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Using crop diversity to lower pesticide use: socio-ecological approaches

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1 **Using crop diversity to lower pesticide use: socio-ecological approaches**

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10

11 **Abstract**

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

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

30

31 1. Introduction

32 Intensive agriculture has negative effects on the environment and on human health
33 (Tscharntke et al., 2005; Jokanovic, 2018; Forkuoh et al., 2018; Wahlang, 2018). These
34 negative effects are caused by habitat destruction, low crop diversity, intensive soil tillage and
35 intensive use of agrochemicals, including pesticides and fertilizers (FAO, 2019). Pesticides
36 have been used in agriculture for over a century to increase food production and they have
37 proven their efficiency in increasing food accessibility worldwide (Pingali, 2012; Nelson and
38 Burchfield, 2021). Now agriculture is facing the negative consequences of the intensive use of
39 pesticides, notably through the increase of health issues affecting farmers (Jokanovic, 2018)
40 and consumers (Forkuoh et al., 2018; Wahlang, 2018), and also through the destruction of
41 biodiversity in fields and surrounding land (Liu T. et al., 2018), on soil biota (Lew et al.,
42 2009; Velki et al., 2019), water (Leach and Mumford, 2008; Ibrahim et al., 2019), and on
43 arthropod biodiversity including natural enemies (Desneux et al. 2007; Van der Valk et al.,
44 2011; Lundgren et al., 2013; Woodcock et al., 2017; Wagner 2020). These natural enemies
45 can be microscopic (fungi, bacteria, virus and nematodes) (Lacey et al., 2001) and
46 macroscopic (predators and parasitoids) (Stiling and Cornelissen, 2005). In addition to
47 negative effects due to pesticides, the use of large scale monocultures makes it difficult for
48 natural enemies to find food and shelter after the crop is harvested, resulting in the loss of
49 their populations and a reduction in biological control impact (Schellhorn et al., 2014).
50 Biological control consists of “*the use of living organisms - i.e. natural enemies - to suppress*
51 *the population density or impact of a specific pest organism, making it less abundant or less*
52 *damaging than it would otherwise be*” (Eilenberg et al., 2001). Changing pest management
53 practices by increasing the biological control potential, including the reduction of pesticide
54 use, is an objective for the future as agriculture faces three challenges: to sustain healthy food
55 production for the growing world population, to reduce the negative impacts of agrochemicals

56 on the environment and on human health, and ensure reasonable profit or return for the
57 producer.

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

68 Increasing plant, i.e. crop or non-crop, species diversity (referred to as inter-specific diversity
69 later in the paper) (Andow, 1991; Letourneau et al., 2011; Wratten et al., 2012; Nicholls and
70 Altieri, 2013), plant genotypic and phenotypic diversity (referred to as intra-specific diversity
71 later in the paper) and plant functional diversity across spatial and temporal scales has been
72 found to benefit biological pest control services and limit yield losses by increasing the
73 presence and the activity of natural enemies (top-down effects) and by reducing pest pressure
74 (bottom-up effects). Plant diversification includes both crop and non-crop habitats and can be
75 managed at the field (e.g. flower and grass strips, intercropping), farm (e.g. crop rotations)
76 and landscape scales (e.g. hedgerows, forest) (Letourneau et al., 2011; Lin, 2011; Jeanneret et
77 al., 2012). During the last thirty years of research a large number of studies focused on inter-
78 specific diversity at the field scale or on non-crop habitat density at the farm and landscape
79 scale and demonstrated beneficial effects of these diversification schemes on biological pest
80 control services (Bianchi et al., 2006; Rusch et al., 2016; Karp et al., 2018). However, few

81 studies investigated how crop diversification (within and between crop species) at the
82 landscape scale could be a major management option to enhance biological pest control
83 services in agricultural landscapes. Diversifying crop species in space and time can not only
84 be positive for ecosystem services but might also be positive from economic and social
85 aspects (Craheix et al., 2016).

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

95 In the rest of the paper we will refer to an agricultural system, which is a system where crops
96 are diversified, intra or inter-specifically, at a landscape scale. The landscapes are defined as
97 areas shared between humans, flora and fauna, considered at different radial dimensions
98 depending on the species observed – a 1.5 km radial unit is usually appropriate to achieve an
99 effect from landscapes on arthropods (Gardiner and Neal, 2009) – and often contains different
100 types of land uses, such as urban areas, natural areas and cropped areas (see Fig. 1 for more
101 details on the landscape considered). The socio-economic network studied in this paper is
102 composed of farmers, environmentalists, retailers, consumers and policy makers. These actors
103 are all linked by diversified relationships and are connected to environmental, social and
104 economic pillars through a range of individual purposes, objectives and hopes (see Fig. 2).
105 For example, policy makers hope to sustain the State economy by creating new projects and at

106 the same time, aim at sustaining social stability with diverse financial supports. Policy makers
107 also have the global objective to protect the environment by creating laws forbidding or,
108 conversely, encouraging some farming practices - for example, greening of the Common
109 Agricultural Policy (CAP) proposed by the EU Member States (Matthews, 2013). Farmers, on
110 the other hand, aim to maintain sustainable markets in order to preserve the economy of their
111 enterprises and at the same time aim to work with environmentally friendly techniques in
112 order to preserve their health and the health of consumers. Finally, an indirect farming
113 objective, often not explicitly claimed, is to preserve the environment as the farming industry
114 is in permanent interaction with it.

