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A conceptual framework linking ecosystem services, socio-ecological systems and sociotechnical systems to understand the relational and spatial dynamics of the reduction of pesticide use in agrifood systems Short communication

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4

5 *Short communication*

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10

11 **Abstract**

12 **CONTEXT**

13 Reducing pesticide use is a challenging issue in the construction of sustainable agrifood systems. It
14 requires innovations of various kinds at different scales. Reaching the objective of reduced pesticide
15 use means that the different stakeholders which compose agrifood systems have to coordinate their
16 actions in order to innovate. Dealing with the transformation process in agrifood systems therefore
17 focuses attention on the context of the interactions between stakeholders.

18 **OBJECTIVE**

19 This article sheds light on the dynamics and modes of interaction between stakeholders in order to
20 help us to understand how agrifood systems may evolve in the context of agroecological transitions.
21 Agrifood systems connect human and non-human dynamics from which production, processing,
22 distribution and regulation activities emerge. Agrifood systems are therefore networks of stakeholders
23 linked to agroecosystems and embedded in complex ecological, economic and social processes.

24

25 We argue that the territorial scale is particularly relevant in describing the relational and spatial
26 dynamics in agrifood systems and for understanding the diverse initiatives that emerge from
27 stakeholders. This article therefore aims to provide a deeper understanding of the inter-relationship
28 between the dynamics of stakeholders and the dynamics of ecosystems in agroecological transitions,
29 and more specifically in the perspective of reduced pesticide use.

30 **METHODS**

31 Surveying the literature, we identified and compared three key frameworks that handle ecological and
32 social issues, and help formalise the capacity for action to promote sustainable systems. The three
33 approaches refer to (i) ecosystem services, (ii) socio-ecological systems and (iii) socio-technical
34 systems. Each approach offers a partial analysis for unravelling specific scales of actions and fails to
35 fully scrutinise the spatiality and temporality of stakeholder interventions.

36 **RESULTS AND CONCLUSIONS**

37 From these three approaches, we developed an integrative conceptual framework that relies on
38 systemic, multi-stakeholder and multi-scale reasoning. The suggested approach grasps agrotechnical
39 and socioeconomic concerns, links micro, macro and mesoeconomic levels, and enables a relational
40 and spatial analysis of the dynamics of the ecologisation of agroecosystems to reduce pesticide use.

41 **SIGNIFICANCE**

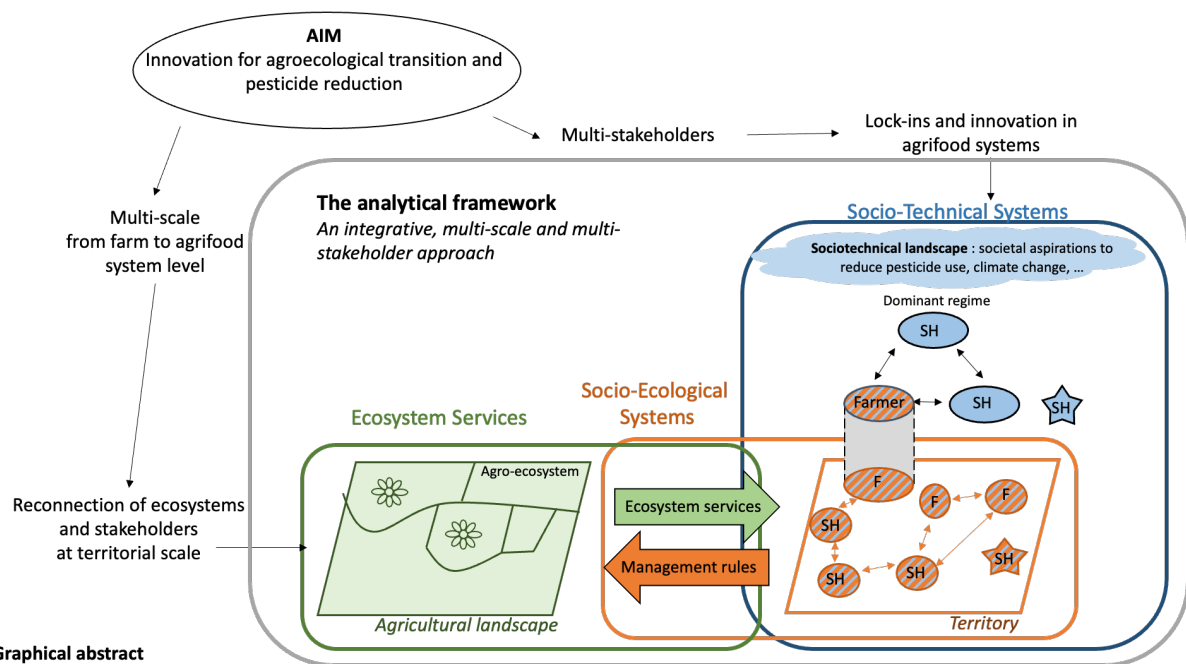
42 By identifying stakeholders and their roles in conceiving and implementing innovations, the suggested
 43 framework helps to understand the current sociotechnical lock-ins in agrifood systems and how such
 44 systems could be unlocked by coupling innovations implemented at different levels of agrifood
 45 systems. This means our approach should be useful in reinforcing capacity building and providing the
 46 support needed to improve transition processes.

