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Landscape-scale approaches for enhancing biological pest control in agricultural systems

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Abstract Over the last decades, land management options have been investigated that aim at enhancing services to agriculture delivered by biodiversity and its associated biotic interactions. Such services can be promoted through land management strategies ranging from in-field single agricultural practices, long-term strategies compiling these agricultural practices at the crop rotation scale, to management strategies at the landscape scale. In this paper, we provide an overview of the land management options that can be implemented at multiple scales, with a specific focus on the provision of one service that is key in agriculture, i.e. pest control. We present existing knowledge and highlight current gaps and limitations in our understanding of pest control response to land management. Based on this analysis, we propose two promising and complementary research approaches that could help filling existing knowledge gaps and provide guidelines for designing landscapes for agroecological services: (1) landscape monitoring networks (LMN), based on long-term monitoring of ecological and managerial processes within sets of landscapes located in contrasted production contexts; (2) agroecological system experiments (ASE), which design and assess combinations of land management options at multiple embedded spatial scales.

Keywords Pest control · Landscape monitoring network · Agroecological system experiment · Cropping system

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Introduction

The biodiversity of agroecosystems has declined markedly in recent decades with the intensification of agricultural management (Stoate et al. 2009) with concomitant falls in agroecosystem functioning (Geiger et al. 2010; Cardinale et al. 2012; Oliver et al. 2015). In the context of a necessary shift towards pesticide reduction in agriculture, much effort is currently devoted to the identification of land management options enhancing biodiversity and beneficial biotic interactions that deliver services to agriculture (Duru et al. 2015). Such biodiversity-based management options require the integration of management activities and ecological processes occurring over a wide range of spatial and temporal scales (Médiène et al. 2011; Petit et al. 2018).

There is little consensus as to an 'optimum' scale for the management of economically important biodiversity, i.e. species to be harvested, pest species and natural enemies contributing to pest control. Indeed, species vary in their ecological requirements and respond to their environment at different spatial scales (Petit et al.

2013; Begg et al. 2017). However, there is increased awareness that a number of key agricultural issues require a landscape-scale approach that takes into account of the composition and spatial organisation of the agricultural land. These issues include the prevention of crop diseases (Meentemeyer et al. 2012), the durability of crop resistance to pathogens (Fabre et al. 2012), novel trait confinement (Bagavathiannan et al. 2012), including for example the spread of herbicide resistance in agricultural weeds. They also include services provided by biodiversity sheltered in agricultural landscapes such as crop pollination (Ricketts et al. 2008) and the stability and resilience of functional trophic networks to control crop pests (Tscharntke et al. 2007; Massol and Petit 2013).

As a result, redesigning agricultural landscapes that would deliver services to agriculture has probably never been so high on the political and research agenda (Landis 2017). Ecological research conducted over the last decades is providing concepts that could guide the design of multifunctional agricultural landscapes. However, shifting to biodiversity-based agriculture with an emphasis on landscape design will require new models of research, with enhanced integration of ecological and agronomical knowledge, efforts devoted to targeted research for context-specific solutions, and increased empirical testing of existing design concepts. It will also require to engage with stakeholders to assess their perception and willingness to move from habitat or field-scale management to landscape-scale management and ultimately to landscape design.

In this paper, we provide an overview of the land management options that can be implemented at multiple scales, with a specific focus on the provision of one service that is key in agriculture, pest control. We present existing knowledge and highlight current gaps and limitations in our understanding of pest control response to land management. Based on this analysis, we propose two promising and complementary research approaches that could help filling existing knowledge gaps and provide guidelines and empirical testing of landscape design for agroecological services.

Land management strategies across spatial and temporal scales

There is increasing evidence that land management options have an impact on the functioning of the agroecosystem over a wide range of ecological and managerial spatio-temporal scales encompassing the plant, the field, the farm, and the landscape level (Firbank et al. 2008). To restore or sustain the delivery of ecosystem services, diverse land management options promoting functional biodiversity (i.e. components of biodiversity contributing to biological control of pests) exist at these different scales (Fig. 1). They include the diversification of planned domestic (plant) biodiversity at the field scale and in adjacent field boundaries, with expected positive impacts on ecological processes and on other taxa underpinning the delivery of pest control. The impact of landscape properties on pest control has been addressed by comparative landscape ecological studies, with few experimental tests due to obvious logistical constraints.

In-field spatial and temporal management options

In-field planned biodiversity can be increased in space and time, through options that are integrated at the scale of the cropping system, i.e. the combination of a crop succession and the crop management strategies for each crop (Sébillotte 1990). Crop management strategy is the logical and ordered combination of cultural techniques aiming to manage the biological, physical and chemical environment to reach qualitative and quantitative production targets of the land manager, e.g. the famer or the experimenter. The choice of a cropping system has important implications for biodiversity, pest control and the general performance of the system (Lechenet et al. 2014; Petit et al. 2015).