115 2. Exploiting crop diversity to design pest suppressive landscapes

116 2.1. Potential for reducing pest pressure through landscape crop diversification

117 Crop diversification across spatial and temporal scales can affect pest populations dynamics
118 through two non-exclusive mechanisms: bottom-up (the resource concentration hypothesis)
119 and top-down (the natural enemy hypothesis) effects. On one hand, bottom-up effects can be
120 activated by diluting the plant resources used by pests. Diversifying plant species and/or
121 genotypes has been demonstrated to be efficient in reducing pest pressure as individuals are
122 less able to find their food sources across the agricultural fields (Letourneau et al., 2011;
123 Koricheva and Hayes, 2018; Snyder et al., 2020; Wan et al., 2020; Li et al., 2020). In a recent
124 review Koricheva and Hayes (2018) have highlighted that crop genotype diversity seems to
125 have a stronger effect in reducing pest pressure than does wild plant genotype diversity. The
126 authors explain this difference as an effect of associational resistance to pests being stronger
127 (Root, 1973) against a specifically targeted pest in crop experiments than in wild plant
128 experiments (Koricheva and Hayes, 2018). On the other hand, top-down effects can be
129 activated by increasing the accessibility of diversified food resources and shelter to natural
130 enemies in order to enhance their abundance and performances (Letourneau et al., 2011; He et

131 al., 2019). To date, both inter-specific and intra-specific diversity has demonstrated positive
132 effects on natural enemies and pest reduction but only crop inter-specific diversity effects on
133 arthropods have been studied at the landscape scale, studies on the effect of crop intra-specific
134 diversity being limited to single field studies (Koricheva and Hayes, 2018; Snyder et al.,
135 2021). We therefore detail in the following section only the effects of crop inter-specific
136 diversity at a landscape scale on natural enemies, pests and biocontrol (i.e. predation and
137 parasitism).

138 A growing number of studies have addressed the question of landscape inter-specific crop
139 diversity impact on natural enemies, pests and biocontrol (Bosem Baillod et al., 2017; Liu B.
140 et al., 2016 and 2018; Redlich et al., 2018; Sirami et al., 2019; Aguilera et al., 2020;
141 Kheirodin et al., 2020; Zhao et al., 2021). These studies related various effects of agricultural
142 landscape crop diversity: (1) positive effects on parasitism (Liu B. et al., 2016), predation
143 (Redlich et al., 2018), on the abundance of natural enemies (Liu B. et al., 2018; Zhao et al.,
144 2021) and their diversity (Aguilera et al., 2020; Sirami et al., 2019; Zhao et al., 2021), (2)
145 negative effects on the abundance of pests when crops were not host crops (Bosem Baillod et
146 al., 2017; Kheirodin et al., 2020) (support of the resource concentration hypothesis) and (3) a
147 higher ratio of natural enemies to pests (Zhao et al., 2021). Diversifying agricultural
148 landscapes through crop manipulation can therefore have a positive impact on biodiversity of
149 natural enemies, even higher than from semi-natural habitats (Sirami et al., 2019), and on
150 biocontrol, when many different crop types are grown or when crop hosts are not usually
151 cultivated in the same landscape unit of potential interaction. Even though the number of
152 papers reporting the effect of landscape crop inter-specific diversification is modest, we can
153 presume that using crop inter-specific diversity at a large scale might be positive for natural
154 enemies and/or on biocontrol as suggested by Nicholson and Williams (2021) or Larsen and
155 Noack (2021).

156 The positive effects of crop inter-specific diversity at a landscape scale can be the
157 consequence of two main mechanisms: 1) complementary landscape hypothesis for natural
158 enemies enhancement (top down control of pests) and 2) resource dilution hypothesis for pest
159 reduction (bottom-up control of pests). Concerning the complementary landscape hypothesis,
160 alternative crops can act as reservoirs for natural enemies that can spill over from one crop
161 type to another when resources are increasing, notably pest resources (Liu B. et al., 2018).
162 They can also act as shelter and food resources when the main crops are harvested or treated
163 with pesticides (Liu B. et al., 2018; Aguilera et al., 2020). Parasitism rates can be increased
164 through direct bottom-up forces: the increase of crop species can increase the presence of
165 generalist pests and in consequence can increase the parasitism rates on this pest by
166 parasitoids that can find their main host in multiple crops (Liu B. et al., 2016). Some authors
167 underline the importance of combining both crop and semi-natural habitat diversity at a
168 landscape scale for more biocontrol efficacy, defined as potential to reduce pest abundance
169 (the complementary landscape hypothesis suggests a strong complementarity of semi-natural
170 habitats and crops for resources and shelter) (Sirami et al., 2019; Aguilera et al., 2020).
171 Sirami et al. (2019) found that the proportion of semi-natural area cover in a landscape had a
172 positive effect on the level of increase of multi-trophic arthropod diversity as crop species
173 diversity was increased in the landscape. They show that crop diversity is particularly
174 important in maintaining arthropod diversity when the proportion of semi-natural cover in the
175 landscape is very low. The authors suggest that complementarity of both crop and semi-
176 natural areas comes from spatial and temporal resource continuity given by crop inter-specific
177 diversity and shelter given by semi-natural areas (Sirami et al., 2019). More than crop
178 diversity, choice of crop types to include can highly influence the diversity and abundance of
179 natural enemies, as has been shown in oilseed rape for spiders and carabids (Aguilera et al.,
180 2020) suggesting that only increasing inter-specific diversity might not be sufficient, but

