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A social–ecological approach to managing multiple agro-ecosystem services

Françoise Lescourret[1,*], Danièle Magda[2,*], Guy Richard[3], Anne-Françoise Adam-Blondon[4], Marion Bardy[5], Jacques Baudry[6], Isabelle Doussan[7], Bertrand Dumont[8], François Lefèvre[9], Isabelle Litrico[10], Roger Martin-Clouaire[11], Bernard Montuelle[12], Sylvain Pellerin[13], Manuel Plantegenest[14], Elise Tancoigne[15], Alban Thomas[16], Hervé Guyomard[17] and Jean-François Soussana[17]

The sustainability of agro-ecosystems depends on their ability to deliver an entire package of multiple ecosystem services, rather than provisioning services alone. New social and ecological dimensions of agricultural management must be explored in agricultural landscapes, to foster this ability. We propose a social–ecological framework for the service-based management of agro-ecosystems, specified through an explicit and symmetric representation of the ecosystem and the social system, and the dynamic links between them. It highlights how management practices, with their multiple effects, could drive the provision of multiple services. Based on this framework, we have identified the design of collective multiservice management as a key research issue. It requires innovations in stakeholder organizations and tools to foster synergy between ecosystem functioning and social dynamics, given the complexity and uncertainties of ecological systems.

Addresses
[1] INRA, UR1115 PSH, Domaine Saint-Paul, Site Agroparc, F-84914 Avignon Cedex 9, France
[2] INRA, UMR1248 Agir, BP 52627, F-31326 Castanet Tolosan Cedex, France
[3] INRA, UAR1155 Département Environnement et Agronomie, Centre de Recherche Val de Loire, 2163 avenue de la Pomme de Pin, CS 40001, Ardon, F-45075 Orléans Cedex 2, France
[4] INRA, UR1164 URGI, Route de Saint-Cyr, F-78026 Versailles Cedex, France
[5] INRA, US1106 InfoSol, F-45075 Orléans, France
[6] INRA, UR0980 SAD-Paysage, CS84215, F-35042 Rennes Cedex, France
[7] INRA, USC1365 CREDECO-GREDEG, 250 Avenue Albert Einstein, F-06560 Valbonne, France
[8] INRA, UMR1213 Herbivores, Theix, F-63122 Saint-Genès-Champanelle, France
[9] INRA, UR0629 Ecologie des Forêts Méditerranéennes, Domaine Saint Paul, Site Agroparc, F-84914 Avignon Cedex 9, France
[10] INRA, UR0004 P3F, RD 150 Le Chêne BP 80006, F-86600 Lusignan, France
[11] INRA, UR0875 MIAT, 24 Chemin de Borde-Rouge, Auzeville CS 5627, F-31326 Castanet-Tolosan Cedex, France
[12] INRA, Université de Savoie, UMR0042 CARRTEL, F-74203 Thonon, France
[13] INRA, UMR1391 ISPA, CS 20032, F-33883 Villenave d'Ornon, France
[14] INRA, UMR1349 IGEPP, Domaine de la Motte au Vicomte, BP 35327, F-35653 Le Rheu Cedex, France
[15] INRA, UAR1155 Département Environnement et Agronomie, Domaine Saint-Paul, Site Agroparc, F-84914 Avignon Cedex 9, France
[16] INRA, AgroCampus Ouest, UAR0519 Département Sciences Sociales, Agriculture et alimentation, Espace et Environnement, 4 allée Adolphe Bobière, CS 61103 F-35011 Rennes Cedex, France
[17] INRA, UAR0233 CODIR, 147 rue de l'Université, F-75338 Paris Cedex 07, France

Corresponding author: Lescourret, Françoise (francoise.lescourret@avignon.inra.fr)
[*] Co-first authors.

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Introduction

If we include forestry and inland aquatic systems, agricultural systems cover about 40% of the continental surface of the Earth. The sustainability of these productive systems requires the integration of an ecological dimension. Approaches involving the management of ecosystem services (ES) appear to be a powerful way of developing sustainable agricultural systems. They also add meaning to the concept of 'agro-ecosystems'. However, using the ES concept is a major challenge, as it introduces new ecological and social dimensions into the design and management of agricultural systems.

