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COMMENTARY

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Applying ecological knowledge to the innovative design of sustainable agroecosystems

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Abstract

1. The design of sustainable agroecosystems is crucial to meet contemporary environmental challenges such as biodiversity loss and global change. Ecological knowledge, although expected to be an important component of such an endeavour, is to date mainly used under a problem-solving paradigm.
2. Applying recent design theories, which highlight the differences between innovative design and problem solving, we assess the potential of using ecological knowledge in agroecosystem design in three contrasted French case studies representative of agricultural intensification world-wide.
3. In all cases, a design approach generated unexplored agroecosystem configurations and management alternatives. This analysis highlights that ecological science is critical for designing sustainable social-ecological systems, because it orients the design process by identifying key ecological properties to maintain, while opening the range of management options stakeholders can explore.
4. *Synthesis and applications*. Participatory design approaches of agroecosystems based on ecological knowledge might be key for planning and change: they allow a diversity of stakeholders to contribute to building solutions, thereby strengthening their sense of ownership and responsibility. Infrastructures in support of participatory design processes, set up in close relation to ecological research centres, have the potential to become new cornerstones of innovation for sustainable social-ecological systems.

KEYWORDS
agroecosystem sustainability, biodiversity management, decision making, design theory, grassland, innovative design, landscape design, social-ecological systems

1 | INTRODUCTION

Agriculture, occupying about 38% of Earth's terrestrial surface, is the largest land use (Foley et al., 2011). Intensive agroecosystems are primarily designed and managed for production of agricultural goods. Ecological processes such as trophic regulations are often overlooked, although they are crucial to both functioning ecosystems and farming. As agriculture increases its pressure on ecosystems through intensification and land consumption, causing important biodiversity loss (MEA, 2005), designing sustainable agroecosystems needs to rely increasingly on ecological knowledge (Lovell & Johnston, 2009; Nassauer & Opdam, 2008).

Until recently, the contribution of ecology to the design of intensively managed social-ecological systems (SES) was limited. Landscape designers and planners were not necessarily educated in ecology (Lovell & Johnston, 2009; Steiner, Simmons, Gallagher, Ranganathan, & Robertson, 2013). They often considered ecological approaches and concepts difficult to implement (Grose, 2014; Steiner et al., 2013). Ecologists, for their part, traditionally studied natural and protected areas rather than human-influenced ecosystems (Martin, Blossey, & Ellis, 2012), and worked within an analytical framework rather than a design framework. The development of applied ecology, as well as the increasing involvement of ecologists in human-dominated landscapes, have significantly fostered the reconciliation between design and ecology (Lovell & Johnston, 2009; Ross, Bernhardt, Doyle, & Heffernan, 2015). Applying ecology to the design of SES also implies its articulation with other types of knowledge, raising ontological, epistemological, and application challenges (Raymond et al., 2010). Adaptive governance or community-based natural resource management are examples of approaches developed to overcome these challenges.

Design theories may shed a new light on the contribution of ecology to SES design. All the approaches presented above are embedded in a decision paradigm. In a decision paradigm, objectives and selection criteria are defined at the outset; the aim is to choose the best option(s) among known solutions according to specific criteria (see Figure 1). Innovative design differs from decision in that it generates alternatives beyond an existing set of solutions. In addition, objectives and selection criteria can be revised during the process and degrees of freedom are maintained as long as possible (Hatchuel, 2002). Decision is often more suitable when objectives can be set at the beginning of management and when stakeholders' interests are not conflicting. Innovative design may be more relevant in situations where existing solutions have failed, conflicts between stakeholders emerge, or clear objectives are difficult to set in advance. Thus, in a context of global change, innovative design seems more appropriate than decision to provide flexibility and open the range of alternatives to agroecosystem managers.

According to one of the most recent design theories, the *Concept-Knowledge theory* (Hatchuel & Weil, 2009), a design process starts with a *concept*, a proposal that is partly unknown but imaginable. The *concept* is considered "non-observable" in that one does not know whether it exists, but it is "desirable" due to at least one desirable property. The objective of the design process is to generate at least one object with the desirable property. From this perspective, the application of ecology to agroecosystem design requires that ecologists identify a *concept* specified by a desirable property. Berthet, Segrestin, and Hickey (2016) identify such a *concept* as an *ecological fund* and suggest that it is specified by a *key ecological property* to be maintained to ensure the environmental sustainability of the agroecosystem. We apply this analytical framework to three cases in which scientists have addressed contrasting problems affecting agroecosystems. In each case study, we assess the potential of using ecological knowledge in agroecosystem innovative design, in comparison with their use in decision processes.