181 paying attention to the function of the specific crop types involved should also be part of the
182 decision. Finally, diversifying crop types at a landscape scale increases natural enemy
183 community diversity, which implies higher potential for pest control (Zhao et al., 2021).
184 Concerning the resource dilution hypothesis, increasing crop inter-specific diversity has been
185 demonstrated to reduce pest abundance, more specifically specialist pest abundance, reducing
186 their capacity to find their principal host plant (Bosem Baillod et al., 2017; Kheirodin et al.,
187 2020). It is important to mention that even though proofs of the potential high effect of crop
188 intra-specific diversification, through genetic diversification of crops, at a landscape scale are
189 absent from the literature. This lack of studies on the intra-specific diversity effects at the
190 landscape scale seems to come from the complexity of the potential interactions and the crop
191 species quality issue. There are a lot of potential types of diversity, but some have more
192 diverse quality than others and so the effects are very variable. This species quality issue
193 needs to be studied further as it shows substantial potential in pest reduction and natural
194 enemies increase.

195 2.2. Levers to promote biocontrol

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

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

214 Understanding the movement of natural enemies is another a key to design pest-suppressive
215 landscapes. The movement of natural enemies can be driven by multiple factors: biotic factors
216 – such as the presence of conspecifics (Tuda and Shima, 2002), herbivore-induced plant
217 volatiles (Gillespie et al., 2016), plant phenological stages (Schellhorn et al., 2014),
218 movement capacity of the guild (Osawa, 2000; Chapman et al., 2006; Jauker et al., 2009;
219 Wang and Keller, 2003) - and abiotic factors – such as the climate (Schellhorn et al., 2014).
220 However, movements of arthropods in a landscape are also conditioned by landscape
221 structure, both in terms of composition and configuration (Karp et al., 2018; Martin et al.,
222 2019; Haan et al., 2020). The amount of habitat sources for natural enemies, such as semi-
223 natural habitats, is the main determinant of natural enemy presence and abundance (Sirami et
224 al., 2019). It has been recently suggested that a minimum of 20% of semi-natural habitats
225 within a few kilometers, such as forests or natural grasslands, is needed to maintain a
226 significant pool of natural enemy species (Tschamtkke et al., 2007; Garibaldi et al., 2021). In
227 addition to the amount of habitats, the spatial configuration of habitats in the landscape affects
228 movements of natural enemies. Natural enemies are usually more abundant in fine-grained
229 agricultural landscapes, i.e. landscape with smaller patches of habitats, that enhance spillover
230 of natural enemies and connectivity (Bailey et al., 2010; Martin et al., 2016; Haan et al.,

231 2020). Reducing the amount of roads, hedgerows and tree lines that can act as shelter and
232 increasing edges between crops and corridors are criteria to take into account to optimize
233 biocontrol in agricultural landscape (Schellhorn et al., 2014). However, it should also be
234 noted that for some natural enemies these landscape features may act as barriers to movement,
235 rather than enhancing access. Evidently the relative importance of landscape composition and
236 configuration for natural enemies depends on specific natural enemy traits, such as dispersal
237 ability (Martin et al., 2019; Haan et al., 2020).

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

253 2.3. Choice of the scale to diversify crops
254

255 Diversifying crops in order to suppress pests and/or increase natural enemy efficacy can be
256 done at three different scales: (1) at the field scale – generally through polyculture schemes
257 (companion cropping, push-pull, intercropping, trap-crops, etc.) (Letourneau et al., 2011;
258 Beillouin et al., 2019) or through rotation schemes (Rusch et al., 2013; Barzman et al., 2015;
259 Beillouin et al., 2019) activating bottom-up forces through the resource dilution hypothesis,
260 (2) at the farm scale – diversifying crops in multiple fields but in one farm only (Jeanneret et
261 al., 2012), and (3) at the landscape scale – a scale that has been only recently studied as shown
262 in Section 2.1 (see Fig. 3 for more details on the different scales described). Manipulating
263 plant diversity at the field scale seems to be most efficient, but for issues of technical
264 feasibility these systems are under-used in modern agriculture (Schaller, 2012; Meynard et al.,
265 2013; Meynard et al., 2018; Morel et al., 2020). In order to avoid any conflicting effect of
266 practices on the efficacy of natural enemies (Brittain et al., 2010) applying the proposed
267 agricultural system based on crop diversity and reduced pesticide use at a large scale would be
268 the most efficient scale (Landis, 2017; Brewer and Goodell, 2012; Goldman et al., 2007; Haan
269 et al., 2021). Additionally, as argued by Landis (2017), even though a particular farm is
270 efficient, in terms of biocontrol increase through crop diversification, other less efficient
271 farms interspersed with the efficient farm might reduce the overall efficacy of the method
272 used by that efficient farmer (Landis, 2017), for example in the case of pesticide drift. Taking
273 decisions at larger scales than individual farms is therefore a key to success but will require
274 efficient planning and coordination among different farms (Landis, 2017; Haan et al., 2021).