Agricultural systems must do much more than simply deliver provisioning services. They must also provide a web of supporting and regulating services, such as soil fertility, pest control and pollination [1,2]. In ES-based management, farmers must consider to a much larger extent than they ever have before, the effects of management practices on complex biophysical systems. Simultaneous ES management is challenging, because of the multiple positive (synergies), negative (tradeoffs) and non-linear relationships between services and the multiple levels at which management can be applied. Management greatly affect the synergies and tradeoffs between services and the strength of the relationships between them, in agro-ecosystems [3••]. The effect of crop protection on the apparent relationship between crop yield and natural pest control (two functionally linked services) depends on whether natural pest control is favored (in which case, the relationship is positive) or heavy use is made of nonspecific pesticides with adverse effects not only on pests, but also on their enemies (resulting in a negative relationship). Furthermore, agricultural practices acting on two services that are not functionally linked may create apparent relationships between these services. For example, fertilizer use increases crop yield but decreases water quality, creating a negative correlation between these services [3••].

Use of the ES concept may also strengthen and modify the social interactions through which farmers develop their activities. Agricultural management plays a key role in the delivery of ES [4••,5], but farmers are only one group of stakeholders producing or benefiting from ES. Different stakeholders may have different perceptions of services, as exemplified by the work of Hauck *et al.* [6]. Hauck *et al.* showed that the relationship between timber production and other ES was perceived as negative by some stakeholders (from the nature conservation and forestry sector), but synergic by others (from the agriculture sector). By considering ES, new social interactions can be established, resulting in new management choices modifying the value of services and the relationships between them.

A more integrated assessment of ecological and social issues is therefore required when developing sustainable agricultural systems based on ES management. Agro-ecosystem services have been increasingly studied recently, but with a focus on biotechnical aspects and single services. Most studies of multiple services published to date have been based on mapping and scenario analyses at the regional level, using land use/land cover indices, and including the agro-ecosystem categories, such as forests or orchards, as proxies [7,8]. Other studies have compared broad classes of agricultural systems, such as organic and conventional systems, over a narrower range of services, generally focusing on pest control [9]. Many studies have considered the relationship between specific agricultural practices, such as crop rotation or irrigation, and ES. However, most dealt with single services, rather than with bundles of services [10]. The rare exceptions include an examination of tradeoffs between several services in row-crop agriculture, along a gradient of cropping system intensification [11•]. Most approaches to social interactions between stakeholders with different perceptions of services and their interactions due to differences in interest and knowledge [12] have not involved ecological or agronomic approaches.

