proven their efficiency in increasing food accessibility worldwide (Pingali, 2012; Nelson and Burchfield, 2021). Now agriculture is facing the negative consequences of the intensive use of pesticides, notably through the increase of health issues affecting farmers (Jokanovic, 2018) and consumers (Forkuoh et al., 2018; Wahlang, 2018), and also through the destruction of biodiversity in fields and surrounding land (Liu T. et al., 2018), on soil biota (Lew et al., 2009; Velki et al., 2019), water (Leach and Mumford, 2008; Ibrahim et al., 2019), and on arthropod biodiversity including natural enemies (Desneux et al. 2007; Van der Valk et al., 2011; Lundgren et al., 2013; Woodcock et al., 2017; Wagner 2020). These natural enemies can be microscopic (fungi, bacteria, virus and nematodes) (Lacey et al., 2001) and macroscopic (predators and parasitoids) (Stiling and Cornelissen, 2005). In addition to negative effects due to pesticides, the use of large scale monocultures makes it difficult for natural enemies to find food and shelter after the crop is harvested, resulting in the loss of their populations and a reduction in biological control impact (Schellhorn et al., 2014). Biological control consists of "*the use of living organisms* - i.e. natural enemies - *to suppress the population density or impact of a specific pest organism, making it less abundant or less damaging than it would otherwise be*" (Eilenberg et al., 2001). Changing pest management practices by increasing the biological control potential, including the reduction of pesticide use, is an objective for the future as agriculture faces three challenges: to sustain healthy food production for the growing world population, to reduce the negative impacts of agrochemicals on the environment and on human health, and ensure reasonable profit or return for the producer.

Natural enemies can be used in agriculture in several ways (inundative, classical and conservation biological control) (Bale et al., 2008). Conservation biological control using macroscopic natural enemies, on which we will focus in this study, works by managing the environment to promote naturally occurring natural enemies (Eilenberg et al., 2001). Its main principle is to "enhance the activity of existing natural enemies to provide pest suppression" (Haan et al., 2021) notably by increasing plant diversity (Andow, 1991; Altieri, 1999) providing continuous access to diversified food sources (pollen, nectar, alternative hosts and prey) and shelter, despite harvest, crop senescence, or even pesticide use in some fields (Josson et al., 2008; Gurr et al., 2017), as well as overwintering sites (Gurr et al., 2017; Haan et al., 2021) between seasons.

Increasing plant, i.e. crop or non-crop, species diversity (referred to as inter-specific diversity later in the paper) (Andow, 1991; Letourneau et al., 2011; Wratten et al., 2012; Nicholls and Altieri, 2013), plant genotypic and phenotypic diversity (referred to as intra-specific diversity later in the paper) and plant functional diversity across spatial and temporal scales has been found to benefit biological pest control services and limit yield losses by increasing the presence and the activity of natural enemies (top-down effects) and by reducing pest pressure (bottom-up effects). Plant diversification includes both crop and non-crop habitats and can be managed at the field (e.g. flower and grass strips, intercropping), farm (e.g. crop rotations) and landscape scales (e.g. hedgerows, forest) (Letourneau et al., 2011; Lin, 2011; Jeanneret et al., 2012). During the last thirty years of research a large number of studies focused on inter-specific diversity at the field scale or on non-crop habitat density at the farm and landscape scale and demonstrated beneficial effects of these diversification schemes on biological pest control services (Bianchi et al., 2006; Rusch et al., 2016; Karp et al., 2018). However, few studies investigated how crop diversification (within and between crop species) at the landscape scale could be a major management option to enhance biological pest control services in agricultural landscapes. Diversifying crop species in space and time can not only be positive for ecosystem services but might also be positive from economic and social aspects (Craheix et al., 2016).

In this paper, we envision that cropping patterns with intra-specific and inter-specific diversity at the landscape scale might be a key management options to promote biological pest control services and to ensure greater and more stable incomes for farmers while limiting negative externalities related to farming activities (Nicholson and Williams, 2021). We first address how crop diversification at the landscape-scale could be a major management option to limit pest pressure and define the ecological requirements to optimize biological control of pests in agricultural landscapes. Then, we propose ways to meet socio-economic needs of stakeholders, conditions for acceptance of such innovations and technical opportunities to overcome difficulties in applying such management options in real-life landscapes.

In the rest of the paper we will refer to an agricultural system, which is a system where crops are diversified, intra or inter-specifically, at a landscape scale. The landscapes are defined as areas shared between humans, flora and fauna, considered at different radial dimensions depending on the species observed – a 1.5 km radial unit is usually appropriate to achieve an effect from landscapes on arthropods (Gardiner and Neal, 2009) – and often contains different types of land uses, such as urban areas, natural areas and cropped areas (see Fig. 1 for more details on the landscape considered). The socio-economic network studied in this paper is composed of farmers, environmentalists, retailers, consumers and policy makers. These actors are all linked by diversified relationships and are connected to environmental, social and economic pillars through a range of individual purposes, objectives and hopes (see Fig. 2). For example, policy makers hope to sustain the State economy by creating new projects and at the same time, aim at sustaining social stability with diverse financial supports. Policy makers also have the global objective to protect the environment by creating laws forbidding or, conversely, encouraging some farming practices - for example, greening of the Common Agricultural Policy (CAP) proposed by the EU Member States (Matthews, 2013). Farmers, on the other hand, aim to maintain sustainable markets in order to preserve the economy of their enterprises and at the same time aim to work with environmentally friendly techniques in order to preserve their health and the health of consumers. Finally, an indirect farming objective, often not explicitly claimed, is to preserve the environment as the farming industry is in permanent interaction with it.

2. Exploiting crop diversity to design pest suppressive landscapes

2.1. Potential for reducing pest pressure through landscape crop diversification

Crop diversification across spatial and temporal scales can affect pest populations dynamics through two non-exclusive mechanisms: bottom-up (the resource concentration hypothesis) and top-down (the natural enemy hypothesis) effects. On one hand, bottom-up effects can be activated by diluting the plant resources used by pests. Diversifying plant species and/or genotypes has been demonstrated to be efficient in reducing pest pressure as individuals are less able to find their food sources across the agricultural fields (Letourneau et al., 2011; Koricheva and Hayes, 2018; Snyder et al., 2020; Wan et al., 2020; Li et al., 2020). In a recent review Koricheva and Hayes (2018) have highlighted that crop genotype diversity seems to have a stronger effect in reducing pest pressure than does wild plant genotype diversity. The authors explain this difference as an effect of associational resistance to pests being stronger (Root, 1973) against a specifically targeted pest in crop experiments than in wild plant experiments (Koricheva and Hayes, 2018). On the other hand, top-down effects can be activated by increasing the accessibility of diversified food resources and shelter to natural enemies in order to enhance their abundance and performances (Letourneau et al., 2011; He et al., 2019). To date, both inter-specific and intra-specific diversity has demonstrated positive effects on natural enemies and pest reduction but only crop inter-specific diversity effects on arthropods have been studied at the landscape scale, studies on the effect of crop intra-specific diversity being limited to single field studies (Koricheva and Hayes, 2018; Snyder et al., 2021). We therefore detail in the following section only the effects of crop inter-specific diversity at a landscape scale on natural enemies, pests and biocontrol (i.e. predation and parasitism).