275 Arthropods, especially large ones (e.g. ladybirds, lacewings, hoverflies, but also spiders), can
276 move over long distances (ranging up to several kilometers) in order to find their food and
277 mate (Roh, 2013; Evans, 2003; Chifflet et al., 2011; Villenave-Chasset, 2006). Studying the
278 effect of a cropping system on a small or partial landscape, such as a field or farm, would
279 therefore omit a large part of the landscape covered by the natural enemies, and consequently

280 the impact of the rest of the landscape on these animals. In landscape ecology, the landscape
281 scale to study a broad spectrum of natural enemies is usually between 1 km (e.g. Rusch et al.,
282 2016) and 2 km radius (e.g. Karp et al., 2018). The study of Gardiner and Neal (2009) has
283 shown that the 1.5 km scale is best to explain the variation in biocontrol and abundance of
284 ladybirds, a large long distance flying predator. Many levers of landscape manipulation for
285 natural enemy preservation have been shown to be effective (Landis, 2017): 1) landscape
286 heterogeneity needs to be preserved and both composition and configuration of the landscape,
287 not only composition as developed in the previous section, need to be considered when
288 managing a landscape (Holzschuh et al., 2010; Fahrig et al., 2011; Perović et al., 2015), 2)
289 landscapes need to be connected and field sizes reduced in order to allow spillover between
290 fields and entire exploitation of resources in the fields (Fahrig et al., 2015; Fischer et al.,
291 2006; Haan et al., 2020), 3) food provision or natural enemies needs to be continuous in time
292 and space (Schellhorn et al., 2015) and 4) disturbing events, such as ploughing, harvesting,
293 vegetation clearance, cutting and pesticide treatments, need to be adapted to arthropod life
294 cycles (Fischer et al., 2013).

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

304 terms of movement, wind direction, etc, in order to optimize biocontrol and 2) farm
305 management needs for a simple system to manage.

306

307 3. Meeting stakeholder needs and sticking to market realism to 308 apply crop diversification

309 3.1. Socio-economic aspects – how to get stakeholder acceptance for such 310 systems?

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

326 3.1.1. Questions about farmers technical capacity, added value of the system and the right
327 business model to adopt

328 After understanding clearly the problems articulated by farmers (economic, social and
329 environmental issues), the first question to address is the way to efficiently train farmers the
330 role of crop diversity (within their overall farming objectives) in order to boost natural enemy
331 activity and increase economic efficiency. Modern farming is first of all an enterprise where
332 profitability is a major objective (Bernués et al., 2016). Responding to farmer needs through
333 training toward new environmentally friendly concepts is often associated with ideas which
334 are not seen to have immediate direct and obvious economic return for the farmer (Kilpatrick
335 and Rosenblatt, 1998). Above all, it is necessary that, when learning together as farmers and
336 ecologists, farmers gain knowledge relevant to their personal situation, by demonstrating
337 concepts associated with practical examples (Kilpatrick and Rosenblatt, 1998). Finally,
338 training farmers must 1) overcome any lack of confidence farmers may have in trainers when
339 training is compulsory and in the accuracy of new information given, 2) overcome any fear of
340 learning new knowledge or skills as it might induce a change of practices and habits,
341 problems that have been found to be the main reasons why training fails to reach or be
342 adopted by farmers (Kilpatrick and Rosenblatt, 1998) and 3) show that working together as
343 farmers and ecologists to develop a training curriculum is relevant to the needs of growers and
344 opens up new practical and effective management options for them. Implementing a new
345 agronomic system will therefore need to be done with a clear view of the added value for the
346 farm owner. One additional advice would be for other farmers who have already tested the
347 system to train further farmers to ensure the efficiency of the program proposed and to
348 increase the relevance of training (Kip-Tot et al., 2011; Bouttes et al., 2019). Local actions led
349 by community organizations and group training could be important, to involve farmers
350 directly in the decisions and the organization of the landscape (Stallman and James, 2015).
351 Landscape re-organization in accordance with farmer needs (social and economic) and with

352 the ecological intensification of agriculture will likely need some public coordination and
353 State finance (Fahrig et al., 2011). Implementing a self-learning/self-training program in
354 which farmers convince themselves of good practices would also be useful to encourage
355 farmer groups to experiment at a local scale with landscape coordination and keep records of
356 impacts on natural enemies and pest challenge (affecting pesticide use).