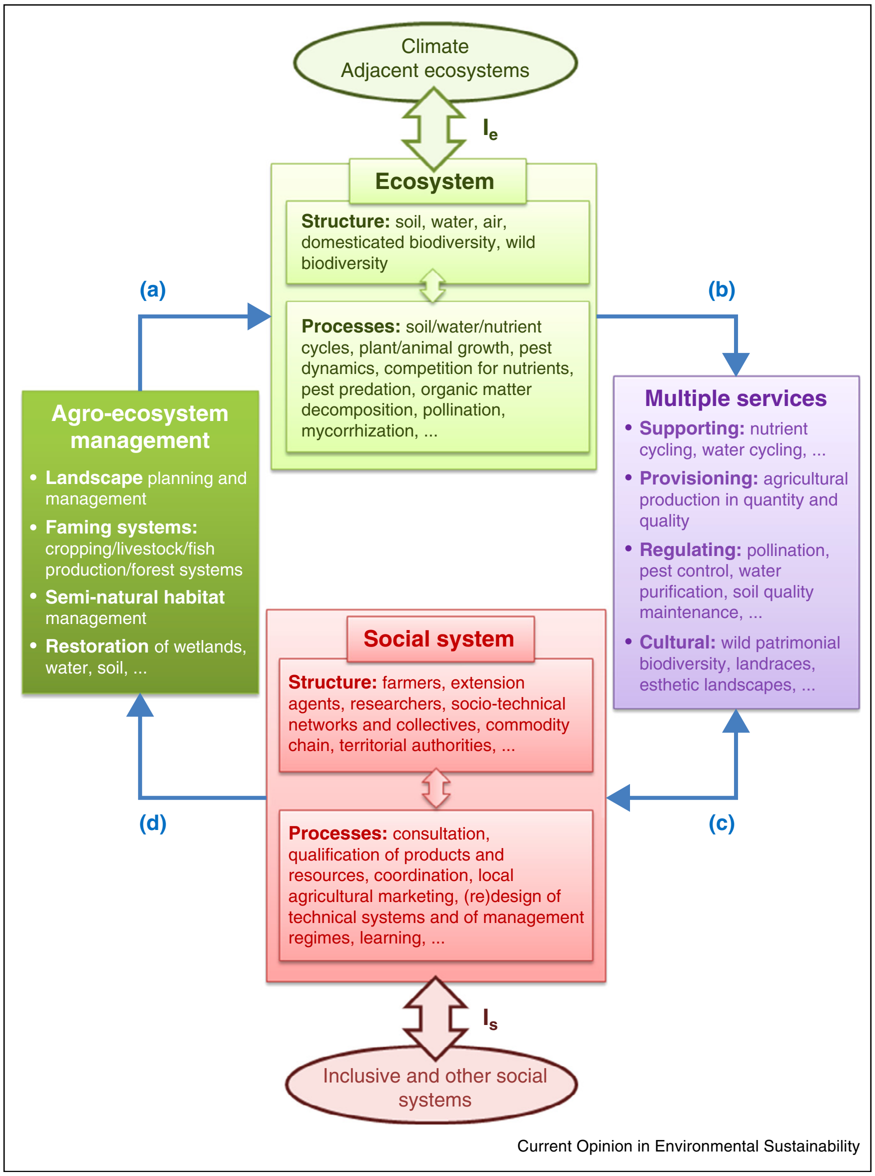
Implementing multiservice management in agricultural systems requires a conceptual framework exploring social and ecological interactions. We used existing social–ecological views to develop an agro-ecosystem-specific scheme with dynamic connections between social and ecological systems. We use this framework to discuss the essential issues that must be addressed by the research community to foster the collective management of multiple agro-ecosystem services.

The need for an integrated social–ecological framework for agro-ecosystems

We propose a social–ecological conceptual framework (CF) addressing the issue of multiservice management in agro-ecosystems in Figure 1. This CF is consistent with previous frameworks consisting of a social system and an ecosystem connected by multiple ES [13–16], including the CF of the recent Intergovernmental Platform on Biodiversity and Ecosystem Services (IBPES) [17••]. ES are thus seen as an output of the ecosystem used and transformed by the social system. However, our CF differs from its predecessors in several ways. First, it targets the agro-ecosystem, highlighting its specific features in terms of both the ecosystem and the social system. Second, it aims to identify the challenges involved in using farming practices to manage multiple services. This approach restricts the CF to the levels of organization of this management. It also requires symmetric representations of the ecosystem and the social system, to clarify the links between them. We used the same template to depict the ecosystem and the social system, and their interconnected structural and functional components. This concern for symmetry responds to the criticism of Binder *et al.* [18••] in their comparative analysis of social–ecological CF. These authors found that social and ecological components were rarely treated equally profoundly and that there was not always reciprocity between the two systems. These aspects limit the implementation of multiservice management.