A growing number of studies have addressed the question of landscape inter-specific crop diversity impact on natural enemies, pests and biocontrol (Bosem Baillod et al., 2017; Liu B. et al., 2016 and 2018; Redlich et al., 2018; Sirami et al., 2019; Aguilera et al., 2020; Kheirodin et al., 2020; Zhao et al., 2021). These studies related various effects of agricultural landscape crop diversity: (1) positive effects on parasitism (Liu B. et al., 2016), predation (Redlich et al., 2018), on the abundance of natural enemies (Liu B. et al., 2018; Zhao et al., 2021) and their diversity (Aguilera et al., 2020; Sirami et al., 2019; Zhao et al., 2021), (2) negative effects on the abundance of pests when crops were not host crops (Bosem Baillod et al., 2017; Kheirodin et al., 2020) (support of the resource concentration hypothesis) and (3) a higher ratio of natural enemies to pests (Zhao et al., 2021). Diversifying agricultural landscapes through crop manipulation can therefore have a positive impact on biodiversity of natural enemies, even higher than from semi-natural habitats (Sirami et al., 2019), and on biocontrol, when many different crop types are grown or when crop hosts are not usually cultivated in the same landscape unit of potential interaction. Even though the number of papers reporting the effect of landscape crop inter-specific diversification is modest, we can presume that using crop inter-specific diversity at a large scale might be positive for natural enemies and/or on biocontrol as suggested by Nicholson and Williams (2021) or Larsen and Noack (2021).

The positive effects of crop inter-specific diversity at a landscape scale can be the consequence of two main mechanisms: 1) complementary landscape hypothesis for natural enemies enhancement (top down control of pests) and 2) resource dilution hypothesis for pest reduction (bottom-up control of pests). Concerning the complementary landscape hypothesis, alternative crops can act as reservoirs for natural enemies that can spill over from one crop type to another when resources are increasing, notably pest resources (Liu B. et al., 2018). They can also act as shelter and food resources when the main crops are harvested or treated with pesticides (Liu B. et al., 2018; Aguilera et al., 2020). Parasitism rates can be increased through direct bottom-up forces: the increase of crop species can increase the presence of generalist pests and in consequence can increase the parasitism rates on this pest by parasitoids that can find their main host in multiple crops (Liu B. et al., 2016). Some authors underline the importance of combining both crop and semi-natural habitat diversity at a landscape scale for more biocontrol efficacy, defined as potential to reduce pest abundance (the complementary landscape hypothesis suggests a strong complementarity of semi-natural habitats and crops for resources and shelter) (Sirami et al., 2019; Aguilera et al., 2020). Sirami et al. (2019) found that the proportion of semi-natural area cover in a landscape had a positive effect on the level of increase of multi-trophic arthropod diversity as crop species diversity was increased in the landscape. They show that crop diversity is particularly important in maintaining arthropod diversity when the proportion of semi-natural cover in the landscape is very low. The authors suggest that complementarity of both crop and semi-natural areas comes from spatial and temporal resource continuity given by crop inter-specific diversity and shelter given by semi-natural areas (Sirami et al., 2019). More than crop diversity, choice of crop types to include can highly influence the diversity and abundance of natural enemies, as has been shown in oilseed rape for spiders and carabids (Aguilera et al., 2020) suggesting that only increasing inter-specific diversity might not be sufficient, but paying attention to the function of the specific crop types involved should also be part of the decision. Finally, diversifying crop types at a landscape scale increases natural enemy community diversity, which implies higher potential for pest control (Zhao et al., 2021). Concerning the resource dilution hypothesis, increasing crop inter-specific diversity has been demonstrated to reduce pest abundance, more specifically specialist pest abundance, reducing their capacity to find their principal host plant (Bosem Baillod et al., 2017; Kheirodin et al., 2020). It is important to mention that even though proofs of the potential high effect of crop intra-specific diversification, through genetic diversification of crops, at a landscape scale are absent from the literature. This lack of studies on the intra-specific diversity effects at the landscape scale seems to come from the complexity of the potential interactions and the crop species quality issue. There are a lot of potential types of diversity, but some have more diverse quality than others and so the effects are very variable. This species quality issue needs to be studied further as it shows substantial potential in pest reduction and natural enemies increase.

2.2. Levers to promote biocontrol

Diversifying crops at a landscape scale appears to have promising potential to reduce pest pressure by increasing natural enemies presence and diversity in arable fields. In order to maintain pest populations at a low level, it is important to maintain diversified guilds of natural enemies with complementary resources needs, i.e. different guilds of pests, in fields (Symondson et al., 2002). Natural enemies have different needs in terms of resources (i.e. pollen, nectar, or alternative preys and hosts) and habitats to realize their life-cycle (e.g., overwintering sites, shelter during the summer) (Gurr et al., 2017; Gardarin et al., 2018; Symondson et al., 2002). Natural enemies can be specialists (e.g. most parasitoids that specifically attack specific species of aphids) (Fischbein et al., 2016; Monticelli et al., 2019) or generalists (e.g. spiders, ladybirds or carabids that can feed on different types of pests)

(Rand and Tscharntke, 2007) and can have specific needs at different stages during their development (e.g. only proteins) or various needs (e.g. pollen and nectar during the adult stage and proteins during the larval stage, as is the case of most parasitoids and hoverflies) (Van Rijn et al., 2013; Fischbein et al., 2016). Positive relationships between species richness of natural enemies and pest suppression have been reported and emerge due to niche partitioning or sampling effects (Letourneau et al., 2009). Maintaining diverse communities of natural enemies is therefore an important lever to efficiently control different pest population types in space and time (Dainese et al., 2017).