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

376 Agricultural landscapes can be associated with specific markets. Agri-tourism can be an
377 additional market to use by farmers in order to make a profit from eco-friendly agrosystems,
378 in some situations: 1) the farm needs to be near a touristic area (Sharpley and Vass, 2006), 2)
379 the project needs to be eligible for environmental public subsidies (Haan et al., 2021), 3) may
380 require training on marketing techniques (Sharpley and Vass, 2006) and means of
381 communication (websites, social networks, etc.). Another market could be local sale of newly
382 introduced crops under an environmentally friendly label at higher prices since consumers are
383 willing to pay higher prices for such products (Elkington, 1994; Cranfield and Magnusson,
384 2003). Labelling can be an option to help consumers learn about the effort made by farmers,
385 and would allow farmers to sell products at higher prices if consumers are willing to pay more
386 for healthier products, as shown by a survey led in the framework of the EUCLID H2020
387 program asking if consumers were willing to pay more for environmentally friendly – not
388 organic – products (up to 20% more), especially for fruits and vegetables (Fornetti, 2019).
389 However, a communication effort about these new brands will need to be done by retailers as
390 consumers are more confident about well-established organic and fair trade labels rather than
391 new labels (Sirieix et al., 2013). The newly introduced crops might also be sold in local
392 markets at higher prices if the farm is located in a peri-urban place, as many consumers today
393 prefer to choose local IPM over non-local organic (Adams and Salois, 2010; Fornetti, 2019).
394 In case none of the markets proposed above are applicable, public subsidies might help
395 farmers to apply environmentally friendly techniques, as for example the current CAP
396 greening, or the Whole Farm Revenue Protection introduced in 2014 in the US allowing
397 farmers to diversify their production in order for them to increase their resilience (Haan et al.,
398 2021). Several systems of payment exist for subsidies based on different units: the simple
399 input area per hectare, the output volume per ton, the output value per currency unit, the
400 action and action avoided payment per unit of approved or proscribed input respectively, and

401 the outcome payment (Table 1). Regarding the different systems of payments, the action
402 payment system would be best adapted in the agro-ecosystem considered in this study.
403 Contrary to output payments, the objective of the system based on multiple crop farming is
404 not to produce more but to produce better. Finally, action payments, as opposed to action
405 avoidance payments, are morally more rewarding.

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

416 3.1.2. Implementing decisions at a large scale

417 As mentioned in Section 2.3, in order to avoid any conflicting effect of practices on the
418 efficacy of natural enemies (Brittain et al., 2010) applying an agro-ecosystem based on crop
419 diversity and reduced pesticide use at a large scale would be most efficient (Landis, 2017;
420 Brewer and Goodell, 2012; Goldman et al., 2007) from an ecological point of view. If we
421 focus now on the political/social point of view, such global decisions could be difficult to
422 organize and might take a long time before being efficiently applied at a national scale.
423 Diversifying crops could be done first at a regional or local scale (Cumming and Spiesman,
424 2006; Valbuena et al., 2010). One example of agri-environmental legislation that has been
425 implemented at a regional scale is the French Regional Action Program (RAP) initiated in

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

451 Slotterback et al. (2016) where farmers' decisions in a region were transferred into a tool
452 called Geodesign. An iterative process helped to assess the resulting changes happening at the
453 landscape scale and helped in the emergence of multifunctional solutions (Slotterback et al.,
454 2016). Networks gathering different agricultural stakeholders have also been developed all
455 across Europe in order to help design efficient agroecological farming systems (e.g.
456 Agroecology Europe Forum which has gathered more than 300 participants, notably farmers,
457 technicians, researchers, students, policy and decision-makers, representatives of national and
458 European institutions, non-governmental organizations, social movements, and civil society
459 (Wezel et al., 2018)).

460 3.1.3. The importance of establishing the system in a win-win process

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

- 472 1. First of all, farmers: Reducing pesticide use that is bad for their health (Jokanovic,
473 2018) would be a high benefit for them. Increasing crop diversity could also raise new
474 markets and push agri-food companies to buy new crops at high prices, at least during

475 the transition phase, in order to meet consumer demand for healthier food (Crawford,
476 2019). The satisfaction induced by adoption of environmentally friendly methods
477 would also improve farmer well-being (Fischer, 1980) by increasing the level of
478 working conditions (Shreck et al., 2006). Direct help from the State in order to switch
479 to more environmentally friendly system could help to ensure stable incomes.

480 2. Then, environmentalists: Arthropod biodiversity preservation, among other animal
481 diversity preservation like birds and mammals, as well as the moderated
482 environmental impacts that might result from adoption of diversified crop systems and
483 reduced pesticide use (Letourneau et al., 2011) are clear positive arguments for
484 environmentalists.

485 3. Consumers: Demand for healthier and environmentally friendly products would also
486 be a “winner” in the proposed system in two ways: 1) reduction of pesticides would
487 generate better quality products with reduced residues (Smith-Spangler et al., 2012),
488 and 2) reduced use of pesticides would reduce potential health problems related to
489 drift (Provost et al., 2007).

490 4. Retailers: With an increase in consumer demand for healthy products, and increasing
491 conversion of farmers to IPM or organic farming, retailers can be included as key
492 actors in promotion and distribution of healthy products, under marketing processes
493 that help to increase sale prices and therefore benefits (Crawford, 2019).

