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

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Abstract

CONTEXT

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

OBJECTIVE

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

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

METHODS

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

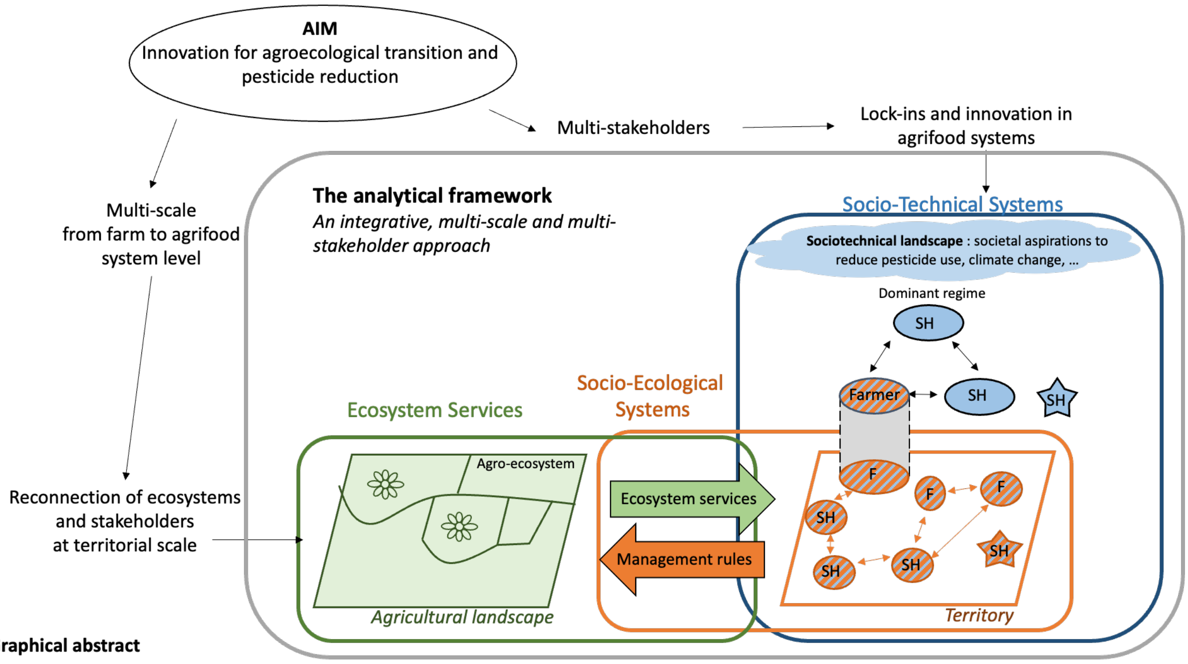
RESULTS AND CONCLUSIONS

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

SIGNIFICANCE

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

GRAPHICAL ABSTRACT



Graphical abstract

Key words

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

Highlights

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

Introduction

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

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

Our starting hypothesis is that the territory is the key scale for achieving a drastic reduction of pesticide use and unlocking agrifood systems. The definition of territory includes three dimensions (Le Berre, 1995): material or physical dimensions (plots, roads, rivers, storage facilities, etc.), organisational or relational dimensions (e.g. coordination between stakeholders along supply chains) and the institutional dimension. Institutions are a society's 'rules of the game' (North, 1990) that shape human behaviours and interactions. Institutions can be formal (political structure, constitutional rules, property rights, contracts, etc.) or informal (beliefs, norms, culture, etc.). These three dimensions allow a wide range of stakeholders to share the same concern (and to be involved in common actions) even if their individual strategies may compete and may be the expression of power relationships. Therefore, we postulate the relevance of the territorial scale for solving production problems in agrifood systems and designing desirable futures, especially for reducing pesticide use, which "embed contrasted visions of the future of agriculture, along with specific representations, values, imaginaries but also material cultures" (Goulet et al., 2023).

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

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

The analysis of agroecosystems and their dynamics can be conducted through a triple conceptual prism: (i) ecosystem services (ES), (ii) socio-ecological systems (SES) and (iii) socio-technical systems (STS) frameworks. They offer partial but complementary analyses for understanding the room for manoeuvre of stakeholders in developing innovative alternatives for pesticide reduction. A previous study (Ollivier et al., 2018) focused on the analysis of SES and STS, identified convergences but also some differences. With regard to the reduction of pesticide use, we suggest a reconnection of the three approaches to build a holistic analysis which jointly grasps ecological and social issues, as well as spatial scales, in order to understand stakeholder decision-making and scope for action. Indeed, there are still few operational frameworks to help stakeholders coordinate with each other, taking into account agroecosystem issues such as the management of cultivated diversity, temporality of crop cycles and specificity of products (orphan crops).