47

48 GRAPHICAL ABSTRACT

49

50



51 Graphical abstract

52 **Key words**

53 Agrifood system; Agroecosystems; Agroecological transition; Coordination between stakeholders;
 54 Territory; Innovation

55 **Highlights**

- 56 • Pesticide use reduction in agriculture requires tailored innovations at stakeholders' scales and
- 57 at the scope of actions
- 58 • Sustainable management of resources requires reconnecting ecosystems and stakeholders at
- 59 a territorial scale
- 60 • Our conceptual framework combines ecosystem services, socio-ecological systems and socio-
- 61 technical systems approaches
- 62 • The multi-stakeholder and multi-scale reasoning of our framework is illustrated in the pursuit
- 63 of pesticide reduction
- 64 • Our approach is useful to support the systemic and multi-stakeholder innovation required for
- 65 agroecological transitions

66

67

68 Introduction

69 The reduction of pesticide use and its associated risks in agriculture responds to general societal
70 aspirations for healthier food and environments, and results from windows of opportunity created by
71 changes in paradigms, standards and institutions that call for the ecologisation of agrifood systems
72 (Jacquet et al., 2022). For example, public policies in France have been expected to produce a large
73 reduction in pesticide use since 2008 (Ecophyto plan). Since the ambitious goal of reducing pesticides
74 by 50% (Guichard et al., 2017) was not achieved by 2018, a new deadline of 2025 has now been
75 set. This target is fully in line with the European Green Deal, in which a 50% reduction is expected by
76 2030. Altieri et al. (2015) have argued that the challenges of such a large reduction would require a
77 profound redesign of cropping systems to combine several agroecological techniques in a systemic
78 manner. A recent review on the potential of plant diversification for the management of pests,
79 including diseases, also argues for the necessity of a major redesign of cropping systems and also of
80 sociotechnical systems and landscapes (Vialatte et al., 2021).

81 However, transitions to agroecological agrifood systems test the incumbent pesticide-intensive
82 regime's resistance (Wilson et Tisdell, 2001; Guichard et al., 2017; Della Rossa et al., 2020; Boulestreau
83 et al., 2021, Clapp., 2021) and face numerous lock-ins: agrotechnical, organisational, economic, social,
84 political, etc. (Belmin et al., 2018; Boulestreau et al., 2021; Clapp., 2021; Conti et al., 2021; Della Rossa
85 et al., 2020; Goulet et al., 2023; Hofmann et al., 2023; Magrini et al., 2016; Meynard et al., 2018). These
86 lock-ins result from the confrontation of different stakeholders' behaviour as their interests and
87 strategies are not necessarily compatible. Lock-in mechanisms exist at different management scales
88 (i.e. cropping system, plot, farm, territory, supply chain).

89 Our starting hypothesis is that the territory is the key scale for achieving a drastic reduction of pesticide
90 use and unlocking agrifood systems. The definition of territory includes three dimensions (Le Berre,
91 1995): material or physical dimensions (plots, roads, rivers, storage facilities, etc.), organisational or
92 relational dimensions (e.g. coordination between stakeholders along supply chains) and the
93 institutional dimension. Institutions are a society's 'rules of the game' (North, 1990) that shape human
94 behaviours and interactions. Institutions can be formal (political structure, constitutional rules,
95 property rights, contracts, etc.) or informal (beliefs, norms, culture, etc.). These three dimensions allow
96 a wide range of stakeholders to share the same concern (and to be involved in common actions) even
97 if their individual strategies may compete and may be the expression of power relationships.
98 Therefore, we postulate the relevance of the territorial scale for solving production problems in
99 agrifood systems and designing desirable futures, especially for reducing pesticide use, which "embed

100 contrasted visions of the future of agriculture, along with specific representations, values, imaginaries
101 but also material cultures” (Goulet et al., 2023).

102 Transitions toward the reduction of pesticide use in agrifood systems require the development of
103 tailored innovative solutions. To implement such innovations, there is a real “challenge to reconnect
104 supply chains’ and ecosystems’ dynamics at territory level” (Madelrieux et al., 2017). First, the territory
105 hosts the farms where farmers - who are the direct applicers of pesticides - can change their practices.
106 Even if some stakeholders are not locally based (e.g. retailers in long supply chains), they interact with
107 farmers or their intermediaries (cooperatives and wholesalers) located in the territory. Therefore, they
108 contribute to fostering or slowing down changes at the farm and plot scales. A deep understanding of
109 stakeholder strategies and coordination is then necessary. This article aims to present a conceptual
110 framework to support current research dealing with alternative solutions for reducing pesticide use
111 and inform policy and practice decisions, demonstrating the relevance of the territorial scale.

112 In their strong and most sustainable forms (Duru et al., 2015a,b), agroecological transitions of agrifood
113 systems call for disruptive innovations. The new levers to be activated generally require a large
114 redesign of cropping and farming systems, at the farm scale or among farmers, but also a
115 reorganisation of stakeholder networks (Meynard et al., 2017) to enable the implementation of new
116 agroecological systems. As forwarded by Jacquet et al. (2022), the objective of reducing pesticide use
117 (including their banning) requires a deep redesign of the farming and agrifood systems . Indeed, these
118 stakeholders organise themselves to produce and sell agricultural products and implement decisions
119 (e.g. technological choices) and thereby influence and shape agroecosystems (e.g. biodiversity-based
120 agriculture). Such ecosystems are made up of natural, semi-natural, technological and cultural
121 resources comprising both material (i.e. physical and biological) and immaterial (i.e. landscape
122 aesthetics) components, as well as ecological and human dimensions. In this sense, these
123 agroecosystems are social and technical systems and the resources they are made up of are the basis
124 of the services provided by these ecosystems.