The structural components of the ecosystem are its physical, geochemical (soil, water, air) and biological compartments. The biological compartment includes both domesticated and wild biodiversity. The functional components are biophysical processes (soil, water and nutrient cycles) and biological processes, involving individuals and populations, and extending to metacommunity dynamics. The structural component of the social system takes into account the diversity of individual stakeholders (e.g. farmers, foresters), organizations and

Figure 1



Agro-ecosystem management for the delivery of multiple services on the basis of dynamic interplay between the ecosystem and the social system. The conceptual framework of the figure applies to the agricultural territory. In the 'Ecosystem' and 'Social system' boxes, the broad arrows represent the interplay of structure and processes. In the structural part of the 'Social system', sociotechnical networks and collectives include cooperatives, farmers' associations, consumer groups, and environmental associations. In the processes of the same box, 'consultation' denotes consultation between farmers, environmentalists, and other stakeholders in the territory. 'Qualification' refers to product certification or the valorization of resources, such as local breeds or varieties, through collective initiatives by farmers. 'Coordination' targets biodiversity or pest management, landscape planning or agro-ecosystem restoration (in the 'Agro-ecosystem management' box). Arrows I_e and I_s and a to d are described in the main text. The text in the boxes is illustrative, not exhaustive.

institutions, making it possible to consider the diversity of the beneficiaries of the bundle of interacting services [16]. The functional component corresponds to diverse socio-economic processes (see Figure 1 for examples). In these respects, our CF more closely resembles that of Collins *et al.* [14] than those of Reyers *et al.* [16] and Diaz *et al.* [17••], who broke the social system down to highlight particularly important dimensions, such as human wellbeing or institutions. However, Collins *et al.* [14] did not include such structural and functional elements in their CF. Instead, they presented two categories, 'human behavior' and 'human outcomes'.

The other key element of this management-orientated CF is its 'Agro-ecosystem management' box, an outcome of the social system. Management targets — the landscape, farming systems, semi-natural habitats, and natural resources — are highlighted in this box. This box is not the only outcome of the social system, but management is highlighted here because it can drive ecosystem functioning directly. This representation of agro-ecosystem management provides much stronger specifications than previous CFs, which consider management globally, over a wide range of scales. Previous CFs have used a general terminology for management. For example, the IPBES CF uses terms such as 'Anthropogenic assets', 'Governance' and 'Anthropogenic drivers' [17••].

A focus on agro-ecosystem management defines the perimeter of the CF as the agricultural territory, within which individual and collective management actions are organized and implemented. The CF can be scaled within this perimeter, from very local (e.g. the farm plot) to regional scales (e.g. the water basin). Under these conditions, the ecosystem interacts with adjacent ecosystems, because there are spatial flows of energy, materials and organisms across ecosystem boundaries. It is also influenced by climate patterns and extreme events. Similarly, the social system interacts with other social systems and inclusive social systems, such as states, federations of nation-states or international bodies (e.g. intergovernmental organizations, multinational companies) through public policies, regulations, or global marketing, for example. More generally, the social–ecological system of the territory is embedded in a series of nested social–ecological systems, in accordance with the multilevel nature of ES stewardship [17••,19–21]. This series includes reciprocal relationships between upper and lower levels and interactions between adjacent systems, as predicted by hierarchy theory [22]. However, it also includes relationships crossing hierarchical levels, such as the direct influence of national agri-environmental measures on local farming systems.

The CF is dynamic, with successive loops. Ecosystem structure and processes interact, under the direct influence of management (Arrow a), to provide multiple ES (Arrow b). The social system makes use of service metrics, various perceptions and multiple value systems to evaluate ES (Arrow c from the 'Social system' box to the 'Multiple services' box). These value systems underlie the benefits of ES to stakeholders and they may conflict [17••]. A network of interacting and iterative social processes can be used to define ES objectives (Arrow c from the 'Multiple services' box to the 'Social system' box) and to identify series of management actions for achieving these objectives (Arrow d). Among these processes, consultation and coordination should minimize the conflict between the values of different stakeholders. These processes require a scientific knowledge of synergies and tradeoffs between services.