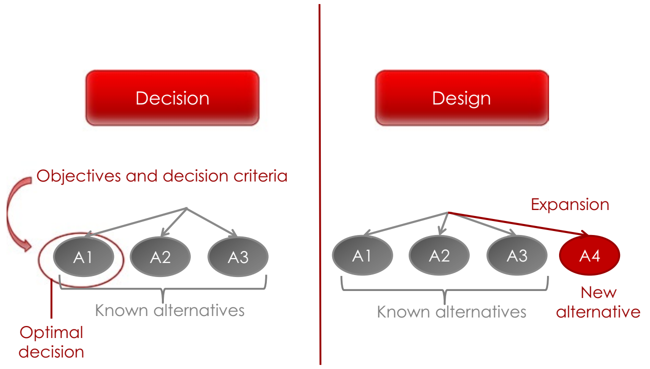

FIGURE 1 A main difference between design and decision: the generation of new alternatives

2 | THE VALUE OF ECOLOGY IN DESIGN: ILLUSTRATION WITH THREE EMPIRICAL CASE STUDIES

The situations studied are ongoing, long-term (10–20 year) research programmes in France that focus on the SES scale (Figure 2). In each, land use has changed rapidly over the past 20–40 years, with major impacts on biodiversity; as such, these situations are representative of many agricultural landscapes world-wide. Each research team intends for its research to be relevant to, and used by, the local stakeholders, with which it interacts. The three situations, however, differ in land use, soil type, climate, and in the social and economic profiles of the human population. The scientific approaches and theoretical frameworks used by the research teams also differ. Case #1 is a cereal plain in western France, in which researchers analyse bird population persistence in relation to prey availability and land use change. Case #2 is a subalpine grassland landscape in the French Alps used to study the provision of ecosystem services (ES) related to grassland functional diversity. Case #3 is a wet grassland area in western France where researchers study the competing concerns of livestock management and bird population viability.

2.1 | Case #1: Cereal plain in western France

2.1.1 | Agroecosystem and ecological issues

In this region, a shift from mixed farming to intensive cereal crop farming has resulted in increased use of chemicals, landscape

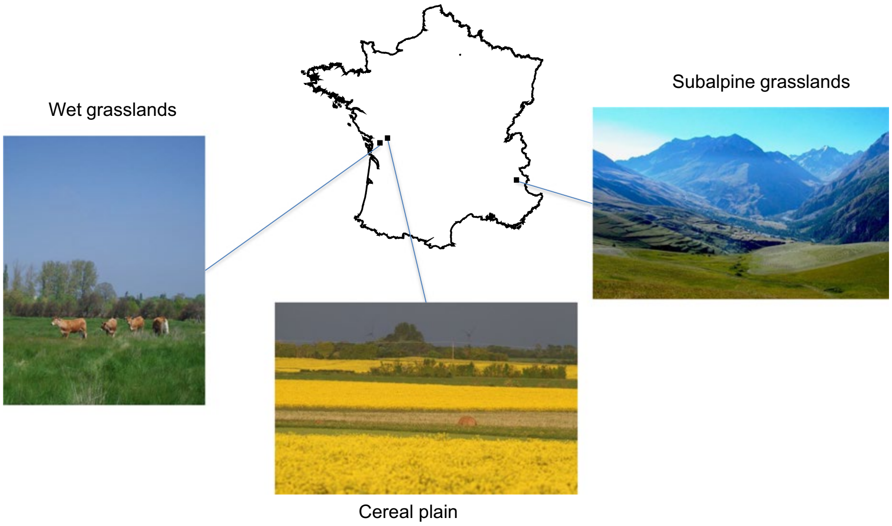

FIGURE 2 Location of the three case studies

homogenization, and decreased grassland cover, with consequent biodiversity loss and water quality degradation. These plains, however, still host species with a strong conservation value, such as the Little bustard (*Tetrax tetrax*), for which the population has declined by 90% in 25 years (Bretagnolle et al., 2011a).