494 5. Policy makers: If the increase of crop diversity at a landscape scale can help reduce the
495 use of pesticides, as the main objective of policy makers is to maintain public health at
496 a high level and preserve biodiversity, this solution might also be a winning solution
497 for them.

498 At this stage it is important to note that reducing the dependency of farmers on pesticides
499 might not be a winning solution for agrochemical companies (Clapp et al., 2021). However,

500 today these companies are incorporating IPM concepts through the adoption of new
501 technologies like RNA-based biocontrol products (Taning et al., 2020), precision agriculture
502 (Birner et al., 2021) or even biocontrol (see “Biologicals by Bayer” as an example) and might,
503 by necessity, switch completely to IPM solutions in order to satisfy consumer and policy
504 demands (but see Deguine et al., 2021). It is important to remember that consumption is the
505 basis of a market, and if the demand for conventional food is reducing, the companies will
506 have to adapt to what consumers want. More details about the influence of agrochemical firms
507 in decision making are given in the following sub-section.

508 3.1.4. Potential difficulties that could be encountered for building-up a landscape system
509 based on crop diversity and conservation biological control

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

517 A second possible blocking point might be the feasibility of implementing the proposed
518 landscape design at a large scale. Communication between farmers to preserve natural enemy
519 communities in fields is necessary as agricultural landscapes are composed of different farms
520 (Cumming and Spiesman, 2006; Goldman et al., 2007; Stallman and James, 2015).
521 Coordination of practices applied by different farmers of a region (Stallman and James, 2015)
522 might help to optimize choice of crops to implement, pesticide use and resulting biocontrol
523 services. Cooperation between farmers on practices to increase biocontrol is possible but
524 might not always work, as farmers with more inclusion in community organizations or

525 farmers that are concerned about pesticides in the environment seem more willing to
526 cooperate than those who don't (Stallman and James, 2015). Local scale (neighboring farms)
527 cooperation might also be more efficient than a larger county-wide scale (Stallman and James,
528 2015). All in all, cooperation between farmers, that could be enhanced by regional managers,
529 might be possible only at small scales where farmers agree on principles of pesticide
530 reduction and timing of applications that allow natural enemies to establish in the landscape.
531 A last point where farmers may need to collaborate in a diversified crop landscape is on
532 purchase of agricultural equipment. The management of different crop types requires different
533 type of equipment: combines for cereals, mowers for fodder, harvesters and leaf strippers for
534 beets, but also various types of seed drills at the beginning of the cropping season, as well as
535 specific cultivation, etc. Increasing the number of crops on a farm will require more machine
536 types and might be very expensive if farmers must purchase these machines alone. To share
537 purchase of equipment, as is already done in France with the CUMAs (Cooperatives for the
538 Use of Agricultural Machineries), might be a good option.

539 A third blocking point might be that the proposed landscape design might not be easy to
540 implement in all types of farms. Even though we mainly specified that landscape crop
541 diversity needs to be managed at a landscape scale, it is possible that some farms might have
542 more or less difficulties to implement such management practices. The size of the farm might
543 be one excluding criteria. The size of a farm can be defined in relation to its area cultivated or
544 its capital (standard gross margins) (Potter and Lobley, 1993; Nagayets, 2005). Based on the
545 economic status of each type of farm, diversifying crop systems may be more easily adopted
546 by small farms (35 ha large and less) (Burton et al., 1999; Rigby et al., 2001) at the season
547 scale through rotations. As small scale farmers have generally little capital investment, they
548 may have more flexibility through contracted equipment suppliers and therefore may be more
549 able to switch easily from one crop type to another from season to season. However,

550 implementation of diversifying crop practices and lower pesticide inputs to increase
551 biocontrol might have more impact in areas where large scale monocultures are usually
552 farmed. Large scale farms (above 100 ha, see Burton et al., 1999) could more easily diversify
553 their crops in space and time as they usually have more capital (Haspel, 2014) and have more
554 area to work on. The larger the farm, the greater the investments can be and the production
555 cost per unit goes down (Haspel, 2014). We raise the hypothesis that risks taken in
556 diversification of crops might be less feared than in middle scale farms. Additionally, large
557 scale farms with high capital could test crop diversification and pesticide reduction on a small
558 part of the farm to begin with, to take less risks. This system is already used by big vine
559 producers in France, where small parts of the vineyards are converted to biodynamic vine
560 production, this product being more and more appreciated by consumers who are willing to
561 pay more for it. Finally, the system might be more difficult to apply to mid-size farms as they
562 might be committed to specialized capital equipment which would make temporal crop
563 diversification more difficult and are too small to manage diversification in space.