Understanding the movement of natural enemies is another a key to design pest-suppressive landscapes. The movement of natural enemies can be driven by multiple factors: biotic factors – such as the presence of conspecifics (Tuda and Shima, 2002), herbivore-induced plant volatiles (Gillespie et al., 2016), plant phenological stages (Schellhorn et al., 2014), movement capacity of the guild (Osawa, 2000; Chapman et al., 2006; Jauker et al., 2009; Wang and Keller, 2003) - and abiotic factors – such as the climate (Schellhorn et al., 2014). However, movements of arthropods in a landscape are also conditioned by landscape structure, both in terms of composition and configuration (Karp et al., 2018; Martin et al., 2019; Haan et al., 2020). The amount of habitat sources for natural enemies, such as semi-natural habitats, is the main determinant of natural enemy presence and abundance (Sirami et al., 2019). It has been recently suggested that a minimum of 20% of semi-natural habitats within a few kilometers, such as forests or natural grasslands, is needed to maintain a significant pool of natural enemy species (Tscharntke et al., 2007; Garibaldi et al., 2021). In addition to the amount of habitats, the spatial configuration of habitats in the landscape affects movements of natural enemies. Natural enemies are usually more abundant in fine-grained agricultural landscapes, i.e. landscape with smaller patches of habitats, that enhance spillover of natural enemies and connectivity (Bailey et al., 2010; Martin et al., 2016; Haan et al., 2020). Reducing the amount of roads, hedgerows and tree lines that can act as shelter and increasing edges between crops and corridors are criteria to take into account to optimize biocontrol in agricultural landscape (Schellhorn et al., 2014). However, it should also be noted that for some natural enemies these landscape features may act as barriers to movement, rather than enhancing access. Evidently the relative importance of landscape composition and configuration for natural enemies depends on specific natural enemy traits, such as dispersal ability (Martin et al., 2019; Haan et al., 2020).

Landscape compositional and configurational traits, as well as arthropod needs and capacity to disperse, are important factors to consider in order to maximize our chances to reach a landscape rich in biocontrol potential (Haan et al., 2021). Spatial and temporal resource continuity is a key to increase natural enemy spillover from one pest host resource to another with no decrease in their population abundance (Vasseur et al., 2013; Schellhorn et al., 2015; Iuliano and Gratton 2020). Selecting crops to reach a successful diversification scheme should therefore consider: 1) the landscape crop composition, such as the complementarity of resources given by the crops available for a high number of natural enemies (pollen and nectar provision but also alternative preys and potential shelter) (Gardarin et al., 2018); 2) the landscape crop configuration (Haan et al., 2020), such as fields size, field shape, field connectivity making the resources continuous in time and space by selecting smaller crop areas that follow and overlap each other in time to maintain a continuous food source and shelter for natural enemies (Vasseur et al., 2013; Schellhorn et al., 2015; Sirami et al., 2020; Nicholson and Williams, 2021). We do not refer to any specific species associations, as conditions in each location can change regarding climate, soil, landscape composition, etc.

2.3. Choice of the scale to diversify crops

Diversifying crops in order to suppress pests and/or increase natural enemy efficacy can be done at three different scales: (1) at the field scale – generally through polyculture schemes (companion cropping, push-pull, intercropping, trap-crops, etc.) (Letourneau et al., 2011; Beillouin et al., 2019) or through rotation schemes (Rusch et al., 2013; Barzman et al., 2015; Beillouin et al., 2019) activating bottom-up forces through the resource dilution hypothesis, (2) at the farm scale – diversifying crops in multiple fields but in one farm only (Jeanneret et al., 2012), and (3) at the landscape scale – a scale that has been only recently studied as shown in Section 2.1 (see Fig. 3 for more details on the different scales described). Manipulating plant diversity at the field scale seems to be most efficient, but for issues of technical feasibility these systems are under-used in modern agriculture (Schaller, 2012; Meynard et al., 2013; Meynard et al., 2018; Morel et al., 2020). In order to avoid any conflicting effect of practices on the efficacy of natural enemies (Brittain et al., 2010) applying the proposed agricultural system based on crop diversity and reduced pesticide use at a large scale would be the most efficient scale (Landis, 2017; Brewer and Goodell, 2012; Goldman et al., 2007; Haan et al., 2021). Additionally, as argued by Landis (2017), even though a particular farm is efficient, in terms of biocontrol increase through crop diversification, other less efficient farms interspersed with the efficient farm might reduce the overall efficacy of the method used by that efficient farmer (Landis, 2017), for example in the case of pesticide drift. Taking decisions at larger scales than individual farms is therefore a key to success but will require efficient planning and coordination among different farms (Landis, 2017; Haan et al., 2021).

Arthropods, especially large ones (e.g. ladybirds, lacewings, hoverflies, but also spiders), can move over long distances (ranging up to several kilometers) in order to find their food and mate (Roh, 2013; Evans, 2003; Chifflet et al., 2011; Villenave-Chasset, 2006). Studying the effect of a cropping system on a small or partial landscape, such as a field or farm, would therefore omit a large part of the landscape covered by the natural enemies, and consequently the impact of the rest of the landscape on these animals. In landscape ecology, the landscape scale to study a broad spectrum of natural enemies is usually between 1 km (e.g. Rusch et al., 2016) and 2 km radius (e.g. Karp et al., 2018). The study of Gardiner and Neal (2009) has shown that the 1.5 km scale is best to explain the variation in biocontrol and abundance of ladybirds, a large long distance flying predator. Many levers of landscape manipulation for natural enemy preservation have been shown to be effective (Landis, 2017): 1) landscape heterogeneity needs to be preserved and both composition and configuration of the landscape, not only composition as developed in the previous section, need to be considered when managing a landscape (Holzschuh et al., 2010; Fahrig et al., 2011; Perović et al., 2015), 2) landscapes need to be connected and field sizes reduced in order to allow spillover between fields and entire exploitation of resources in the fields (Fahrig et al., 2015; Fischer et al., 2006; Haan et al., 2020), 3) food provision or natural enemies needs to be continuous in time and space (Schellhorn et al., 2015) and 4) disturbing events, such as ploughing, harvesting, vegetation clearance, cutting and pesticide treatments, need to be adapted to arthropod life cycles (Fischer et al., 2013).

If biocontrol is to be increased through crop diversification, large monoculture fields might need to be divided into multiple small fields of different crop types. Dividing large fields into long narrow fields of effective polyculture might facilitate natural enemy circulation between fields of different crops and at the same time decrease the possibility for pests to find their host plants (resource dilution hypothesis) and facilitate crop management by farmers. Indeed, this way of arranging fields has been applied for a long time in China and has been proved, when applied at a landscape scale, to be efficient in increasing the abundance and species richness of natural enemies in the cultivated fields (Zhao et al., 2021). These technical decisions on field shape will therefore need to match 1) ecological needs of natural enemies in terms of movement, wind direction, etc, in order to optimize biocontrol and 2) farm management needs for a simple system to manage.