2.1.2 | Ecological approach and theoretical framework

Scientists first studied the ecological requirements of *T. tetrax*, focusing on breeding biology and carrying capacity. The decline in the bustard population was attributed to failure of the species to reproduce, mostly due to food shortage during the early chick-rearing period, when chicks rely solely on insects, especially grasshoppers (Inchausti & Bretagnolle, 2005). Field ploughing, which destroys grasshopper nesting habitat, together with herbicide use, lead to dramatic declines in their populations. The researchers modelled the agroecosystem as a matrix composed of grasslands (semiperennial or perennial vegetation cover favourable to insects breeding) and cropped areas, and employed *metapopulation theory*, which predicts that when a population goes locally extinct, it can be compensated for by recolonization from neighbour populations in high-quality habitats. Using simulations, a minimum of 10% of grasslands in the agricultural landscape was predicted to be required to maintain viable grasshopper populations (Bretagnolle, Gauffre, Meiss, & Badenhausser, 2011).

2.1.3 | Using ecological knowledge to identify a preferred solution

Based on this conclusion, the researchers advised that the grasslands be maintained or restored (Bretagnolle et al., 2011) through agri-environmental schemes funded by the EU. The ecological knowledge was used in a decision process whose objective was clear: protect the Little bustard, and leading to a preferred solution: contracts with farmers to restore grasslands. Grassland area increased in proportion from 9% in 2005 to 13% in 2011 in the cereal plain. But then, the contracting rate with farmers dropped, mainly for economic reasons due to a change in the EU Common Agricultural Policy; so by 2015 the grassland area declined and returned to the 2005 level (V. Bretagnolle, unpubl. data, 2015).

2.1.4 | An attempt to apply ecological knowledge to agroecosystem design

In 2011, a new approach was tried: the ecologists and a farm co-operative organized a collective design workshop involving 30 stakeholders, including farmers, agricultural extension services, and researchers, facilitated by a design researcher. This exploration about an innovative and sustainable alfalfa supply chain was led using a collective design method (KCP®[1]). The ecological fund was formulated as "an agricultural landscape composed of at least 10% grasslands" (Berthet et al., 2016). The research programme also provided measurable variables to predict the ecosystem state in response to land use change, such as distance between grasslands (see Knowledge space in Figure 3a). Using this knowledge as well as their own knowledge, the participants explored potential landscape configurations with respect to the nature, proportion, and distribution of high-quality habitats. They also assessed the potential interests of each configuration for various ES (see Concept space in Figure 3a). A high-quality landscape matrix could have been achieved, for example, by restoring grasslands and by developing no-till crops. Promoting the key ecological property did not drive the agroecosystem designers towards a unique solution, but opened the range of management alternatives. The collective design workshop was followed by a 3-year research-action programme. The cooperative implemented a