125 The analysis of agroecosystems and their dynamics can be conducted through a triple conceptual
126 prism: (i) ecosystem services (ES), (ii) socio-ecological systems (SES) and (iii) socio-technical systems
127 (STS) frameworks. They offer partial but complementary analyses for understanding the room for
128 manoeuvre of stakeholders in developing innovative alternatives for pesticide reduction. A previous
129 study (Ollivier et al., 2018) focused on the analysis of SES and STS, identified convergences but also
130 some differences. With regard to the reduction of pesticide use, we suggest a reconnection of the
131 three approaches to build a holistic analysis which jointly grasps ecological and social issues, as well as
132 spatial scales, in order to understand stakeholder decision-making and scope for action. Indeed, there

133 are still few operational frameworks to help stakeholders coordinate with each other, taking into
134 account agroecosystem issues such as the management of cultivated diversity, temporality of crop
135 cycles and specificity of products (orphan crops).

136 To shed light on stakeholder strategies and coordination with the goal of reducing pesticide use, the
137 article unfolds in three steps. First, it briefly presents the three existing frameworks. Second, it
138 discusses their limitations through the prism of coordination among stakeholders in agrifood systems
139 and the territorial context for their actions. Third, it sets out a suggested conceptual framework and
140 highlights the accuracy of the territorial scale for research and policy making regarding reducing
141 pesticide use.

142 1. Outline of three existing theoretical frameworks relating to agroecosystems

143 Ecosystem services (ES), socio-ecological systems (SES) and socio-technical systems (STS) frameworks
144 have emerged and been popularised at different times; they are part of specific scientific communities
145 and use different methods. Nevertheless, they share the fact that each in its own way provides an
146 account of the relationship between humans and ecosystems, and have been used to address the
147 capacities for action that promote a system's sustainability.

148 1.1. Ecosystem services framework

149 The concept of ecosystem services (ES) deals with interactions between stakeholders and biological
150 systems. It places an emphasis on the natural processes around which stakeholders coordinate for the
151 sustainable management of a territory and stresses the importance of relinking society with ecosystem
152 functioning. The term is commonly used to aggregate a set of positive effects associated with
153 biodiversity and ecosystem functioning (e.g. pollination, climate regulation etc.). This concept,
154 especially its use for monetary evaluation, has been widely debated and criticised. Its latest evolution
155 (Nature's Contribution to People) tends to provide a better inclusion of a diversity of point of views
156 around these benefits (Diaz et al. 2018). We stick to the historical term ES, which retains the advantage
157 of being widely understood. The most consensual definition of ES dates back to the Millennium
158 Ecosystem Assessment: "Ecosystem services are the benefits people obtain from ecosystems" (MEA,
159 2005). Human beings are explicitly mentioned in this definition, but they remain passive entities
160 receiving the benefits of ecosystem functioning. It is only recently that research studies have started
161 to look at how human beings may actively manage ecosystems to steer the production of ES (Birgé et
162 al., 2016) or consider ES as a co-production of human beings and ecosystems (Fischer and Eastwood
163 2016). However, ecosystems have no clear spatial limits as ecological processes may occur at micro to
164 global scales in a hierarchy of nested interacting levels of organisation (Allen et al., 2014). Therefore,
165 in most cases farmers cannot be considered as the only managers of the ecosystem services they
166 benefit from. Landscape structure is a key driver of biological dynamics in agrolandscapes (e.g. Martin

167 et al. 2019) and ecosystem services flows rather depend on the interaction between landscape
168 structure and local agricultural practices. This means that ecosystem services management depends
169 on actions led by different stakeholders at scales beyond the farm scale (van Zanten et al., 2014). The
170 pending question is then how to coordinate such a diversity of stakeholders around the management
171 of landscape-driven ecosystem functioning.

172 1.2. Socio-ecological systems framework

173 The socio-ecological system (SES) framework (Bromley, 1991, 1992; Schlager and Ostrom, 1992;
174 Ostrom et al., 2002) formalises the importance of rules (i.e. bundles of rights) “for the efficiency,
175 equity, and sustainability of natural resource use patterns” (Ostrom, 2000). This framework analyses
176 how stakeholders (users of the natural resource, providers that enable access to the resource)
177 intervene in resource management. These are then known as “management rules”.

178 Therefore, a SES describes any set of social systems in which interdependent relationships between
179 stakeholders crystallise and are mediated by interactions with biophysical and non-human biological
180 entities (Anderies et al., 2004). In this respect, any ecological system, whether it is anthropised (e.g.
181 agroecosystem) or not (e.g. natural grassland) is part of a societal framework. The properties and
182 particularities of this societal context (the relationship between humans and ecosystems, systems of
183 norms and values, enacted rules, etc.) influence the integrity of the ecological system.

184 Seminal works have documented the advantages of analysing the governance of SES (Bodin et al.,
185 2016; Bodin, 2017; Bodin et al, 2017). One of the main arguments is the complex structure of SES. SES
186 span geographical and temporal demarcations and therefore require cross-border and cross-scale
187 collaborations among different stakeholders to efficiently address ecosystem sustainability. Indeed,
188 the way stakeholders get involved in resource management by designing and implementing rules, and
189 how and with whom they interact, impacts the capacity of SES to address environmental
190 challenges. The SES framework analyses how social interactions produce effects on both the
191 maintenance and durability of institutional arrangements (rules) and ecological systems despite
192 external disturbances or shocks¹. In fact, this framework underpins the resilience of SES (Folke, 2016).
193 As explained earlier, the SES framework addresses coordination issues and promotes time- and place-
194 specific solutions. It therefore requires a territorial approach.