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

1. Outline of three existing theoretical frameworks relating to agroecosystems

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

1.1. Ecosystem services framework

The concept of ecosystem services (ES) deals with interactions between stakeholders and biological systems. It places an emphasis on the natural processes around which stakeholders coordinate for the sustainable management of a territory and stresses the importance of relinking society with ecosystem functioning. The term is commonly used to aggregate a set of positive effects associated with biodiversity and ecosystem functioning (e.g. pollination, climate regulation etc.). This concept, especially its use for monetary evaluation, has been widely debated and criticised. Its latest evolution (Nature's Contribution to People) tends to provide a better inclusion of a diversity of point of views around these benefits (Diaz et al. 2018). We stick to the historical term ES, which retains the advantage of being widely understood. The most consensual definition of ES dates back to the Millennium Ecosystem Assessment: "Ecosystem services are the benefits people obtain from ecosystems" (MEA, 2005). Human beings are explicitly mentioned in this definition, but they remain passive entities receiving the benefits of ecosystem functioning. It is only recently that research studies have started to look at how human beings may actively manage ecosystems to steer the production of ES (Birgé et al., 2016) or consider ES as a co-production of human beings and ecosystems (Fischer and Eastwood 2016). However, ecosystems have no clear spatial limits as ecological processes may occur at micro to global scales in a hierarchy of nested interacting levels of organisation (Allen et al., 2014). Therefore, in most cases farmers cannot be considered as the only managers of the ecosystem services they benefit from. Landscape structure is a key driver of biological dynamics in agrolandscapes (e.g. Martin et al. 2019) and ecosystem services flows rather depend on the interaction between landscape structure and local agricultural practices. This means that ecosystem services management depends on actions led by different stakeholders at scales beyond the farm scale (van Zanten et al., 2014). The pending question is then how to coordinate such a diversity of stakeholders around the management of landscape-driven ecosystem functioning.

1.2. Socio-ecological systems framework

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

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

Seminal works have documented the advantages of analysing the governance of SES (Bodin et al., 2016; Bodin, 2017; Bodin et al, 2017). One of the main arguments is the complex structure of SES. SES span geographical and temporal demarcations and therefore require cross-border and cross-scale collaborations among different stakeholders to efficiently address ecosystem sustainability. Indeed, the way stakeholders get involved in resource management by designing and implementing rules, and how and with whom they interact, impacts the capacity of SES to address environmental challenges.The SES framework analyses how social interactions produce effects on both the maintenance and durability of institutional arrangements (rules) and ecological systems despite external disturbances or shocks[1]. In fact, this framework underpins the resilience of SES (Folke, 2016). As explained earlier, the SES framework addresses coordination issues and promotes time- and place-specific solutions. It therefore requires a territorial approach.

1.3. Socio-technical systems framework

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

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

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

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

Radical agroecological innovations, rethinking the relationship between humans and ecosystems[2], have so far developed in the margins of the dominant socio-technical regime based on high levels of pesticide use. The application of he STS framework to agrifood systems analyses the evolution and perhaps even the overthrow of the dominant regime.. Such transition pathways may be impacted by shocks linked to human activities such as political events (Roberts and Geels, 2019), layers of power

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[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.

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

1.4. Farms at the crossroads of the three frameworks

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

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

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

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

2.1. Relational dynamics between stakeholders and ecosystems

There is a clear link between the ES and SES frameworks as they are based on a common object: ecosystems. The two frameworks take into account the interactions between humans and ecosystems. Both question the links between conservation and development issues and focus on the users of ecosystems. However, the entry point for the conceptual framework of ES is the identification of the ecosystem services and their beneficiaries. In contrast, the SES framework entry point are stakeholders who govern these ecosystems. In particular, the SES framework shows that the preservation of resources is consubstantial with the dynamics of the stakeholders who govern them.

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

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

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

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

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

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

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

2.2. – Spatial dynamics relating stakeholders and ecosystems

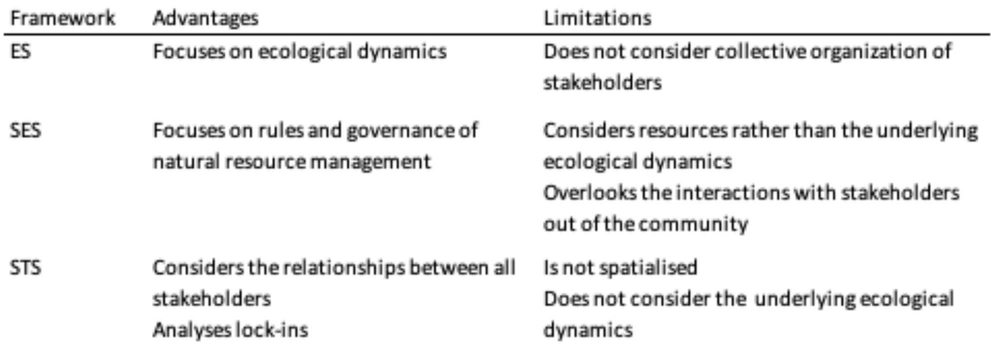
As indicated previously, stakeholders (users, managers, beneficiaries of the services provided by agroecosystems) are constrained by their relational choices: they develop strategic interactions, which means that their decision-making and action plans depend on each other. They are also constrained by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