3. Meeting stakeholder needs and sticking to market realism to apply crop diversification

3.1. Socio-economic aspects – how to get stakeholder acceptance for such systems?

Even though the willingness of farmers to switch from intensive agriculture to more environmentally friendly techniques is increasing, especially with government agri-environmental schemes offering incentives (Bernués et al., 2016; Wezel et al., 2018), the long-term application of pesticides has locked farmers into a situation where it is economically risky to switch to a zero-pesticide system; this situation is called the socio-technical lock-in (Wilson and Tisdell, 2001; Guichard et al., 2017; Meynard et al., 2018), where fear of losing economic gains and uncertainty of new techniques combine to dissuade farmers from switching to another system (Guichard et al., 2017). We propose here to meet the three main objectives needed to achieve a change in agricultural practices. One objective is to address the questions to ask in order to enter the new system. Another objective is to determine the spatial and temporal scale at which this system might be best applied. Finally, a last objective is to consider the importance of establishing this system as a win-win process to achieve rapid and sustainable adoption. We then pose three main challenges that could be encountered when trying to establish a large-scale crop diversification scheme to increase biocontrol and reduce pesticide uses.

3.1.1. Questions about farmers technical capacity, added value of the system and the right business model to adopt

After understanding clearly the problems articulated by farmers (economic, social and environmental issues), the first question to address is the way to efficiently train farmers the role of crop diversity (within their overall farming objectives) in order to boost natural enemy activity and increase economic efficiency. Modern farming is first of all an enterprise where profitability is a major objective (Bernués et al., 2016). Responding to farmer needs through training toward new environmentally friendly concepts is often associated with ideas which are not seen to have immediate direct and obvious economic return for the farmer (Kilpatrick and Rosenblatt, 1998). Above all, it is necessary that, when learning together as farmers and ecologists, farmers gain knowledge relevant to their personal situation, by demonstrating concepts associated with practical examples (Kilpatrick and Rosenblatt, 1998). Finally, training farmers must 1) overcome any lack of confidence farmers may have in trainers when training is compulsory and in the accuracy of new information given, 2) overcome any fear of learning new knowledge or skills as it might induce a change of practices and habits, problems that have been found to be the main reasons why training fails to reach or be adopted by farmers (Kilpatrick and Rosenblatt, 1998) and 3) show that working together as farmers and ecologists to develop a training curriculum is relevant to the needs of growers and opens up new practical and effective management options for them. Implementing a new agronomic system will therefore need to be done with a clear view of the added value for the farm owner. One additional advice would be for other farmers who have already tested the system to train further farmers to ensure the efficiency of the program proposed and to increase the relevance of training (Kip-Tot et al., 2011; Bouttes et al., 2019). Local actions led by community organizations and group training could be important, to involve farmers directly in the decisions and the organization of the landscape (Stallman and James, 2015). Landscape re-organization in accordance with farmer needs (social and economic) and with the ecological intensification of agriculture will likely need some public coordination and State finance (Fahrig et al., 2011). Implementing a self-learning/self-training program in which farmers convince themselves of good practices would also be useful to encourage farmer groups to experiment at a local scale with landscape coordination and keep records of impacts on natural enemies and pest challenge (affecting pesticide use).

A second question that must be raised is how the farmer can get any value from the system. The potential reduction of pesticide use in a system where natural enemies could limit pest outbreaks will reduce exposure of farmers to chemicals and will reduce the probability of pesticide related health problems (Jokanovic, 2018). Additionally, by diversifying crops, farmers might be less subjected to commodity price fluctuations (Olsson, 1988; Gilbert and Morgan, 2010; Haile et al., 2017). Crop price volatility can be due to different factors on which farmers have almost no control: rapid economic growth of some developing countries, decades of underinvestment in agriculture, poor harvests due to climate changes, currency depreciations, diversion of food crops into the production of biofuels and speculative influences (Gilbert and Morgan, 2010). Diversifying crops might reduce the pressure of these previously cited factors, which are principally acting on crops like rice and wheat (Gilbert and Morgan, 2010). Finally, constant exposure of crops to newly introduced pests due to climate change (Ziska et al., 2011; Barzman et al., 2015) and globalization (Hulme, 2003; Peña, 2013) makes a system based on diversified crops less vulnerable to yield losses (Lin, 2013; Degani et al., 2019). Agroecosystems with diversified traits and functions are more resilient to changing biotic and abiotic conditions (Lin, 2013) due to two main reasons: the system is more able to suppress pest outbreaks and pathogen transmission through the resource dilution hypotheses (Otway et al., 2005) and it can buffer the effect of climate variability on production (Lin, 2013).

Agricultural landscapes can be associated with specific markets. Agri-tourism can be an additional market to use by farmers in order to make a profit from eco-friendly agrosystems, in some situations: 1) the farm needs to be near a touristic area (Sharpley and Vass, 2006), 2) the project needs to be eligible for environmental public subsidies (Haan et al., 2021), 3) may require training on marketing techniques (Sharpley and Vass, 2006) and means of communication (websites, social networks, etc.). Another market could be local sale of newly introduced crops under an environmentally friendly label at higher prices since consumers are willing to pay higher prices for such products (Elkington, 1994; Cranfield and Magnusson, 2003). Labelling can be an option to help consumers learn about the effort made by farmers, and would allow farmers to sell products at higher prices if consumers are willing to pay more for healthier products, as shown by a survey led in the framework of the EUCLID H2020 program asking if consumers were willing to pay more for environmentally friendly – not organic – products (up to 20% more), especially for fruits and vegetables (Fornetti, 2019). However, a communication effort about these new brands will need to be done by retailers as consumers are more confident about well-established organic and fair trade labels rather than new labels (Sirieix et al., 2013). The newly introduced crops might also be sold in local markets at higher prices if the farm is located in a peri-urban place, as many consumers today prefer to choose local IPM over non-local organic (Adams and Salois, 2010; Fornetti, 2019). In case none of the markets proposed above are applicable, public subsidies might help farmers to apply environmentally friendly techniques, as for example the current CAP greening, or the Whole Farm Revenue Protection introduced in 2014 in the US allowing farmers to diversify their production in order for them to increase their resilience (Haan et al., 2021). Several systems of payment exist for subsidies based on different units: the simple input area per hectare, the output volume per ton, the output value per currency unit, the action and action avoided payment per unit of approved or proscribed input respectively, and the outcome payment (Table 1). Regarding the different systems of payments, the action payment system would be best adapted in the agro-ecosystem considered in this study. Contrary to output payments, the objective of the system based on multiple crop farming is not to produce more but to produce better. Finally, action payments, as opposed to action avoidance payments, are morally more rewarding.

The last question to ask is how to build a business model for entry and maintenance of the system in a specific chosen market. The products delivered in a farming system where crops are diversified and produced under reduced use of pesticides are healthier and better quality, and can be sold as such. Before introducing new crops, farmers need to assess potential markets for the newly introduced crops. Retailers promoting environmentally friendly products might be the best stakeholders to target for product sales. The "Zero pesticides" tomato from the French Saveol enterprise is a good example showing that large retailers, because of an increasing demand from consumers and thanks to an adapted branding from the firms, are buying and selling more and more environmentally friendly products and therefore are good target markets (Raynaud et al., 2009).