195 1.3. Socio-technical systems framework

196 The analysis of socio-technical systems (STS) has been the subject of renewed interest since the 2000s
197 with the multi-level perspective (MLP) promoted by Geels (2002, 2011) and its application to

¹ There are different kinds of shocks: natural disasters, political crisis, economic disturbances, etc.

198 agroecological transitions (Conti et al., 2021; Vanloqueren and Baret, 2009, Duru et al., 2015a,b). The
199 MLP framework understands a transition as a multi-level, multi-stakeholder and co-evolutionary
200 process within which socio-technical innovations driving change emerge and diffuse. Three levels of
201 analysis are identified (socio-technical landscape at the macro level, socio-technical regime at the
202 meso level and innovation niche at the micro level) from which the dynamics of change can be
203 explained. These levels are not spatial scales but refer to socio-organisational levels.

204 A socio-technical regime is a set of stakeholders who interact around technologies, resources,
205 infrastructures, rules etc. These stakeholders are the basis of relatively stable production and
206 consumption structures. Hence, the regime may change towards an alternative model that promotes
207 the use of nature-based technological solutions only if it is fostered by change at the macro (socio-
208 technical landscape) and/or micro (innovation niche) levels. The socio-technical landscape refers to
209 the macro-institutions (paradigms, societal aspirations) and macro-events (shocks or other natural
210 and/or social disturbances) that underpin the regime. The MLP recognises that the pressures exerted
211 by the landscape create windows of opportunity that favour the integration of new stakeholders,
212 technologies, resources and rules into the regime. The other drivers of change for the dominant socio-
213 technical regime are innovation niches, which are incubation spaces in which alternative technologies
214 emerge. We should note at this stage that the STS framework is non-normative and analyses any type
215 of innovation that may reshape the dominant regime towards more or less sustainable transitions. In
216 this article, we focus on radical innovations in the context of the reduction of pesticide use in
217 agriculture. We then focus on innovations that require profound changes to the dominant socio-
218 technical regime. Such innovations implemented at different levels of agrifood systems may be of
219 different natures and are not only technological, as highlighted by several works (Boulestreau et al.,
220 2022; Elsner et al., 2023; Klerkx and Begemann, 2020; Schiller et al., 2020)..

221 Radical agroecological innovations, rethinking the relationship between humans and ecosystems²,
222 have so far developed in the margins of the dominant socio-technical regime based on high levels of
223 pesticide use. The application of the STS framework to agrifood systems analyses the evolution and
224 perhaps even the overthrow of the dominant regime.. Such transition pathways may be impacted by
225 shocks linked to human activities such as political events (Roberts and Geels, 2019), layers of power

² In the STS framework, technology is an artefact used by individuals. Technology is a way to organise people, man-made devices, natural resources, etc. In this sense, the STS framework addresses human-nature relationships. The STS framework discusses to what extent technology makes it possible to achieve a more or less sustainable future. This is why we consider that STS framework addresses human-nature relationships within the broader context of development.

226 (Grin et al., 2010) etc. Therefore a relevant analysis of lock-ins and path dependence requires the
227 investigation of technological, organisational, institutional and social processes.

228 1.4. Farms at the crossroads of the three frameworks

229 Call for change towards the reduction of pesticide use is expressed not only at the socio-technical
230 landscape level but is also taken up by stakeholders in the socio-technical regime.. Even if some
231 solutions are implemented in some niches (e.g. hyper-diversified vegetable farming), developing
232 agroecological innovations for the dominant socio-technical regime remains quite challenging. Among
233 the stakeholders involved in the dominant regime, several play a central role in promoting or hindering
234 radical innovation. Farms are key places where agroecological innovations are designed and/or
235 implemented. But they are also at the centre of tensions between society's major aspirations and the
236 concrete, technical and economic realities that farmers face. They are places where some individual
237 and/or collective rules are enacted (e.g. choice of cropping practices depending on local production
238 potential), but also where external rules apply (e.g.pesticide authorisations and regulations). As a
239 consequence, farms are at the junction of the local ecosystem and aspatial socio-technical networks
240 which stakeholders belong to (Angeon and Bates, 2020).

241 The reduction of pesticide use raises the question of the consistency of rules for managing the
242 resources that make up these agroecosystems. So, questioning the effective implementation of levers
243 for the development of disruptive innovations invites us to reconcile frameworks that apprehend the
244 ecological and social dimensions of farms, and their insertion within both a socio-technical regime and
245 an ecosystem that provides services. This calls for the study of socio-technical networks and the
246 consideration of territorial agrifood system concerns for reducing pesticide use in the perspective of
247 strong agroecological transitions.

248 2. Limitations and compatibility of the three existing frameworks through the lens of 249 relational and spatial dynamics

250 In this section, we discuss the three theoretical frameworks and their limitations with regard to the
251 way they formalise (i) the interrelations between the dynamics of stakeholders and of ecosystems and
252 (ii) the territoriality of stakeholder actions and ecosystems.

253 2.1. Relational dynamics between stakeholders and ecosystems

254 There is a clear link between the ES and SES frameworks as they are based on a common object:
255 ecosystems. The two frameworks take into account the interactions between humans and ecosystems.
256 Both question the links between conservation and development issues and focus on the users of
257 ecosystems. However, the entry point for the conceptual framework of ES is the identification of the
258 ecosystem services and their beneficiaries. In contrast, the SES framework entry point are stakeholders

259 who govern these ecosystems. In particular, the SES framework shows that the preservation of
260 resources is consubstantial with the dynamics of the stakeholders who govern them.