The three frameworks presented above deal with spatial scales in different ways. ES and SES frameworks, which provide an integrated perspective on ecosystems, favour multi-spatial thinking. In the case of ES frameworks, three elements should be considered. First, the perimeter of the ecosystem is not necessarily clearly delimited. It depends on several nested scales depending on the organisms under consideration. Managing processes involving both infra- and supra-farm scales requires coordination among stakeholders. Second, ecosystem services are dynamic and uncertain. As a human activity, the production and dissemination of ecosystem services are the results of intentional actions that link stakeholders (e.g. service providers and beneficiaries) who are territorially embedded. In this sense, ecosystem services contain a spatial dimension and entail cross-scale relationship dynamics. These relationships are embedded in specific territories, but also emerge from different places and at different spatial scales. Finally, ES frameworks combine global changes with local trends. Anthropogenic pressures can be simultaneously observed at large and local spatial scales.

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

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

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

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

3. A framework that combines stakeholder coordination and territorialities of action

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

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

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

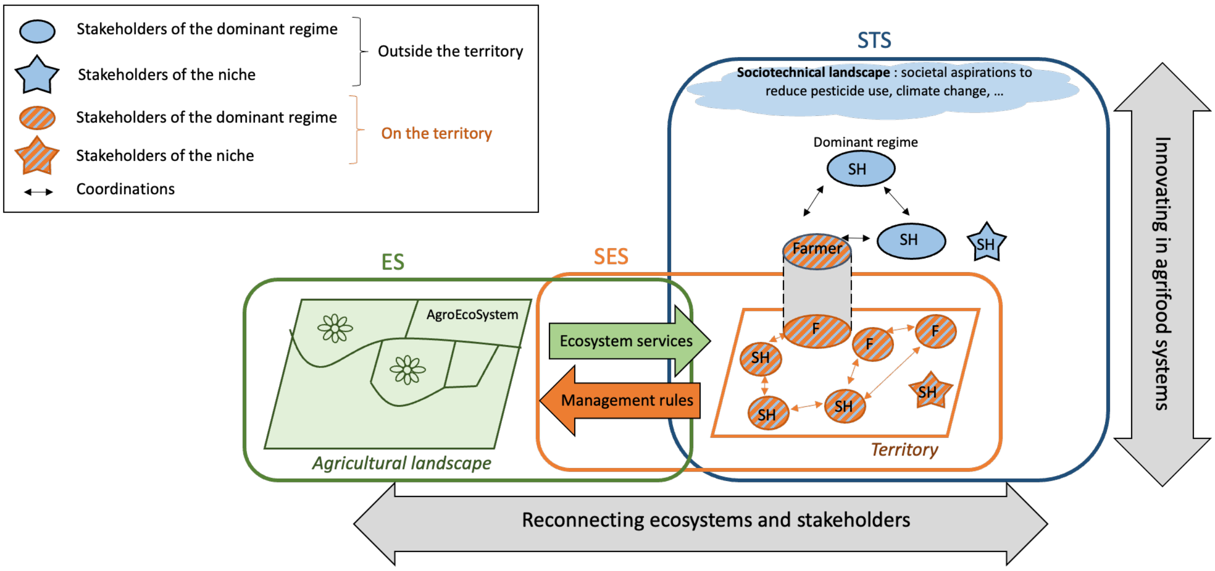


Fig 1. Schematic representation of how the different conceptual frameworks combine together to give a holistic representation of natural resource management.

F stands for farmers and SH for stakeholders.