3.1.2. Implementing decisions at a large scale

As mentioned in Section 2.3, in order to avoid any conflicting effect of practices on the efficacy of natural enemies (Brittain et al., 2010) applying an agro-ecosystem based on crop diversity and reduced pesticide use at a large scale would be most efficient (Landis, 2017; Brewer and Goodell, 2012; Goldman et al., 2007) from an ecological point of view. If we focus now on the political/social point of view, such global decisions could be difficult to organize and might take a long time before being efficiently applied at a national scale. Diversifying crops could be done first at a regional or local scale (Cumming and Spiesman, 2006; Valbuena et al., 2010). One example of agri-environmental legislation that has been implemented at a regional scale is the French Regional Action Program (RAP) initiated in

Haut-de-France in 2018 for protection of water bodies. RAP is experimenting with innovative farm techniques involving nitrogen fertilizer management in order to reduce pollution by nitrates of agricultural origin in the region. Targeting smaller levels of action, such as the farm level, is also possible but might be less efficient in case farm parcels are highly interspersed with other parcels and the farming practices of other farmers are deleterious to natural enemies (Landis, 2017; Slotterback et al., 2016). At a higher level, it is possible that a group of farmers or farm unions could take the decision to increase their crop diversity and decrease pesticide use to promote natural enemies, with possible optimal biocontrol if parcels are adjacent. The design of new agricultural landscapes needs to be done through collaborative networks of different specialists (Landis, 2017; Haan et al., 2021). As stated by Landis (2017) and Haan et al. (2021), the use of different knowledge in order to answer farmer needs could be done through the mobilization of environmentalists (to understand the species needs and biodiversity conservation techniques), geographers (organization of the landscape), economists (establishment of a working business plan for farmers), sociologists (understanding the social objectives and opportunities), agronomists and farmers themselves (technical input, establishment of a working technical program in the region, transfer of the techniques to other farmers). Advice during cropping periods about timing of pesticide applications and natural enemy dynamics will also be needed for maximum efficiency, such as maintenance of pest pressure under the economic threshold, and preservation of natural enemies. Indeed, a clear understanding of natural enemy dynamics and pest outbreaks will be needed to apply pesticides only when natural enemies are in low numbers, and applications may be limited to the center of fields where the natural enemy density might be lowest (Bortolotto et al., 2016). Creation of decision tools adapted to landscape scale management could be used in order to coordinate the choice of crops by different farmers regarding the population dynamics of the different insects. Such a tool has already been developed by

Slotterback et al. (2016) where farmers' decisions in a region were transferred into a tool called Geodesign. An iterative process helped to assess the resulting changes happening at the landscape scale and helped in the emergence of multifunctional solutions (Slotterback et al., 2016). Networks gathering different agricultural stakeholders have also been developed all across Europe in order to help design efficient agroecological farming systems (e.g. Agroecology Europe Forum which has gathered more than 300 participants, notably farmers, technicians, researchers, students, policy and decision-makers, representatives of national and European institutions, non-governmental organizations, social movements, and civil society (Wezel et al., 2018)).

3.1.3. The importance of establishing the system in a win-win process

In the context of market greening, often initiated by legislative requirements, companies have become more competitive and innovative, benefiting in a win-win process from consumer demand for greener products (Elkington, 1994; Peattie, 2001). This win-win process is frequent in organic agricultural markets, as has been shown, for example, in a Globe Newswire interview where organic farmers in the United States were benefiting from premium prices given under an organic brand trusted by consumers (Global Newswire, 2019). Another example of a win-win process, established within a crop diversification scheme in organic crop rotations, is the brand Annie's from General Mills that is buying crops newly introduced in a rotation with previously established crops and that were previously not grown (Crawford, 2019). In an agro-ecosystem based on crop diversification and low pesticide inputs, we identified five main stakeholders potentially positively impacted by the system.

1. First of all, <u>farmers:</u> Reducing pesticide use that is bad for their health (Jokanovic, 2018) would be a high benefit for them. Increasing crop diversity could also raise new markets and push agri-food companies to buy new crops at high prices, at least during

the transition phase, in order to meet consumer demand for healthier food (Crawford, 2019). The satisfaction induced by adoption of environmentally friendly methods would also improve farmer well-being (Fischer, 1980) by increasing the level of working conditions (Shreck et al., 2006). Direct help from the State in order to switch to more environmentally friendly system could help to ensure stable incomes.

2. Then, environmentalists: Arthropod biodiversity preservation, among other animal diversity preservation like birds and mammals, as well as the moderated environmental impacts that might result from adoption of diversified crop systems and reduced pesticide use (Letourneau et al., 2011) are clear positive arguments for environmentalists.
3. Consumers: Demand for healthier and environmentally friendly products would also be a "winner" in the proposed system in two ways: 1) reduction of pesticides would generate better quality products with reduced residues (Smith-Spangler et al., 2012), and 2) reduced use of pesticides would reduce potential health problems related to drift (Provost et al., 2007).
4. Retailers: With an increase in consumer demand for healthy products, and increasing conversion of farmers to IPM or organic farming, retailers can be included as key actors in promotion and distribution of healthy products, under marketing processes that help to increase sale prices and therefore benefits (Crawford, 2019).
5. Policy makers: If the increase of crop diversity at a landscape scale can help reduce the use of pesticides, as the main objective of policy makers is to maintain public health at a high level and preserve biodiversity, this solution might also be a winning solution for them.

At this stage it is important to note that reducing the dependency of farmers on pesticides might not be a wining solution for agrochemical companies (Clapp et al., 2021). However, today these companies are incorporating IPM concepts through the adoption of new technologies like RNA-based biocontrol products (Taning et al., 2020), precision agriculture (Birner et al., 2021) or even biocontrol (see "Biologicals by Bayer" as an example) and might, by necessity, switch completely to IPM solutions in order to satisfy consumer and policy demands (but see Deguine et al., 2021). It is important to remember that consumption is the basis of a market, and if the demand for conventional food is reducing, the companies will have to adapt to what consumers want. More details about the influence of agrochemical firms in decision making are given in the following sub-section.

3.1.4. Potential difficulties that could be encountered for building-up a landscape system based on crop diversity and conservation biological control

We mentioned in the previous section that if crops are diversified inter-specifically, then farmers will need to find new markets in order to sell their newly introduced crop species in their cropping system. Creating new markets might not always be easy if the demand is not present. However, one way to overcome that difficulty would be to diversify the cropping systems intra-specifically, by diversifying the genetics of a cultivated species. Choosing this option will avoid the difficulty of finding new markets in case there is no demand for the proposed new crops (Koricheva and Hayes, 2018).