564 A final blocking point might be the lack of interest, or maybe even the opposition, of large
565 agrochemical companies to the proposed system. Agrochemical companies have a high
566 influence on the agricultural sector. Today, only a few firms own a large part of the
567 agricultural chemical market (Clapp, 2021). These firms exert an important power, more or
568 less directly, on the way food is produced (Clapp, 2021). As they profit directly from the
569 commercialization of chemicals, going toward a system without these chemicals as proposed
570 in this paper could be of huge commercial challenge, but one that is consistent with
571 competitive use of new biotechnologies with more environmentally friendly properties. As
572 stated by Clapp (2021), these companies shape the food markets, technologies and innovation
573 perspectives as well as policy and governance decisions. More and more, these companies are
574 opening market branches in biological control, which actually goes in the direction of

575 reducing the use of chemicals. However, what we propose in this paper is a way to attract and
576 maintain natural enemies already present in the landscape (conservation biological control),
577 with consequently no need for external inputs. It would therefore be quite optimistic to think
578 that implementing such large-scale conservation biological programs might be enhanced by
579 these agrochemical companies if they implement innovative environmentally compatible
580 technologies in their market strategies.

581 3.2. Actions to be taken by the stakeholders to reach the next step

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

588 The implementation of a system based on landscape crop diversity could be feasible if the
589 different agricultural stakeholders are involved (Landis et al., 2017; Haan et al., 2021). Fig. 4
590 is a schematic representation of the agricultural network studied in relation to the economic,
591 social and environmental pillars, including new actions to be taken by the stakeholders of the
592 agricultural chain in the framework of landscape crop diversification. As mentioned earlier,
593 new stakeholders - highlighted in dark green in Fig. 4 – need to enter in the decision making
594 in order to optimize the proposed way to implement crop diversity schemes at a landscape
595 scale. Economists, sociologists, geographers and advisers need to be included in a
596 collaborative framework (Landis et al., 2017; Haan et al., 2021) as well as of course farmers
597 and environmentalists already mentioned in Fig. 2. Specialised advisers could take the role of
598 transferring the specific knowledge to farmers and these farmers should provide feedback on

599 the proposed practices and outcomes. By implementing this new landscape design, new
600 relations between the different agricultural stakeholders could raise. First, in order to avoid
601 any economic losses possibly due to the changes of practices, the State could propose to the
602 farmers a system of insurance encouraging them to take risks. Secondly, environmentalists
603 could propose new agricultural landscape designs in collaboration with geographers,
604 economists, sociologists and farmers in order to stick to realistic solutions. Thirdly, food
605 retailers would inform consumers about the changes of practices in order to encourage them
606 to change their consumption habits and help the farmers to switch from a pesticide dependent
607 practice to a more environmentally friendly one. Within the retail network, cooperatives could
608 be engaged in buying new crops under special market contracts in order to promote the selling
609 of newly introduced plants in the region (Haan et al., 2021).

610

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1 **Figure legends**

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

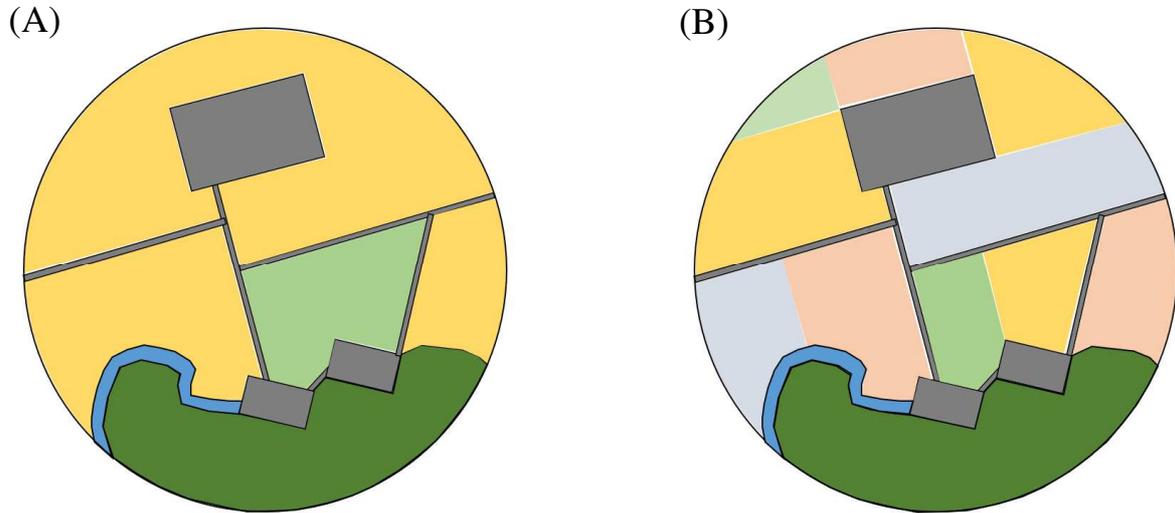
5 Figure 2. Schematic representation of the agricultural network studied in relation to the
6 economic, social and environmental pillars. In grey are represented the stakeholders targeted,
7 in capital letters and bold arrows are the different relations between stakeholders. The thin
8 arrows represent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