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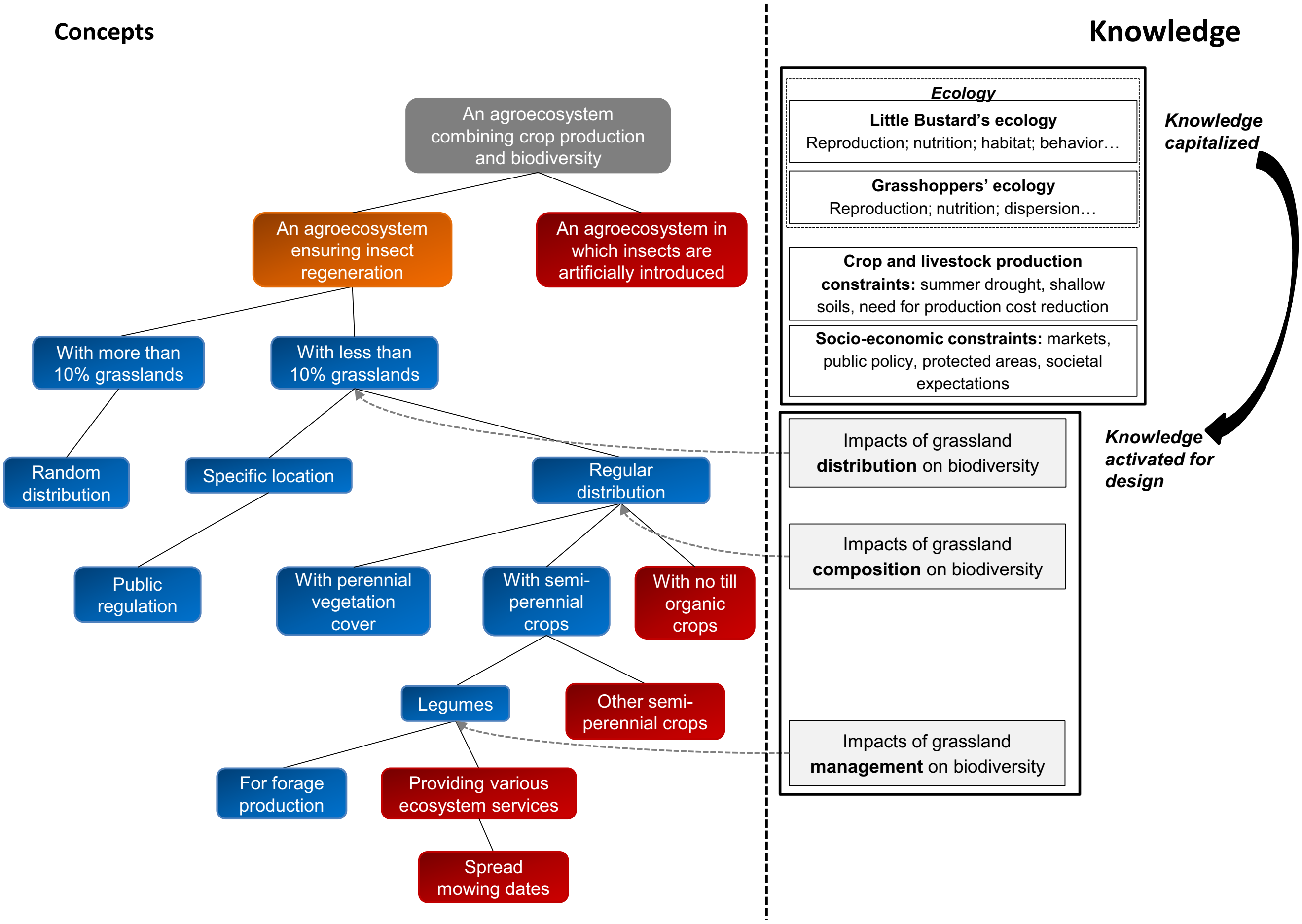
[1] This method includes a series of presentations by experts to share knowledge between the participants, then explorations of innovative concepts in sub-groups.