261 By recognising the existence of two interrelated entities (Human and ecosystems) and thinking about
262 their co-evolution, the SES framework is similar to the ES framework, which postulates that humans
263 are an integral part of ecosystems. There is a dynamic interaction between humans and other
264 ecosystem components. Human activities generate direct and indirect changes in ecosystems, which
265 ultimately lead to changes in the well-being of human populations. Two points deserve particular
266 attention:

267 (i) The notion of ES is often wrongly interpreted as a benefit gained from the presence of a species
268 (e.g. pollination by honeybees). It must be borne in mind that the service provider is the
269 ecosystem as a whole. An ecosystem is therefore an evolving system with blurred boundaries
270 and uncertain dynamics.

271 (ii) The definition of the beneficiary generally remains vague in the ES framework and it is often
272 thought that the beneficiary is society as a whole, which is considered to be homogeneous in
273 its values, expectations and needs. This issue is more explicitly acknowledged in the latest
274 evolutions of the ES framework (Nature's Contribution to People, Diaz et al. 2018) since, from
275 one stakeholder to another, the benefits and disadvantages obtained from ecosystem
276 dynamics may differ strongly (e.g. natural heritage value of the presence of large predators in
277 the ecosystem versus damage inflicted on herds by the same predators).

278 Furthermore, resource management is highly dependent on the characteristics of the group of
279 stakeholders involved in the management, namely its size and degree of homogeneity (Angeon and
280 Caron, 2009). For instance, a SES characterised by a small group of users with homogeneous interests
281 has a strong propensity to prevent opportunistic behaviour. Conversely, a SES based on a complex
282 organisational structure, with a large and heterogeneous number of resource users and infrastructure
283 providers, would require procedures for agreement between agents (routines, degree of collective
284 maturation) for effective community management. These kinds of interaction may generate conflicting
285 power relationships that affect the development and implementation of community management
286 procedures. Power dynamics are widely recognised as drivers of poor environmental governance
287 (McIlwain et al. 2023). This conclusion may be extended to research on agriculture (Clapp, 2021) and
288 agrifood systems. As pointed out by El Bilali (2019), studies on agrifood systems should incorporate
289 analyses of governance and power relationships.

290 In the case of agroecosystem services, farmers act both as beneficiaries of the services and as
291 managers of the ecosystems that provide the services (for them or for other stakeholders). In some

292 cases, a farmer alone has enough influence on the ecosystem to direct its dynamics in such a way as
293 to induce the provision of services from which he or she will benefit. However, most of the time a
294 farmer has only a very minor influence on the ecosystem functioning for two reasons. First, ecological
295 dynamics are based on fundamentally uncertain processes, linked together by multiple feedback loops,
296 making the effect of management practices difficult to predict. Second, ecosystems are multi-scalar.
297 As a result, a farmer is rarely in a position to control the ecosystem that provides the services he or
298 she can benefit from, and will have to coordinate with other stakeholders, whether they are farmers
299 or not (e.g. scientists, industrials, retailers, policy makers etc.). The STS framework integrates this
300 multi-stakeholder dimension. Involved in producing and selling their products, farmers participate in
301 shaping agrifood systems. In this respect, they are stakeholders in socio-technical systems.

302 A farming system can therefore be described not only as a socio-economic system (i.e. a place of
303 decision making and implementation of actions) embedded in a socio-technical system, but also as a
304 socio-ecological system (Angeon et Bates, 2020).

305 As an intermediate conclusion, designing a territorial conceptual framework for pesticide use
306 reduction is not only an invitation to focus on the farm level (as the place where decisions are made
307 and pesticides are applied), but also on the interdependencies between social, ecological and socio-
308 technical systems and individual and collective interactions. Understanding a farmer's decision-making
309 in the light of biophysical and socio-economic dynamics is crucial (Schlüter *et al.*, 2017). So, while
310 reasoning at the level of the individual farm makes sense, it also reflects its inclusion in a social matrix.
311 In the next section, we will show how these stakeholders are territorially embedded and have specific
312 scopes of action at various spatial scales.

313 2.2. – Spatial dynamics relating stakeholders and ecosystems

314 As indicated previously, stakeholders (users, managers, beneficiaries of the services provided by
315 agroecosystems) are constrained by their relational choices: they develop strategic interactions, which
316 means that their decision-making and action plans depend on each other. They are also constrained
317 by their spatial choices: they organise themselves around geographically localised ecosystems.
318 However, their use of resources and management issues may extend beyond the spatial extent of the
319 ecosystems concerned. The coordination processes between stakeholders are therefore embedded
320 (Colletis and Pecqueur, 2005). Consequently, the analysis must be multi-stakeholder and multi-scale
321 and are an invitation to address the question of the spatialities of collective action.

322 The three frameworks presented above deal with spatial scales in different ways. ES and SES
323 frameworks, which provide an integrated perspective on ecosystems, favour multi-spatial thinking. In
324 the case of ES frameworks, three elements should be considered. First, the perimeter of the ecosystem

325 is not necessarily clearly delimited. It depends on several nested scales depending on the organisms
326 under consideration. Managing processes involving both infra- and supra-farm scales requires
327 coordination among stakeholders. Second, ecosystem services are dynamic and uncertain. As a human
328 activity, the production and dissemination of ecosystem services are the results of intentional actions
329 that link stakeholders (e.g. service providers and beneficiaries) who are territorially embedded. In this
330 sense, ecosystem services contain a spatial dimension and entail cross-scale relationship dynamics.
331 These relationships are embedded in specific territories, but also emerge from different places and at
332 different spatial scales. Finally, ES frameworks combine global changes with local trends.
333 Anthropogenic pressures can be simultaneously observed at large and local spatial scales.