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

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

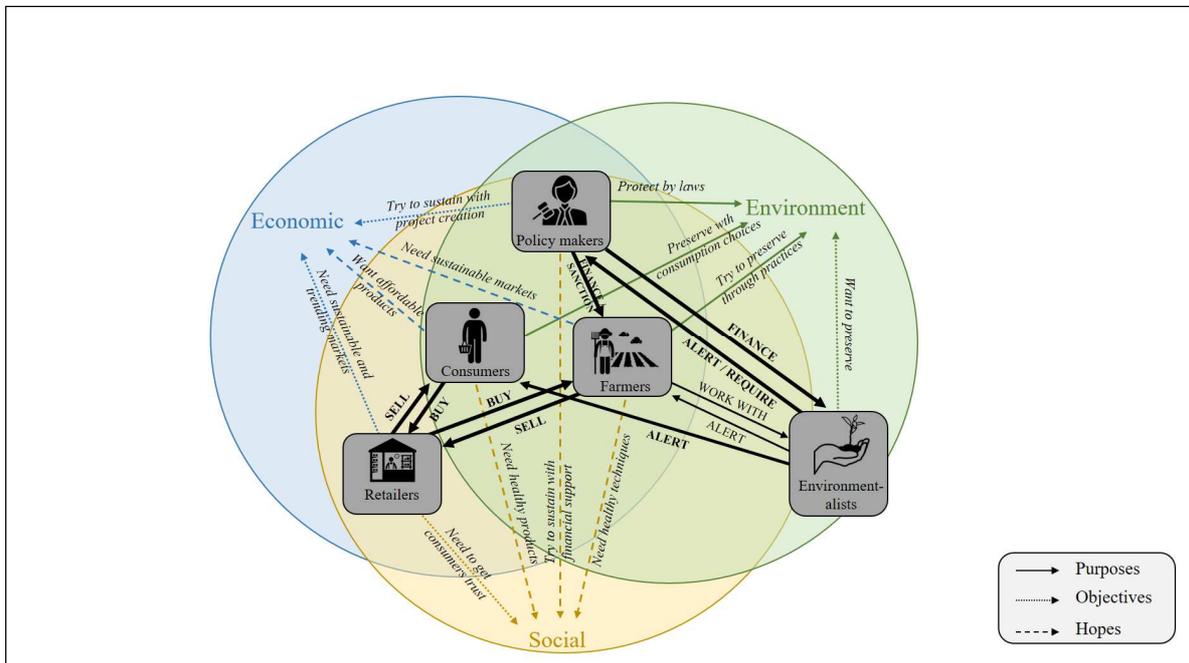
23 **Figures**

24 Figure 1.



25

26 Figure 2.



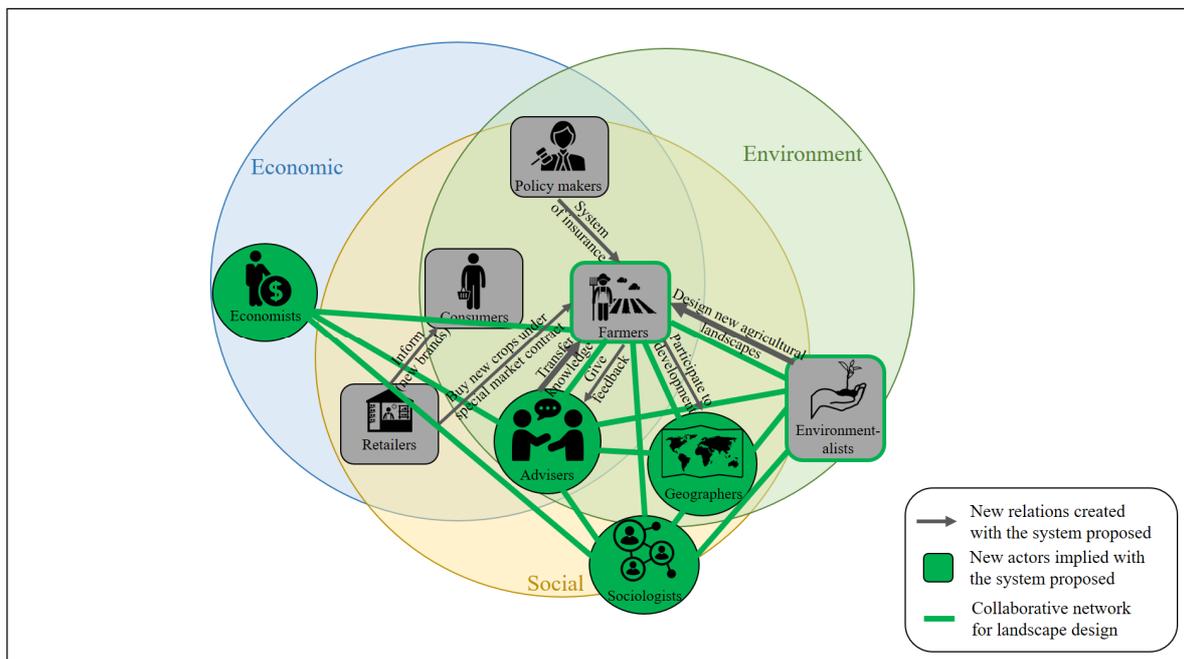
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28 Figure 3.



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30 Figure 4.



31

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.