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

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

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

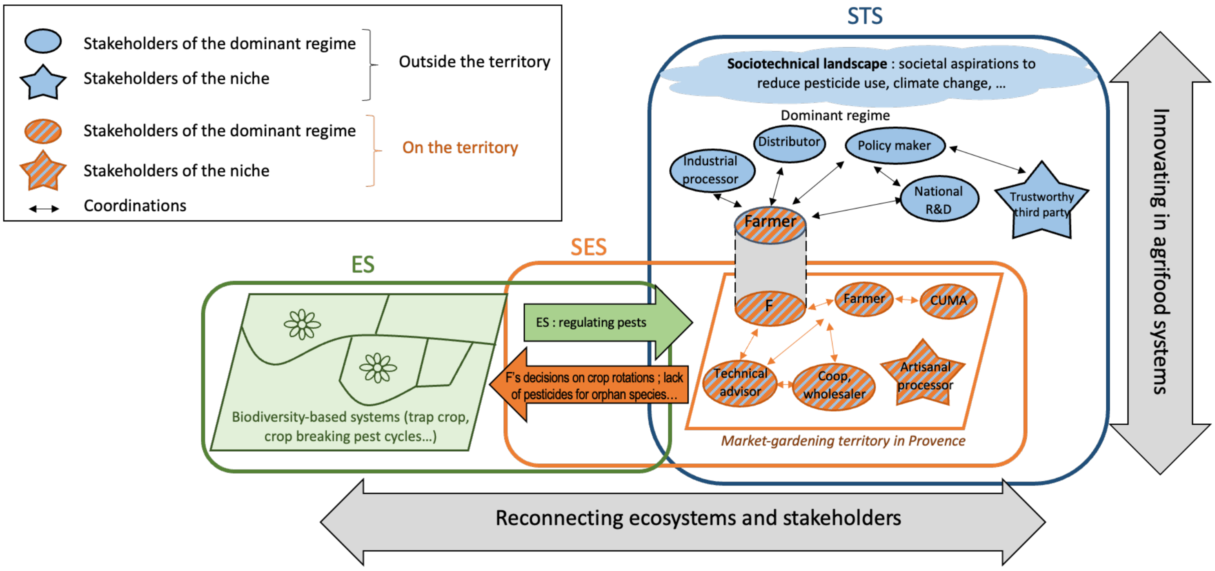


Fig 2. Implementation of the analytical framework in a case study: soil-borne pest control enabled by crop diversification in market gardening in Provence, South-East France

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

Here we are considering the case of a farmer seeking to shift to a non-chemical strategy based on the ecosystem service of regulation (green arrow and the ES part of our conceptual framework, Fig. 2). In his non-chemical strategy, these ecosystem services are fully activated by the farmer, which is an example of farmer management rules for natural resources (orange arrow and the SES part of our conceptual framework, Fig 2). This carefully thought-out strategy requires a major redesign of cropping systems, introducing orphan species into traditional rotations. These orphan species include non-host or poor-host species (slowing down RKN cycles) or species capable of trapping nematode juveniles in their roots and impeding their reproduction (Boulestreau et al., 2022). However, such actions go far beyond the farm scale and require coordination with other managers of the agrifood system sharing a similar point of view (blue elements on Fig.2 and the STS part of our conceptual framework). For example, the farmer needs new equipment (specific sowing or harvesting machines for orphan species), that can be shared with other farmers in the territory through an agricultural equipment cooperative (known as a CUMA in French). The farmer also needs to find new commercial outlets in the territory (cooperatives and shippers) or beyond the territory (national distributors or industrial processors). However, this poses difficulties because these stakeholders have built their strategies on economies of scale (focusing on specialised products or a few major vegetables) rather than economies of scope (large range of vegetables). The farmer may therefore develop new relations with niche stakeholders in the territory (e.g. an artisanal processor capable of processing limited volumes of an orphan species) or at the national level (e.g. a trustworthy third party supporting the coordination between farmers trying to diversify their crops and some distributors committed to conservation agriculture and living soils).

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

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

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

Conclusion

Aspirations to change the model of production and consumption of agricultural and food goods are crystallising around the reduction of pesticide use. They are shared by various types of stakeholders and are observable in a number of initiatives: innovative practices, changes in action plans and programmes, renewal of public policy reference systems etc. Research is currently being developed about coupled innovation that is capable of unlocking systems and enabling greater dissemination of agroecological cropping systems (Boulestreau et al., 2022; Jacquet et al., 2022). They mark a real paradigm shift that has been taken up in the literature. However, our analysis of the challenges of reducing pesticide use in agriculture shows the importance of considering the relational and spatial essence of the process. However, these intrinsically linked dimensions have currently received scant joint investigations in the literature. We have therefore suggested a conceptual framework that combines the three key frameworks of ES, SES and STS to describe and understand the dynamics at work in agroecosystems. The integrative framework is intended to be multi-stakeholder and multi-scale. This proposal needs to be further tested on case studies experiencing complex problems that require a fine understanding of territorial dynamics. Nevertheless, our framework makes it possible to formulate research questions that are slightly different to those produced by the work of ecology scientists alone. Starting with the understanding of the ecological problem to be solved and the characteristics of the agroecosystems, the first step is to identify the stakeholder networks that have a specific impact on farmers' scope for change. Problem-solving paths are not given at the outset, as each of these actors has unique representations and ways of doing things. Our conceptual framework provides some keys to solving about the an environmental problem in a systemic, multi-level, multi-actor way.

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

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

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