334 SES frameworks are intrinsically spatial. SES are circumscribed in their two dimensions (physical and
335 human) even if the spatial scale of human societies and biotopes are not necessarily the same.
336 Furthermore, these frameworks consider the local scale as the relevant level for drawing up,
337 implementing and ensuring compliance with the collective agreements necessary for the sustainable
338 management of resources.

339 While the ES and SES frameworks can be described as multi-spatial, STS frameworks are fundamentally
340 aspatial (Geels, 2011; Coenen and Truffer, 2012). Regimes, niches and landscapes are presented as
341 levels of analysis. The question of their relationship to space deserves further attention. At what spatial
342 scales do each of these levels operate? How are these different levels reflected in stakeholders' fields
343 of action? STS frameworks do not focus on the places where changes and transitions emerge; nor do
344 they consider geographical configurations or the dynamics of the networks within which transitions
345 are forged and disseminated (Coenen et al., 2012). Several works have pointed out the need to
346 formalise the geography of sustainability transitions (Hansen and Coenen, 2015; Elsner et al., 2023).

347 In the case of agroecosystems with the final objective of reducing pesticide use, understanding these
348 relational and spatial determinants remains central, because a number of biological processes are
349 spatially dependent (e.g. pesticide flows within a river watershed, the flow of insects between plots).
350 To this end, we propose a holistic analysis framework that, based on the strengths of the three
351 frameworks presented, links micro, macro and mesoeconomic issues as well as spatial concerns. We
352 therefore suggest a territorial approach to agrifood system ecologisation processes.

Framework	Advantages	Limitations
ES	Focuses on ecological dynamics	Does not consider collective organization of stakeholders
SES	Focuses on rules and governance of natural resource management	Considers resources rather than the underlying ecological dynamics Overlooks the interactions with stakeholders out of the community
STS	Considers the relationships between all stakeholders Analyses lock-ins	Is not spatialised Does not consider the underlying ecological dynamics

353

354 **Table 1.** Summary of the advantages and limitations of the three frameworks

355 [3. A framework that combines stakeholder coordination and territorialities of action](#)

356 To foster pesticide use reduction, we propose an analytical framework in which the farmer is at the
357 centre (see Figure 1). The farmer is not only the main manager of the agroecosystem, but also at the
358 heart of the network of stakeholders who are directly or indirectly involved in the management of this
359 agroecosystem. The agroecosystem constitutes a set of interacting ecosystems with their own
360 dynamics, and in which the farmer implements actions (practices, rules) in order to influence the
361 various flows of services that result from them.

362 This analytical framework focuses on the dynamic interactions between agroecosystems and economic
363 and social systems. More specifically, as shown in Fig. 1, it borrows from the ES framework for the
364 characterisation of agroecosystems and for the identification of services provided. From the SES
365 framework it maintains that the preservation of resources is fundamentally linked to the capacity of a
366 stakeholder network to develop, prioritise and impose management practices and rules. More broadly,
367 it includes agroecosystems and stakeholder systems in socio-technical systems where tensions
368 crystallise, as highlighted by the STS framework.

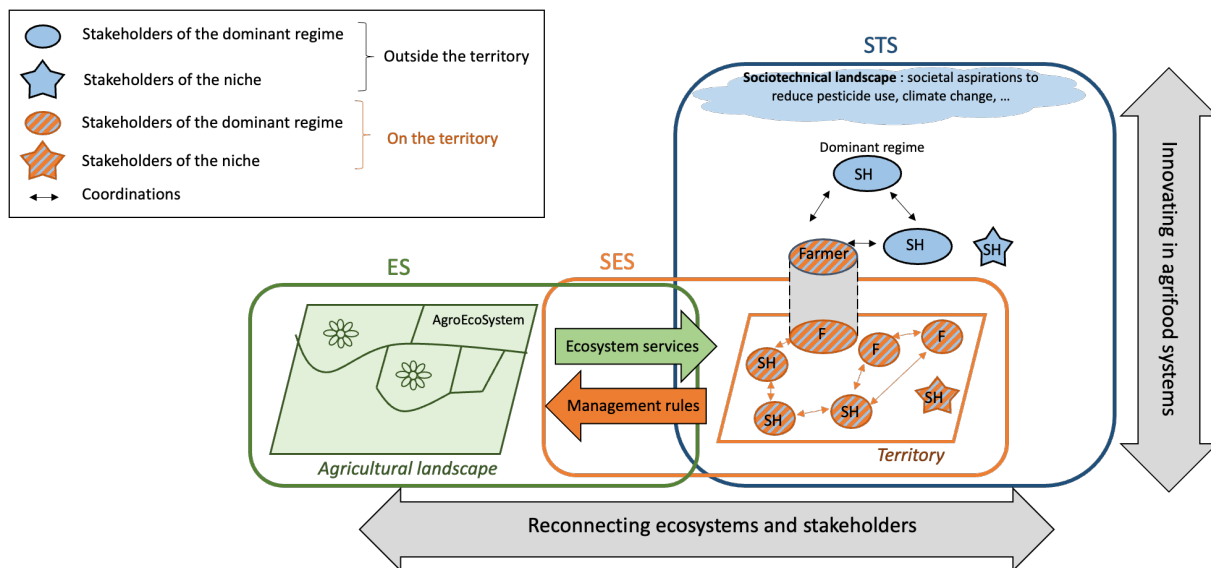
369 The proposed framework shows evidence of the biophysical and socio-economic dynamics at work. It
370 is resolutely spatialised. It analyses the scales of intervention of individual or collective stakeholders.
371 These interactions and their consequences call for relationships in time and space. They can be
372 established within and/or outside of the territory.