(a) Cereal plain



(b) Subalpine grasslands

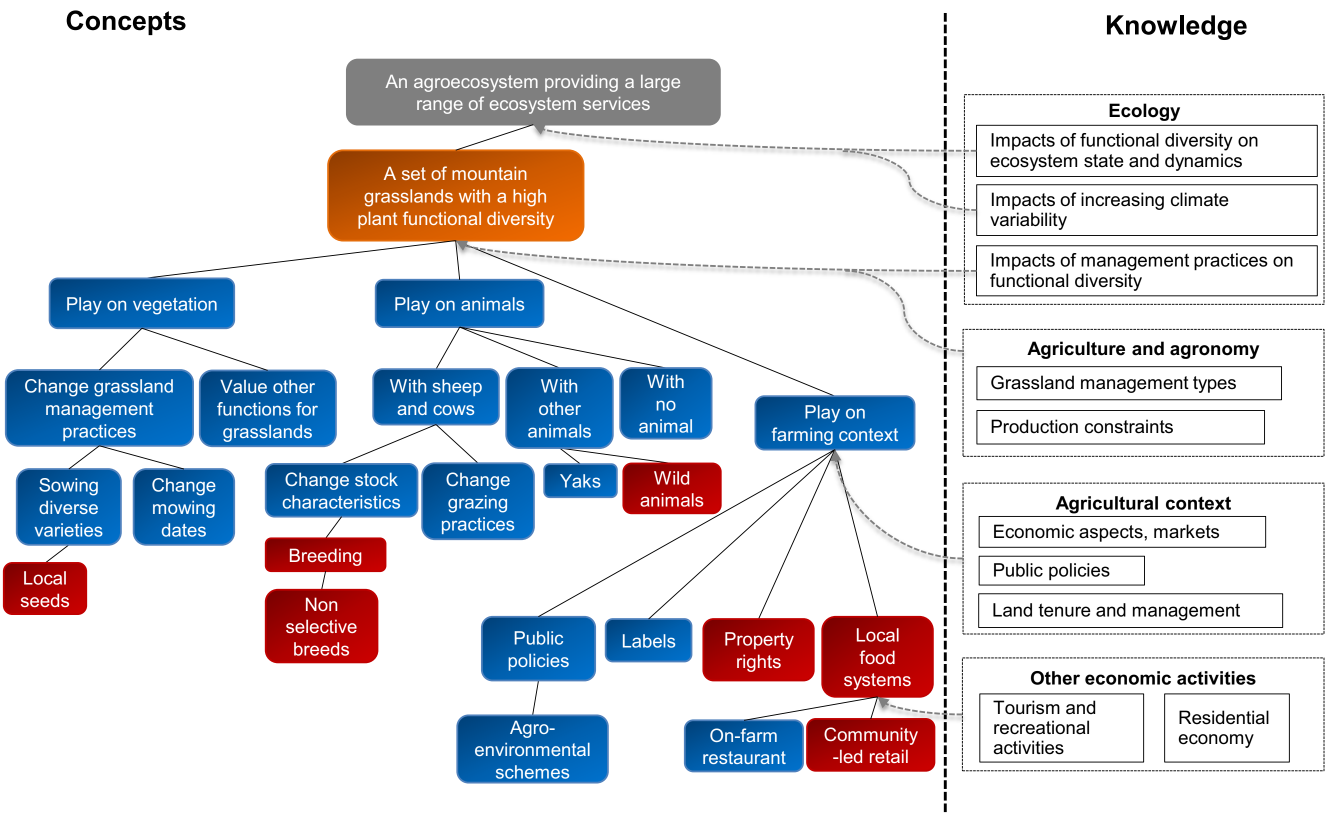


FIGURE 3

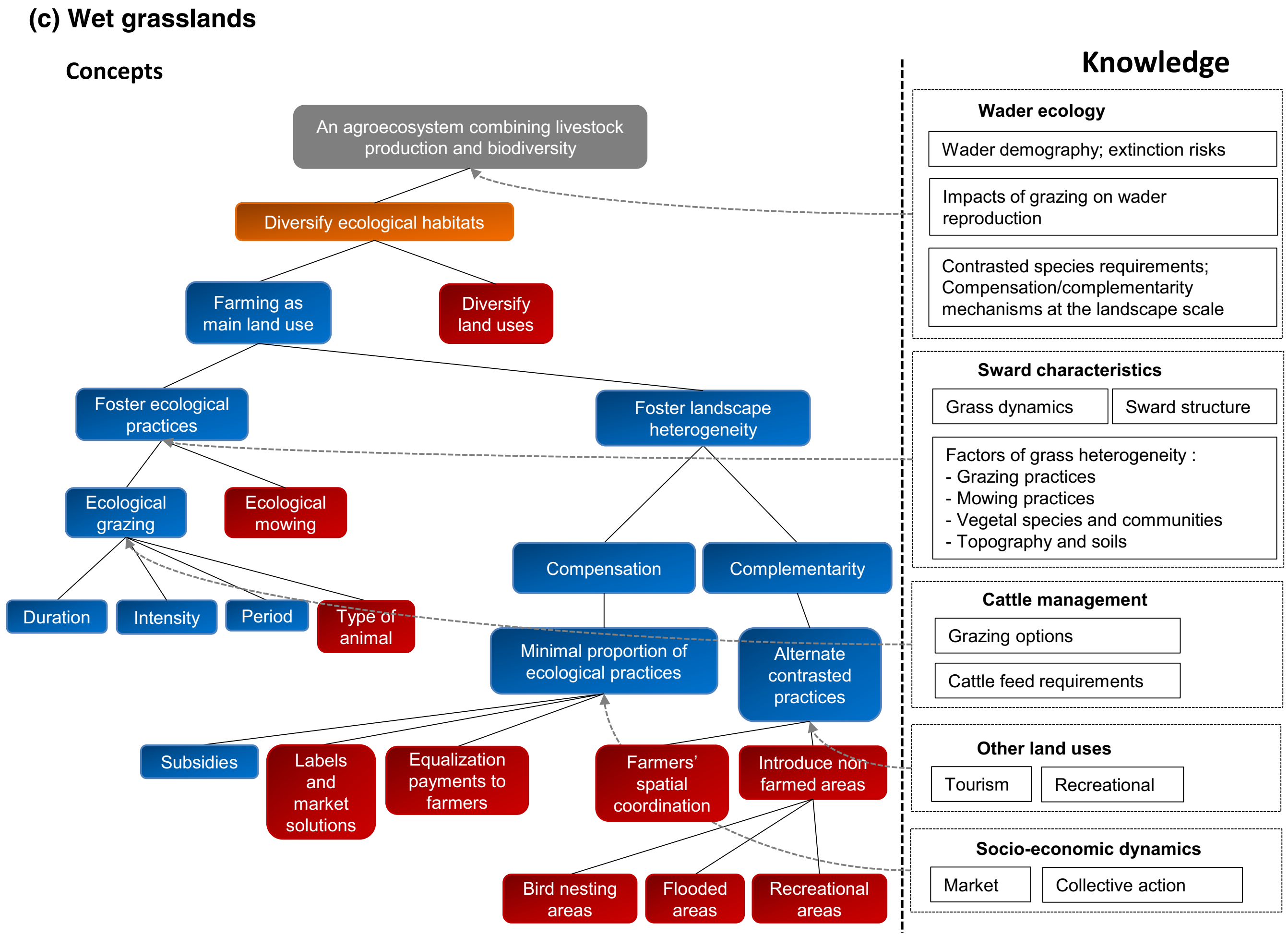


FIGURE 3 (a) Cereal plain. (b) Subalpine grasslands. (c) Wet grasslands. Exploration of alternatives for enhancing agroecosystem sustainability. The three figures highlight some alternatives explored by the ecologists in interaction with local stakeholders to design a more sustainable agroecosystem. Concepts are on the left and knowledge is on the right. The design process starts with the formulation of an initial aim (in grey), problematized with the identification of an ecological fund (in orange); then the design process progresses with the simultaneous specification of concepts (in blue and red) and collection of relevant knowledge; dotted arrows show how knowledge permits the generation of concepts. Concepts generated by the design process that have not been explored by researchers to date are in red

local alfalfa supply chain, but its development remained limited due to economic difficulties, and the exploration of innovative ways to combine forage production and environmental preservation was not pursued, mainly due to a lack of facilitation. The environmental impacts of the supply chain were thus limited (V. Bretagnolle, unpubl. data, 2015).

2.2 | Case study #2: Subalpine grasslands in the French Alps

2.2.1 | Agroecosystem and ecological issues

This mountain landscape comprises a mosaic of hay meadows and pastures for livestock production with various management practices. The meadows are mown and some are fertilized (Quétier, Thébault, & Lavorel, 2007). As with many European mountain areas, hay meadows are increasingly converted to extensive grazing. Pasture abandonment is common in the region. Such changes in grassland management decrease culturally valuable biodiversity and ES such as fodder production, soil fertility, and slope stability (Lavorel et al., 2011).

2.2.2 | Ecological approach and theoretical framework

The ecologists sought to quantify the effects of changes in land use on composition of the plant community, agroecosystem properties, and provision of ES, by implementing the trait-response effect framework (Lavorel & Garnier, 2002). They combined state-and-transition models (Quétier et al., 2007) with spatially explicit ES models (Lavorel et al., 2011) to characterize ecosystem states that vary with respect to climate, land use, and their interactions. This research demonstrated that grasslands with greater plant functional diversity produced more ES, with fewer trade-offs, and were more resilient to climate change (Lavorel et al., 2011).