Finally, agro-ecosystem management, at the core of the CF shown in Figure 1, has multiple effects, consistent with the multiple-service concept. For example, sowing mixtures of plants directly modifies the structure of the biological compartment (domesticated biodiversity, Figure 1a), with multiple, cascading effects. These effects concern other structural compartments (soil), and various processes, such as competition for light, water or nutrients, and the dynamics of pests and diseases, through changes to the functioning and architecture of food webs and ecological networks [23,24]. These effects may generate synergy between provisioning and supporting or regulating services. Schipanski *et al.* [25] carried out an experimental study on a three-year soybean–wheat–corn rotation with and without cover crops. They estimated that cover crops could increase the value of eight of the 11 ES studied (including erosion control, soil carbon storage, and NO_3 retention), with no negative impact on crop yield. Kragt and Robertson [26] simulated technical strategies in a biophysical farm-systems model. They showed that increasing the retention of crop residues in Australian mixed crop-livestock farming would both increase production and improve the provision of several ES: groundcover, soil carbon and nitrogen supply. The CF shown in Figure 1 addresses the consequences of a particular intervention for the total bundle of ES. Very few CF have dealt with this issue [16].

We present a re-analysis of two case studies with this CF in Box 1 and Box 2.

New stakeholder organizations and instruments of coordination are required for the implementation of multiservice management in agricultural territories

The CF raises many key research issues. We focus here on two issues relating to the collective dimension of management in an agricultural territory, the target level of the CF. Collective management is the key to achieving acceptable tradeoffs between multiple ES, because it both minimizes value conflicts between stakeholders and operates on an ecological landscape, the level decisive for service provision and relationships [35]. It raises questions about the most effective structures and processes in the social system (Figure 1). New organizations promoting long-term coordinated, collective action are required, together with new instruments facilitating coordination and innovation processes. We need to determine what knowledge is required for ecological dynamics and the effect of management practices, and the form of that knowledge. We also need to work out how to deal with the complexity and uncertainties of the ecological systems to be managed.

In agricultural territories, farmers and other stakeholders are involved in agricultural organizations (cooperatives,

Box 1 Certification processes in the coffee value chain in Central America as a means of fostering the provision of ES through agricultural management.

Product certification is one of the most promising instruments for fostering the provision of ES through agricultural management. The review by Soto and Le Coq [27] of the development of the certified coffee market in Central America provides an illustrative example.

The organic and Fair Trade labels were first developed in the early 1990s, and other labels, such as Rainforest Alliance, Starbucks CAFE practices and Utz Certified, were created in the late 1990s. Some of these labels were established through consultation with organic farmers and consumer groups ('Social system' box). The coffee crisis of the 1990s gave a new impetus to all coffee certification systems, due to the higher prices and lower perceived risk (Arrow I_s). The standards developed aim to achieve a balance between the provision of multiple ES ('Multiple services' box) and farmers' access and profitability; this corresponds to the perception of consumers (Arrow c). However, this balance is variable. Some labels, such as CAFE practices, focus on coffee quality, both a service and a means of increasing producer revenues, whereas others, such as Rainforest Alliance, focus on so-called 'environmental services', such as protecting endangered species and habitat provision. Technical support design ('Social system' box) differs between these standards, from limited use of scientific data relating to ES in the initial versions of the organic standards, to a sound scientific basis. The Smithsonian Bird Friendly certification scheme was initially developed to provide a high-quality habitat for neotropical migratory birds. It was based on published research data on this topic. Given the multifunctional role of shade trees in tropical agroforestry landscapes [28], shade structure and management are key components of the cropping systems implemented (Arrow d and 'Agro-ecosystem management' box). Very specific standards, such as Smithsonian Bird Friendly certification, define the density and height of shade trees and a minimum shade percentage. Some standards, such as the Rainforest Alliance, were adapted to local biophysical and socio-economic conditions through consulting processes involving farmers, cooperative technicians, extension agents and the academic sector ('Social system' box). Local relays are involved in compliance control systems for certification, reducing costs by overcoming the need for international inspectors or governmental certification agencies. Collective certification for small producer groups has also been developed, with local inspectors and agencies ('Social system' box).