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379 **Fig 1. Schematic representation of how the different conceptual frameworks combine together to**
 380 **give a holistic representation of natural resource management.**

381 *F stands for farmers and SH for stakeholders.*

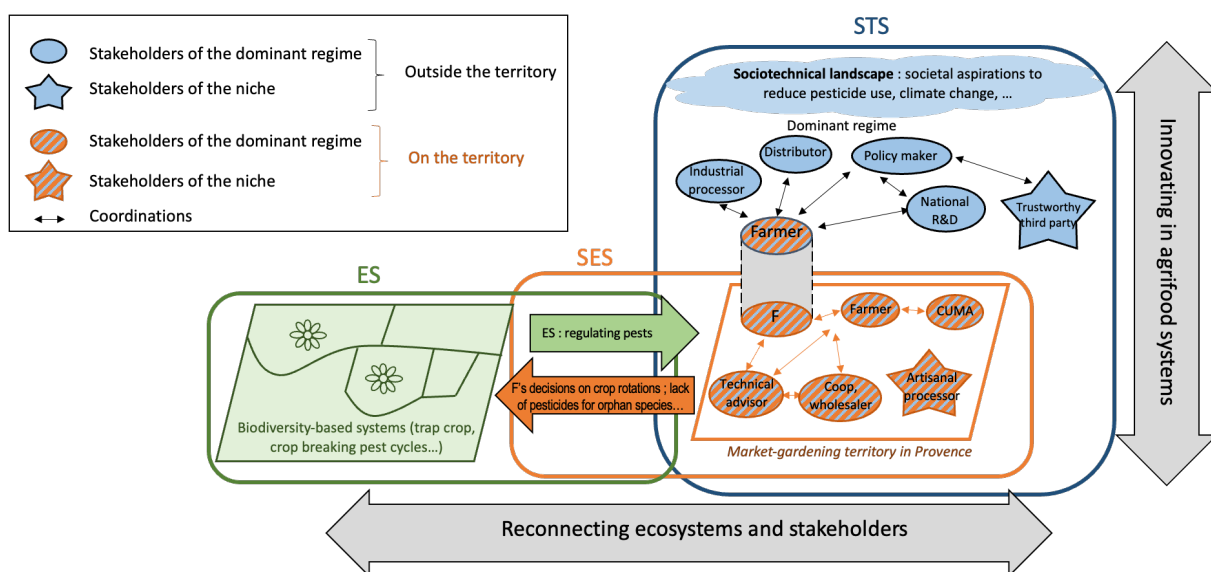
382 The ecosystem service concept (ES) describes the benefits that the stakeholders of the territory obtain
 383 from the functioning of the ecosystem in the agricultural landscape. The socio-ecological system
 384 framework (SES) describes how stakeholders (SH) of the territory, and among them farmers (F),
 385 interact to define the rules for resource management in the agricultural landscape. Farmers belong to
 386 both a dominant aspatial regime (blue on the figure) and to a network of stakeholders of the territory
 387 (orange on the figure). The socio-technical systems framework (STS) describes how the niche and
 388 dominant regime 'co-inhabit'. Note that stakeholders of the niche may or not belong to the territory
 389 and do not necessarily interact. Symmetrically, stakeholders of the dominant regime may or not belong
 390 to the territory.

391

392 We think this framework can be helpful in contributing to reduced pesticide use. Pesticide
 393 consumption developed as agroecosystems became increasingly specialised, preventing natural
 394 regulation from limiting pest development. The aim is now to promote agroecosystems that foster
 395 natural regulations and in particular biological balances between pests and natural enemies. This
 396 involves acting at various scales (plot, farm and landscape), depending on the nature of the pest in
 397 question (Vialatte et al. 2021). The main resources are the ecosystem services of regulation, soil health
 398 and, more generally, support services. As stated in the previous section, the dynamic, uncertain,
 399 invisible, intangible and non-commensurable characteristics of such resources make their
 400 management by a farmer particularly tricky. Moreover, resources are only partially localised and
 401 stakeholders only have partial control over them.

402 Boulestreau et al. (2021) showed that the suppression of chemical nematicides requires several
 403 stakeholders from the dominant socio-technical regime to adopt new strategies and practices (e.g.
 404 development of R&D activities on new resistant cultivars, new outlets for niche species naturally
 405 resistant to root-knot nematodes, creation of an organic input supply chain capable of providing active
 406 organic matter to farmers). The following example illustrates the interest of linking the three
 407 frameworks to develop self-regulating agroecosystems, from plot to landscape, capable of producing
 408 crops without pesticides.

409



410
 411 **Fig 2. Implementation of the analytical framework in a case study: soil-borne pest control enabled**
 412 **by crop diversification in market gardening in Provence, South-East France**

413 In South-East France, market gardening in plastic tunnels faces difficulties in reducing pesticide use
 414 due to increasing pressure from soil-borne pests and diseases. Among them, root-knot nematodes
 415 (RKN, *Meloydogyne* spp.) are particularly problematic.