2.2.3 | Using ecological knowledge to elaborate scenarios with known alternatives

These results were used, in collaboration with local stakeholders, to elaborate scenarios that explore land management decisions under different climate and socio-economic conditions (Lamarque, Lavorel, Mouchet, & Quétier, 2014a). This exercise enabled stakeholders to make more informed decisions about the best management practices under uncertain conditions (Lamarque, Meyfroidt, Nettier, & Lavorel, 2014b). However, the exploration of farming practices and governance that might increase sustainability was mainly limited to known alternatives.

2.2.4 | A perspective: Applying ecological knowledge to agroecosystem design

An innovative design process could be initiated with the ecological fund defined as "a set of mountain grasslands with a high plant functional diversity" (see Figure 3b for a first exploration proposed by the authors). The research programme provided a range of measurable variables to predict the ecosystem properties in response to land use and climate changes at various scales. The main variables were community-mean traits that explain variation in main ecosystem properties such as primary productivity (Lavorel et al., 2011), as well as functional divergence, the within-community variance in trait values, which has been hypothesized to operate through functional complementarity. The formulation of the ecological fund leaves many options open: the plant species that comprise this functional diversity are not predetermined and are interchangeable as they have similar trait values. There are a variety of management practices—and all may not be known yet—that may improve functional diversity, such as sowing or diversifying mowing dates. Functional diversity can be achieved at the field, farm, or landscape scale, permitting the exploration of new forms of collective action. Innovative thinking also enables exploration of new values for this agroecosystem, such as resilience to climate change.

2.3 | Case #3: Wet grasslands in western France

2.3.1 | Agroecosystem and ecological stakes

The third case study is wet grasslands, which are ecosystems of major concern for biodiversity conservation. The ecological interest of these areas is profoundly affected by their management. The wet grasslands under study harbour some of the largest French populations of waders, ground-nesting bird species (Northern lapwing (*Vanellus vanellus*), Common redshank (*Tringa totanus*), and Black-tailed godwit (*Limosa limosa*)). Grazing management is critical to their reproduction (Tichit, Durant, & Kernéïs, 2005): if absent, swards are too tall for bird reproduction, but intensive grazing results in nest trampling.

2.3.2 | Ecological approach and theoretical framework

The researchers studied the competing concerns of livestock management and bird populations with a model developed within the mathematical framework of the *viability theory* (Sabatier, Doyen, & Tichit, 2010; Tichit, Doyen, Lemel, Renault, & Durant, 2007). This theory aims to identify the set of management options that will ensure that identified basic needs are met so that the system is sustainable; it dictates compliance with constraints instead of maximizing quantities or utilities. The ecological constraints identified were the sward height necessary for maintaining bird habitat quality and maximum cattle density to limit nest trampling; the production constraints concerned livestock feeding requirements. The researchers identified innovative solutions at the field, farm, and landscape scales to improve trade-offs between cattle production and bird preservation: for example, autumn grazing might reduce grass height and limit nest trampling in spring (Tichit et al., 2005), and increasing configurational heterogeneity of landscapes might improve ecological performance with low production costs (Sabatier, Doyen, & Tichit, 2014).

2.3.3 | Using ecological knowledge to build a decision support tool

The knowledge produced by this research was used to design a role-playing game coupled with a computational model, used as a decision support tool for a group of farmers. The farmers explored new combinations of agricultural and water management practices, and appraised them. However, this decision support tool was not designed to explore innovative agroecosystem management options.

2.3.4 | A perspective: Applying ecological knowledge to agroecosystem design

To initiate an innovative design process, the ecological fund could be defined as "a set of wet grasslands providing a diversity of bird ecological habitats." The ecologists identified management solutions, such as duration, timing, and intensity of pasture, and provided quantitative and qualitative information on their impacts. The ecologists identified the variable "sward's height" as key to monitor habitat quality. They also assessed various compensation and complementarity mechanisms between landscape patches to design a landscape fostering biodiversity. Yet, other management factors could be explored to open design options; new forms of collective action, production systems, and markets could be envisioned; and other values related to heterogeneous grasslands may be explored, such as resilience to climate change and water management (see Figure 3c for a first exploration proposed by the authors).