Studies of ES provision on certified coffee farms have shown positive impacts of organic, Smithsonian Bird Friendly and Rainforest Alliance certification (Arrows a and b). Biodiversity and the abundance of natural enemies of pests ('Ecosystem' box) used as indicators of pest control (in 'Multiple services' box), were greater on certified coffee farms than on conventional farms. The certified farms generally had a more diverse ecosystem, with more complex shade structures. Water conservation ('Multiple services' box) was improved by Rainforest Alliance certification. Several indicators of soil biological and chemical components and functions, such as organic matter, microbial biomass, earthworms and mycorrhizae, together with P, Ca and K contents ('Ecosystem' box), suggested that soil quality ('Multiple services' box) was better on organic than on conventional farms. Coffee productivity ('Multiple services' box) was lower on organic farms. More comparative studies are required, with greater harmonization between studies. To this end, the ISEAL alliance has proposed a code of good practice (http://www.isealalliance.org/our-work/defining-credibility/codes-of-good-practice/impacts-code; Arrow c—new loop in the CF).

The certification processes in the coffee value chain in Central America seem to be promoting the provision of ES through the agricultural management of coffee systems. However, there is still room for improvement (new loops in the CF), by reducing the cost of compliance control structures and increasing the remuneration of producers, to distribute the 'premium' more widely along the commodity chain (process in the 'Social system' box). Better technical knowledge is required to improve the provision of ES, including crop productivity (especially for organic farms). Furthermore, the processes focus on the farm scale and the management of shade, which is operational at this scale. However, we will need to focus on landscape planning and management ('Agro-ecosystem management' box) and encourage coordination between multiple actors within a landscape ('Social system' box), to take advantage of the effects of landscape structure and processes on biodiversity and the provision of ES in these tropical agroforestry systems [29].

networks, supply chains, among others) and resource management bodies (regional nature parks, biodiversity conservation associations, among others). These organizations have proved effective for coordinating management to achieve a particular target. For example, farmers' organizations have been involved in developing area-wide pest management, demonstrating that the regional coordination of integrated pest management actions can enhance pest management area-wide, for longer periods than would be possible with an uncoordinated field-by-field approach [36]. Another example is provided by cooperation for wildfire risk management, which involves various organizations, including local collaborative groups funded by programs for reducing hazardous fuel use and restoring the ecosystem in forested areas of the USA [37]. However, few studies have demonstrated successful territorial coordination for the management of multiple ES. This raises questions about whether the existing organizations have the 'right' configuration for this form of management. For example, reconnecting the C and N cycles by integrating livestock and cropping systems would increase synergy between food production and various ES [38,39]. It remains unclear which type of organization would be most likely to encourage local interactions between specialist farms for this purpose. However, recent management science studies have shown the collective design of innovative management strategies by a wide range of stakeholders in an agricultural territory to be possible (example in Box 2).

Most of the methods developed to date to facilitate the coordinated management of shared resources or ecological systems have used models and/or scenarios to highlight and guide management choices, in participatory approaches. Such methods have proved effective, as reported for participatory agent-based modeling processes for resolving conflicts relating to forest management between villagers, foresters and park rangers [40]. These methods are particularly relevant when dealing with asymmetries between stakeholders in power, knowledge and the relative status of producers and beneficiaries of ES [41•]. However, they are not entirely relevant for these stakeholders, as they provide insufficient insight into the function of the ecosystem for the development of learning

Box 2 Planned collective design for the management of ES in a territory of high environmental value in the cereal-growing area south east of Niort (France).

In this cereal-growing area, two groups of stakeholders ('Social system' box) came together in 2010 for a management project aiming to reconcile agricultural production and biodiversity (Arrow c): ecologists working to protect the birds of the area, such as the little bustard, and a small agricultural cooperative wishing to support cereal production and a return to livestock production, whilst respecting biodiversity and protecting water quality. Both groups were aware of the limitations of agri-environmental schemes (Arrow I_s), which had decreased the impact of agriculture on biodiversity [30], but were based on short-term individual contracts not very compatible with the ecological scales operating within a territory [31]. They therefore tried to develop other strategies. The ecologists suggested the introduction of alfalfa into crop rotations, to create favorable habitats for insects (including the crickets eaten by the little bustard, in particular), together with refuge zones for birds (Arrow d and 'Agro-ecosystem management' box) [32].