416 Here we are considering the case of a farmer seeking to shift to a non-chemical strategy based on the
 417 ecosystem service of regulation (green arrow and the ES part of our conceptual framework, Fig. 2). In
 418 his non-chemical strategy, these ecosystem services are fully activated by the farmer, which is an
 419 example of farmer management systems rules for natural resources (orange arrow and the SES part of our
 420 conceptual framework, Fig 2). This carefully thought-out strategy requires a major redesign of cropping
 421 systems, introducing orphan species into traditional rotations. These orphan species include non-host
 422 or poor-host species (slowing down RKN cycles) or species capable of trapping nematode juveniles in
 423 their roots and impeding their reproduction (Boulestreau et al., 2022). However, such actions go far
 424 beyond the farm scale and require coordination with other managers of the agrifood system sharing a
 425 similar point of view (blue elements on Fig.2 and the STS part of our conceptual framework). For
 426 example, the farmer needs new equipment (specific sowing or harvesting machines for orphan
 427 species), that can be shared with other farmers in the territory through an agricultural equipment
 428 cooperative (known as a CUMA in French). The farmer also needs to find new commercial outlets in
 429 the territory (cooperatives and shippers) or beyond the territory (national distributors or industrial
 430 processors). However, this poses difficulties because these stakeholders have built their strategies on

431 economies of scale (focusing on specialised products or a few major vegetables) rather than economies
432 of scope (large range of vegetables). The farmer may therefore develop new relations with niche
433 stakeholders in the territory (e.g. an artisanal processor capable of processing limited volumes of an
434 orphan species) or at the national level (e.g. a trustworthy third party supporting the coordination
435 between farmers trying to diversify their crops and some distributors committed to conservation
436 agriculture and living soils).

437 Crop diversification therefore illustrates conflicting visions of the spatial and temporal arrangements
438 of crops. Crops developed to optimise pest control are not the most economically and commercially
439 efficient. Hence, it requires a redesign of both crop rotations at the farm level and the commercial
440 organisation of agrifood systems.

441 In this case, the STS part of our conceptual framework makes it possible to represent relationships with
442 stakeholders located outside the territory (blue oval). Moreover, new technical knowledge is required
443 to manage these orphan crops, that have to be developed by technical advisers in the territory and/or
444 by national R&D stakeholders. Finally, farmers have to deal with contradictory policies. Some national
445 and European policies ban most chemical nematicides to preserve ecosystems and human health, but
446 the support of biodiversity-based farming systems is insufficiently supported by public funds.

447

448 To summarise, our suggested analytical framework makes it possible to understand what is at stake in
449 fully achieving the target of pesticide reduction. Farmers have to manage some key elements of the
450 agricultural landscape (ES) that in return benefit the socio-ecosystem (SES) as a whole. The farmers
451 involved in such ecological transitions interact with all the stakeholders in socio-technical systems
452 (STS). Altogether, the three approaches make it possible to get a holistic understanding of relational
453 and spatial processes, highlighting current lock-ins and identifying how to overcome such barriers.

454

455 Conclusion

456 Aspirations to change the model of production and consumption of agricultural and food goods are
457 crystallising around the reduction of pesticide use. They are shared by various types of stakeholders
458 and are observable in a number of initiatives: innovative practices, changes in action plans and
459 programmes, renewal of public policy reference systems etc. Research is currently being developed
460 about coupled innovation that is capable of unlocking systems and enabling greater dissemination of
461 agroecological cropping systems (Boulestreau et al., 2022; Jacquet et al., 2022). They mark a real
462 paradigm shift that has been taken up in the literature. However, our analysis of the challenges of
463 reducing pesticide use in agriculture shows the importance of considering the relational and spatial
464 essence of the process. However, these intrinsically linked dimensions have currently received scant
465 joint investigations in the literature. We have therefore suggested a conceptual framework that
466 combines the three key frameworks of ES, SES and STS to describe and understand the dynamics at
467 work in agroecosystems. The integrative framework is intended to be multi-stakeholder and multi-

468 scale. This proposal needs to be further tested on case studies experiencing complex problems that
469 require a fine understanding of territorial dynamics. Nevertheless, our framework makes it possible to
470 formulate research questions that are slightly different to those produced by the work of ecology
471 scientists alone. Starting with the understanding of the ecological problem to be solved and the
472 characteristics of the agroecosystems, the first step is to identify the stakeholder networks that have
473 a specific impact on farmers' scope for change. Problem-solving paths are not given at the outset, as
474 each of these actors has unique representations and ways of doing things. Our conceptual framework
475 provides some keys to solving about the an environmental problem in a systemic, multi-level, multi-
476 actor way.

477 Moreover, by depicting the inter-relations between ES, SES and STS and the various scales
478 (agroecosystems, farms, landscapes, socio-technical systems), we assume that our conceptual
479 framework could help policy makers to improve their actions, or at least to better take into account
480 how human and natural components interact at territorial scales. In particular, the framework
481 highlights that farmers' capacities to reduce pesticide use through the diversification of farming
482 systems requires other stakeholders to adapt their strategies. And yet currently, most public policies
483 are sector-specific. A new approach would require the development of territorial and non-sectoral
484 environmental policies. More generally, currently huge amounts of money are dedicated to human
485 diseases caused by chemical pesticides. There is a big challenge for the future to build an
486 aggregated/trans-sectoral public policy that could reallocate these amounts repairing pesticide
487 damage to pay farmers for carrying out environmental practices for cropping without chemical
488 pesticides. Such a redesign based on reducing the ultimate impact of pesticides on citizens would go
489 far beyond the one needed when focusing only on reducing the amounts of pesticides used but we
490 advocate that pesticide reduction is a pragmatic first step towards a more holistic approach.

491 Such an ambition is likely to strengthen empirical evidence and to inform policy and practice decisions.
492 The proposal is currently being used for innovation design, fostering the ecologisation of agrifood
493 systems. This opens up new avenues of research for better scrutiny of agricultural innovation systems
494 (Gaitán-Cremachi et al., 2019; Klerkx and Bergemann, 2020; Pigford et al., 2018).

495

496

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