A second possible blocking point might be the feasibility of implementing the proposed landscape design at a large scale. Communication between farmers to preserve natural enemy communities in fields is necessary as agricultural landscapes are composed of different farms (Cumming and Spiesman, 2006; Goldman et al., 2007; Stallman and James, 2015). Coordination of practices applied by different farmers of a region (Stallman and James, 2015) might help to optimize choice of crops to implement, pesticide use and resulting biocontrol services. Cooperation between farmers on practices to increase biocontrol is possible but might not always work, as farmers with more inclusion in community organizations or farmers that are concerned about pesticides in the environment seem more willing to cooperate than those who don't (Stallman and James, 2015). Local scale (neighboring farms) cooperation might also be more efficient than a larger county-wide scale (Stallman and James, 2015). All in all, cooperation between farmers, that could be enhanced by regional managers, might be possible only at small scales where farmers agree on principles of pesticide reduction and timing of applications that allow natural enemies to establish in the landscape. A last point where farmers may need to collaborate in a diversified crop landscape is on purchase of agricultural equipment. The management of different crop types requires different type of equipment: combines for cereals, mowers for fodder, harvesters and leaf strippers for beets, but also various types of seed drills at the beginning of the cropping season, as well as specific cultivation, etc. Increasing the number of crops on a farm will require more machine types and might be very expensive if farmers must purchase these machines alone. To share purchase of equipment, as is already done in France with the CUMAs (Cooperatives for the Use of Agricultural Machineries), might be a good option.

A third blocking point might be that the proposed landscape design might not be easy to implement in all types of farms. Even though we mainly specified that landscape crop diversity needs to be managed at a landscape scale, it is possible that some farms might have more or less difficulties to implement such management practices. The size of the farm might be one excluding criteria. The size of a farm can be defined in relation to its area cultivated or its capital (standard gross margins) (Potter and Lobley, 1993; Nagayets, 2005). Based on the economic status of each type of farm, diversifying crop systems may be more easily adopted by small farms (35 ha large and less) (Burton et al., 1999; Rigby et al., 2001) at the season scale through rotations. As small scale farmers have generally little capital investment, they may have more flexibility through contracted equipment suppliers and therefore may be more able to switch easily from one crop type to another from season to season. However, implementation of diversifying crop practices and lower pesticide inputs to increase biocontrol might have more impact in areas where large scale monocultures are usually farmed. Large scale farms (above 100 ha, see Burton et al., 1999) could more easily diversify their crops in space and time as they usually have more capital (Haspel, 2014) and have more area to work on. The larger the farm, the greater the investments can be and the production cost per unit goes down (Haspel, 2014). We raise the hypothesis that risks taken in diversification of crops might be less feared than in middle scale farms. Additionally, large scale farms with high capital could test crop diversification and pesticide reduction on a small part of the farm to begin with, to take less risks. This system is already used by big vine producers in France, where small parts of the vineyards are converted to biodynamic vine production, this product being more and more appreciated by consumers who are willing to pay more for it. Finally, the system might be more difficult to apply to mid-size farms as they might be committed to specialized capital equipment which would make temporal crop diversification more difficult and are too small to manage diversification in space.

A final blocking point might be the lack of interest, or maybe even the opposition, of large agrochemical companies to the proposed system. Agrochemical companies have a high influence on the agricultural sector. Today, only a few firms own a large part of the agricultural chemical market (Clapp, 2021). These firms exert an important power, more or less directly, on the way food is produced (Clapp, 2021). As they profit directly from the commercialization of chemicals, going toward a system without these chemicals as proposed in this paper could be of huge commercial challenge, but one that is consistent with competitive use of new biotechnologies with more environmentally friendly properties. As stated by Clapp (2021), these companies shape the food markets, technologies and innovation perspectives as well as policy and governance decisions. More and more, these companies are opening market branches in biological control, which actually goes in the direction of reducing the use of chemicals. However, what we propose in this paper is a way to attract and maintain natural enemies already present in the landscape (conservation biological control), with consequently no need for external inputs. It would therefore be quite optimistic to think that implementing such large-scale conservation biological programs might be enhanced by these agrochemical companies if they implement innovative environmentally compatible technologies in their market strategies.

3.2. Actions to be taken by the stakeholders to reach the next step

Diversifying crop species, and potentially crop genetics, at the landscape scale seems to have high potential for the preservation of natural enemies and for the increase in their efficacy. Economically, the switch from a conventional system to a more diversified one will require specific attention to the markets targeted by farmers and to the possibility of providing technical support to farmers. In order to improve the success of such agricultural systems, it is important to take into consideration the point of view and the advice of different specialists.

The implementation of a system based on landscape crop diversity could be feasible if the different agricultural stakeholders are involved (Landis et al., 2017; Haan et al., 2021). Fig. 4 is a schematic representation of the agricultural network studied in relation to the economic, social and environmental pillars, including new actions to be taken by the stakeholders of the agricultural chain in the framework of landscape crop diversification. As mentioned earlier, new stakeholders - highlighted in dark green in Fig. 4 – need to enter in the decision making in order to optimize the proposed way to implement crop diversity schemes at a landscape scale. Economists, sociologists, geographers and advisers need to be included in a collaborative framework (Landis et al., 2017; Haan et al., 2021) as well as of course farmers and environmentalists already mentioned in Fig. 2. Specialised advisers could take the role of transferring the specific knowledge to farmers and these farmers should provide feedback on the proposed practices and outcomes. By implementing this new landscape design, new relations between the different agricultural stakeholders could raise. First, in order to avoid any economic losses possibly due to the changes of practices, the State could propose to the farmers a system of insurance encouraging them to take risks. Secondly, environmentalists could propose new agricultural landscape designs in collaboration with geographers, economists, sociologists and farmers in order to stick to realistic solutions. Thirdly, food retailers would inform consumers about the changes of practices in order to encourage them to change their consumption habits and help the farmers to switch from a pesticide dependent practice to a more environmentally friendly one. Within the retail network, cooperatives could be engaged in buying new crops under special market contracts in order to promote the selling of newly introduced plants in the region (Haan et al., 2021).

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Figure legends

Figure 1. Schematic representation of two contrasted sites with low crop richness (A) and high crop richness (B). Water is represented by blue, natural habitats by dark green and human-mediated uses by dark grey. All the other land uses are different types of crops.

Figure 2. Schematic representation of the agricultural network studied in relation to the economic, social and environmental pillars. In grey are represented the stakeholders targeted, in capital letters and bold arrows are the different relations between stakeholders. The thin arrows represent purposes (normal arrows), objectives (dotted arrow) and hopes (dashed arrow) of each stakeholder toward each pillar.