The cooperative rapidly took up the idea of developing alfalfa use to diversify crop rotation, to create exchanges between cereal producers and livestock farmers, and to contribute to various ES ('Multiple services' box) by limiting the erosion of the most fragile soils through greater water retention or lower levels of nitrogen fertilizer use (Arrow c). Given the multiple benefits of alfalfa, and to reconcile the divergent views of the stakeholders, the project leaders initiated a collective design approach supervised by management science researchers. Two water companies, agronomists, extension agents and diverse local government representatives joined the project. The researchers shared their knowledge on alfalfa with the other stakeholders during a collective design workshop ('Social System' box).

This workshop explored the bundles of services potentially produced for each of the possible configurations of the agro-ecosystem ('Multiple services' box). Alfalfa was thus considered as an element of the landscape infrastructure beneficial for bundles of services. The various stakeholders were able to identify intermediate pathways, between the intensive management of alfalfa, which was detrimental to biodiversity, and management systems significantly decreasing production [33]. For example, reasonable levels of production can be achieved by mowing at appropriate dates to control weeds thereby limiting pesticide use and protecting insects. This exploration revealed the importance of the parameters of collective management, including the coordination of mowing dates and the concentration of plots around reservoirs or in zones in which soils are susceptible to leaching, to improve water quality (Arrow d).

Following the design workshop, the project leaders set up a research-action project funded by local authorities, to facilitate the establishment of an alfalfa sector through scientific knowledge generation ('Social System' box). In 2014, 150 ha of alfalfa were planted, for forage or seed production. The cooperative decided not to increase the area under alfalfa too rapidly and not to impose plot location constraints on farmers, despite the ecologists' recommendations based on metapopulation models for crickets. According to the cooperative, there is a need to identify suitable markets for this sector and ways of dealing with climatic events likely to decrease yields, and the difficulties of achieving consistent forage quality (new loops in the CF).

Unanswered questions remain about how to maintain this design process in the long term and the nature of the modes of governance required (new loops in the CF). However, this example shows that, in situations in which collective design is required but the stakeholders are initially in conflict, collective innovation and cooperation should be promoted. The experimental method used here aimed to ensure the use of the information provided by the stakeholders to explore previously unimagined but desirable pathways in a collaborative manner, rather than addressing the constraints imposed by different stakeholders individually and negotiating on the basis of supposedly known values [34].

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processes and skills for managing ES in the long term, in different situations. We need to develop practical instruments combining scientific knowledge about potential synergies and tradeoffs between ES with the objectives, perceptions, values and management skills of stakeholders. No models of multiple agro-ecosystem services explicitly including management option effects are available [42]. Considerable progress in visualizing and graphically representing observed and modeled data is also required, these aspects being particularly important at the interface between science and policy-making. Improvements will be particularly crucial for visualizing uncertainty and decreasing the dimensionality of information displays [43]. Furthermore, tradeoff analyses have generally been exploratory, using graphics and multivariate analyses, as exemplified by Raudsepp-Hearne *et al.* [8] and Lavorel *et al.* [44]. Complementary multi-objective evaluation and optimization methods should be more widely used. These methods are particularly useful for designing management options in the context of agro-ecosystem services [45,46•,47]. Finally, we need to determine how these practical instruments could be used within stakeholder groups in agricultural areas (farmers, foresters, local companies, local environmental associations, basin agencies, among others) to foster cooperation in management strategy design and implementation.

Conclusions

ES-based management is a promising way of ensuring the sustainability of agricultural systems. It is particularly challenging, because of the multiple relationships between services, the major impact of agricultural management on these links and the diversity of the actors involved. Appropriate dynamic social–ecological approaches could shed light on ways of achieving agro-ecosystem service-based management. The research community must carry out two essential tasks to facilitate the implementation of ES-based agro-ecosystem management in agricultural territories. First, it must design new stakeholder organizations for coordinated management planning. Second, it must identify and build practical instruments for use in participatory approaches by these groups. These instruments must make it possible to share, visualize and use for diagnostic and prospective studies, both the perceptions of the various stakeholders and the available scientific ecological knowledge, to foster synergy between ecosystem functioning and social dynamics.

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