3 | DISCUSSION: IMPLICATIONS OF APPLYING ECOLOGICAL KNOWLEDGE TO DESIGN

We analysed the potential of applying ecological knowledge to innovative design in three contrasted case studies representative of agricultural intensification world-wide. In all cases, the design approach extended the range of options initially identified by the researchers (see Figure 3a–c): In case #1, various acceptable landscape configurations were envisioned for maintaining bird populations. In case #2, unexplored alternatives for maintenance of plant functional diversity of mountain grasslands were identified. In case #3, new alternatives for livestock management and other activities to create a diversity of ecological habitats were explored.

Ecology not only provides knowledge that may support the design process of an agricultural landscape (Lovell & Johnston, 2009; Nassauer & Opdam, 2008) it also permits the identification of a key underlying property that must be maintained to ensure sustainable ecosystem functioning. It thus provides original specifications that can be used to initiate an agroecosystem design process, and that ensures at least its ecological sustainability. Ecological knowledge not only orients the design process but also increases the degrees of freedom by opening new design spaces: its application to agroecosystem design enlarges the range of what can be considered "unknown"—that is, to be explored. When ecological modelling is used to support decision, management actions, and indicators to assess the state of the ecosystem are considered known. When using ecological modelling for innovative design, the new variables identified by ecologists can be used in a design process to explore new management actions as well as new agroecosystem properties and values, necessitating new indicators. The range of solutions explored can thus be considerably enlarged.

This paper highlights the advantages of design for planning and change. Ecological knowledge on agroecosystem functioning indicates the scope of the object to be designed, which includes the stakeholders affected by the design, the variables to be monitored, and the management practices to be activated. Then different stakeholders may propose or validate properties that they consider desirable, which increases the chances of making the ecological fund collectively acceptable. Such an approach places ecology at the forefront of agroecosystem design, and facilitates interactions with other disciplines and with nonscientific factors, hereby offering a new way to integrate various types of knowledge. Instead of providing "ready-made" solutions that local actors might have difficulty implementing in their specific context, a design approach fosters collective exploration before focusing on an acceptable solution. By engaging stakeholders in contributing to building solutions, it may strengthen their sense of ownership and responsibility (Lochner et al., 2003).

The use of ecological knowledge in both decision and design may be fruitful. A design process can be complementary to a decision process and may precede it. Yet examination of their differences may clarify the contribution ecology can bring to agroecosystem management, and guide agroecosystem managers when building their strategy. The design approach based on ecological knowledge proposed in this study is generic, and could be applied to SES other than agroecosystems, such as forests or fisheries. However, initiating and managing a collective design process for a whole SES is challenging (see Case #1) and requires specific management skills, such as involving stakeholders with diverging expectations and power asymmetries, fostering exploration of innovative solutions, and evaluating the outcomes in the mid and long term.

Fostering the application of ecological knowledge to the innovative design of SES would benefit from infrastructures that facilitate the articulation between scientific research and SES management practices. *Innovation platforms*, consisting in nested structures comprising intermediary actors and ICT tools that build bridges between the components of innovation systems (Kilelu, Klerkx, & Leeuwis, 2013), and *living labs* that aim at cocreating innovation through the involvement of concerned users in a real-life setting (Dell'Era & Landoni, 2014), can offer inspiration. These innovation infrastructures could be developed in close relation with ecology research centres or Long-Term Social-Ecological Research platforms (Mirtl, Orenstein, Wildenberg, Peterseil, & Frenzel, 2013) that capitalize knowledge on SES dynamics. By developing collaborations and synergies between design facilitators, ecologists, and local stakeholders, these infrastructures could foster the application of cutting-edge ecological knowledge to the design of innovative and sustainable SES, and contribute to developing an adaptive and complexity-based governance of SES (Loorbach, 2010).

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AUTHORS' CONTRIBUTIONS

E.B. and B.S. conceived the main ideas; E.B. led the collective writing process; V.B., S.L., M.T., and R.S. provided the data related to the case studies; they contributed critically to the paper conception and writing. All authors contributed significantly to the drafts and gave final approval for publication.

DATA ACCESSIBILITY

Data have not been archived because this article does not contain data.

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