Figure 3. Representation of the different scales where crop diversity and biocontrol can be managed. The regional scale is a scale defined politically where decisions can be taken broadly. The landscape scale is a scale defined by landscape ecologists (at least in our case study) where arthropods movements and behavior can be observed and linked to an agricultural practice. The farm scale is a scale defined economically by farmers where management decisions can easily be taken by individuals. The field scale is a scale defined economically by farmers where tests can be done without implying too much economical risks.

Figure 4. Schematic representation of the agricultural network studied in relation to the economic, social and environmental pillars, including new actions to be taken by the stakeholders of the agricultural chain in the framework of landscape crop diversification. New stakeholders are highlighted in dark green and new actions are indicated with a dark grey arrow. The collaborative network for landscape design is indicated by dark green lines.

Figures

Figure 1.

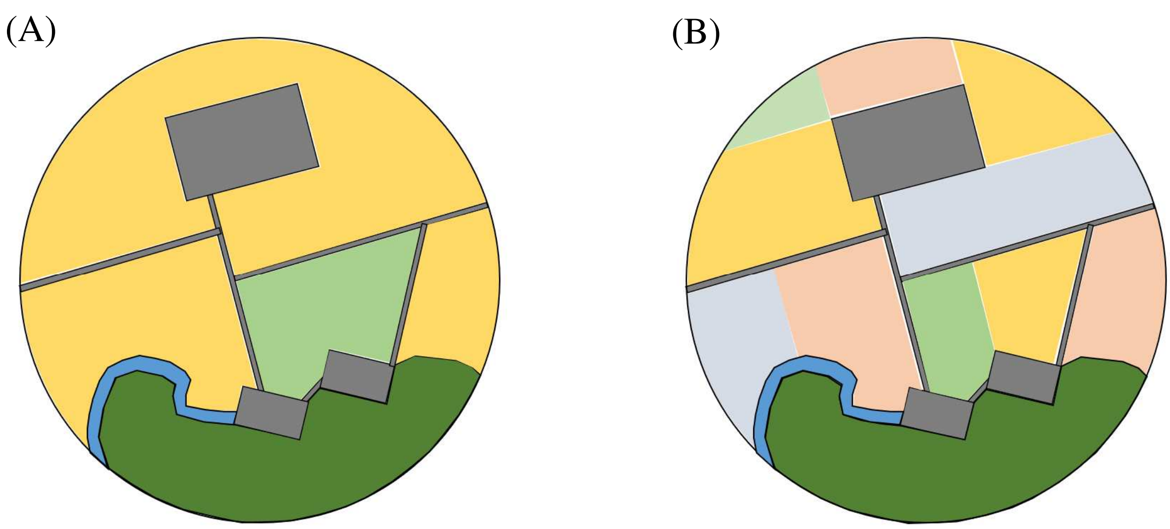


Figure 2.

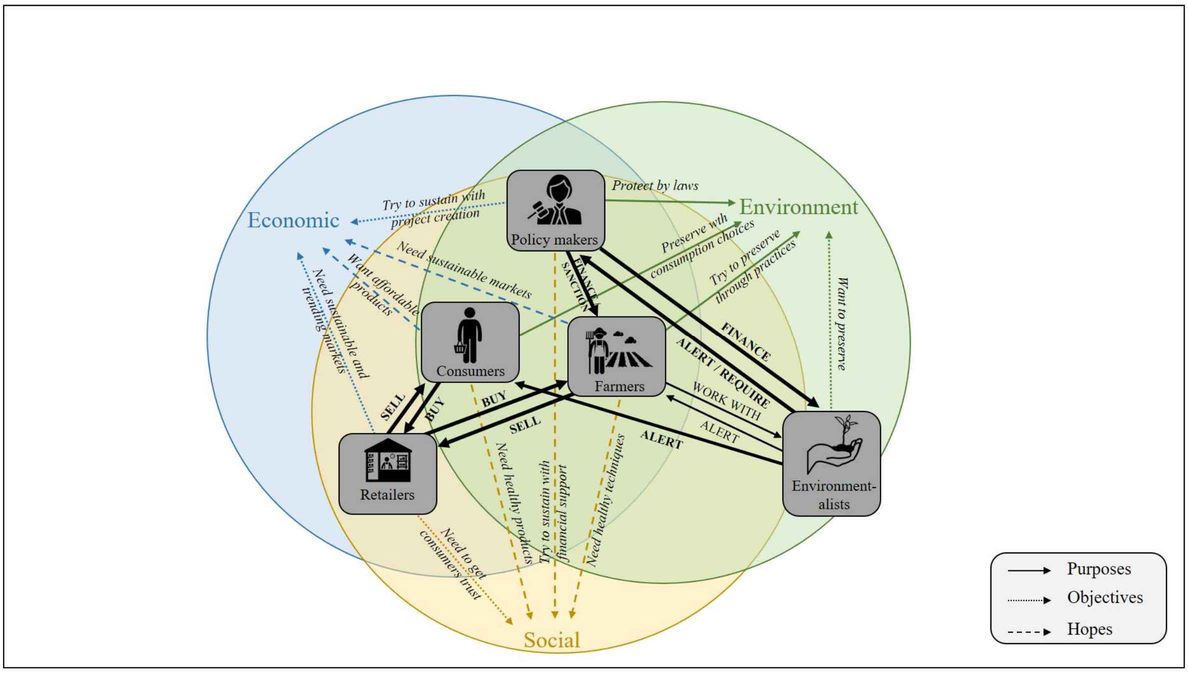


Figure 3.

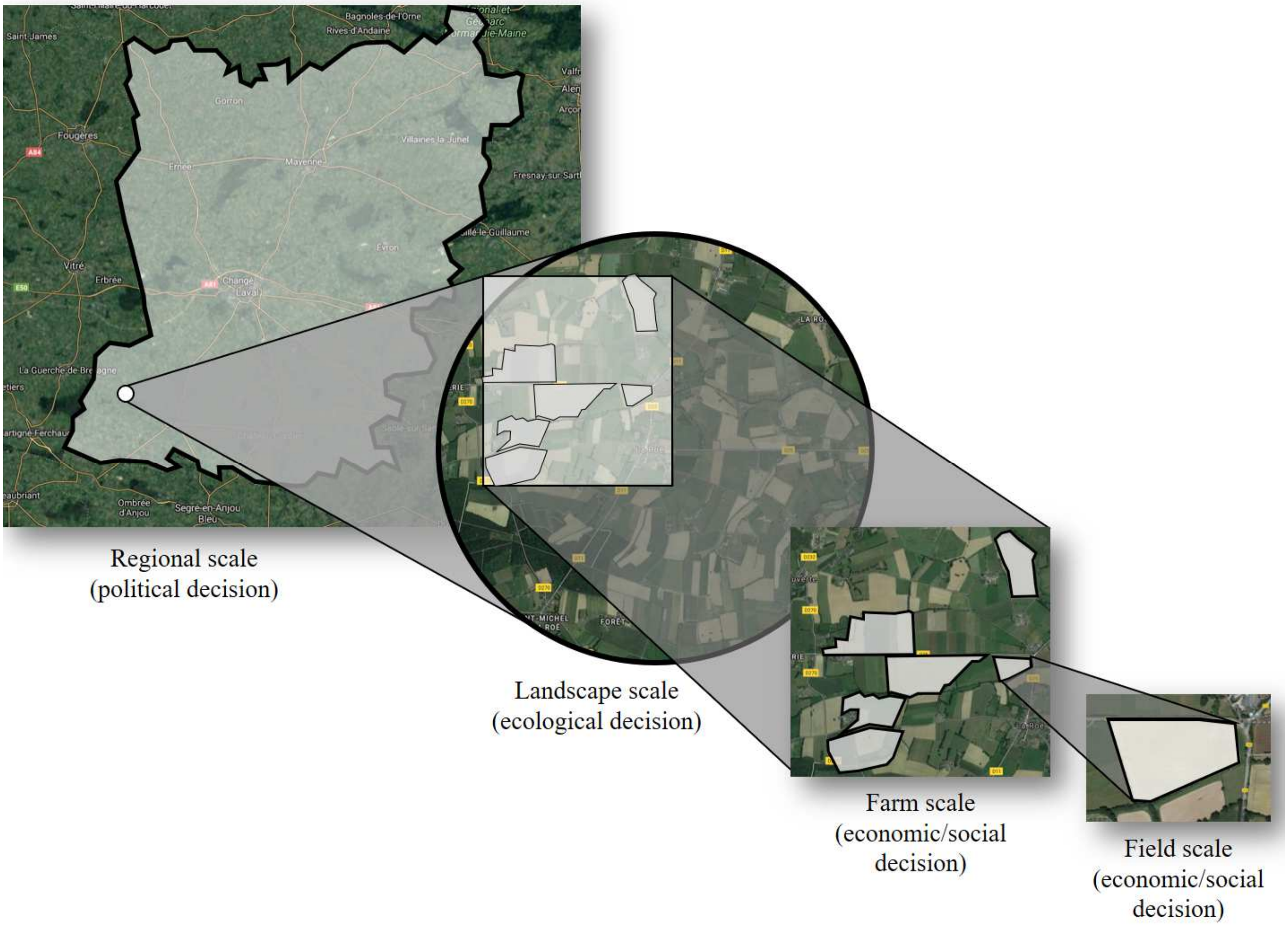
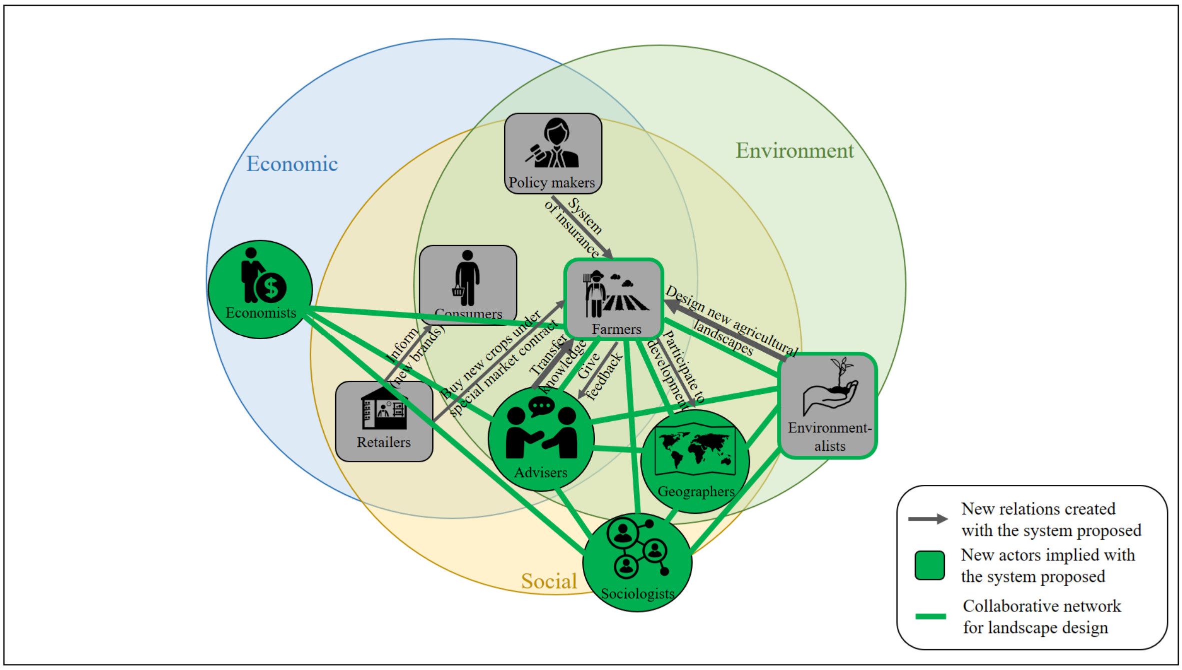

Regional scale
(political decision)
Landscape scale
(ecological decision)
Farm scale
(economic/social
decision)
Field scale
(economic/social
decision)

Figure 4.


Economic
Environment
Social
Policy makers
System of insurance
Economists
Consumers
Farmers
Design new agricultural landscapes
Participate to development
Give feedback
Transfer knowledge
Buy new crops under special market contract
Inform (new brands)
Retailers
Advisers
Geographers
Environment-alists
Sociologists
New relations created with the system proposed
New actors implied with the system proposed
Collaborative network for landscape design

Tables

Table 1. Table relating the different systems of payments proposed by the European states for agricultural subsidies. The payment name, the associated units and definition and the references are reported in the table.

Payment name	Unit	Principle	Reference
Simple input area	per hectare	farmers are offered an amount of money per hectare	Baylis et al., 2008
Output volume	per ton	subsidies support production by giving money per quantity of agricultural commodity produced	Van Zanten et al., 2013
Output value	per euro	subsidies support production by giving money per quantity of benefit produced	
Action payment	per unit of approved input	farmers can be paid to stay on their farm in order to preserve the farmland or can receive a compensation for not attaining quotas	Baylis et al., 2008
Action avoided payment	per unit of proscribed input stopped	for example when a farmer is paid for reducing chemical input or animal units per land area	Baylis et al., 2008
Outcome payments	related to water quality, residue limits, landscape assessment, etc.	payments can be received when farmers measures are taken by the farmer to protect the environment	Baylis et al., 2008; Van Zanten et al., 2013

Graphical abstract.