Several management options lead to increased in-field spatial cropped biodiversity (Fig. 1). They include the use of spatial associations of crop cultivars or crop species during the crop growing season and/or the use of single or multiple species grown during the fallow period (Malezieux et al. 2009). The effects of plant associations on pest regulation have been extensively reviewed by Ratnadass et al. (2012). Pest levels, for example weeds, may be reduced by the use of cover crops during the fallow period (Teasdale 1996) that reduce weed emergence (Cordeau et al. 2015a) or weed biomass if weeds germinate, as demonstrated for legume cover crops (Verret et al. 2017). Local plant diversity enhances pest control by generalist predators (Dassou and Tixier 2016). Undersowing a cover crop may be beneficial to biocontrol by providing an even

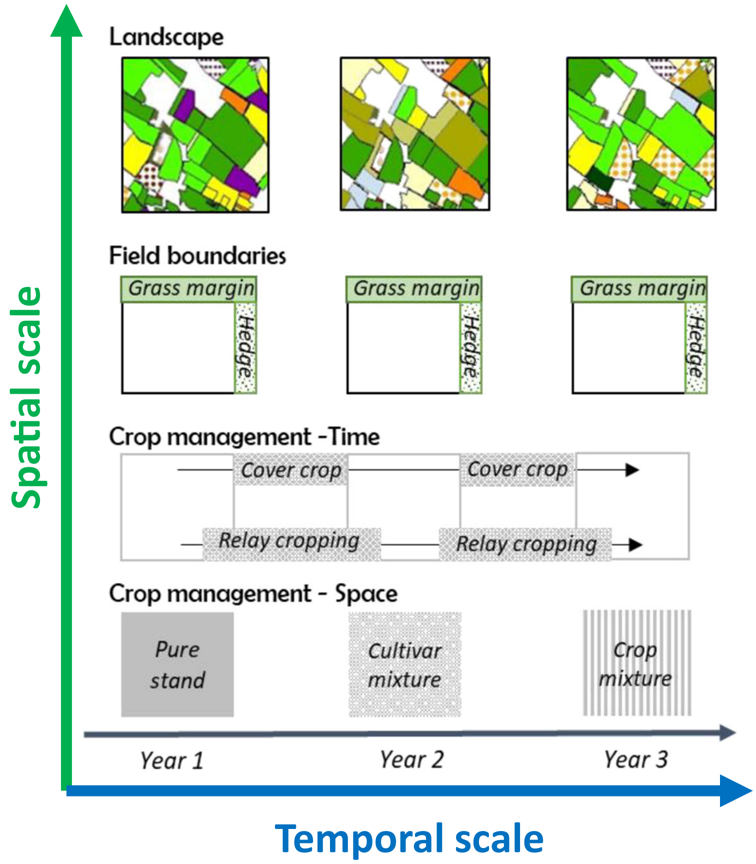

Fig. 1 Land management in space (from the crop plant to the landscape) and time (from the single crop season to the crop sequence)

distribution of natural enemies across fields (Holland et al. 2016).

In-field cropped biodiversity can also be increased in time. The choice of crop rotation can lead to contrasting levels of biodiversity in time (Fig. 1), from very low (monoculture) to very high (highly diversified crop rotation, cover crops and relay cropping). Increasing the number of crop cultivated over time in the same field has been shown to help pest control in many ways. It breaks life cycle of pests by introducing crop that do not favour their establishment or reproduction (e.g. Liebman and Dyck 1993 for weeds). It favours pest avoidance through the desynchronisation of crop susceptibility and the biological cycle of various pests (Meynard et al. 2003).

Management of field boundaries

Field boundaries refers to linear habitats of varied widths that surround cultivated fields and include woody linear habitats (hedgerows, tree lines) and/or grassy habitats that can be more or less permanent (Marshall and Moonen 2002). The theoretical background underpinning potential effects of field boundaries on processes occurring in adjacent fields is that of cross-boundary subsidies between habitats (Polis et al. 1997). Spillovers of organisms occur when semi-natural habitats act as sources of pest predators and/or parasitoids that enter adjacent crops (Landis et al. 2000; Thies and Tscharntke 1999) and, although much less well-documented, from the field to adjacent semi-natural habitats (Blitzer et al. 2012; Rand et al. 2006). Spillover can result from passive diffusion, or active movements in response to shifts in resource availability (e.g. after crop harvest) or because organisms use supplementary or complementary resources in both habitats (Dunning et al. 1992; Rand et al. 2006). Habitat complementation is widespread in agricultural mosaics, as seen in the cyclic recolonisation of crop fields by organisms overwintering in-field boundaries, whether they are crop pests or natural enemies (Wissinger 1997). In terms of management, new field margin habitats can be created (flower strips, conservation headlands, buffer grass strips, beetle banks) and existing one improved with agri-environmental schemes in all EU countries. A recent paper has reviewed the contribution of different types of field margins on the abundance of natural enemies and on the intensity of pest control in the adjacent fields (Holland et al. 2016). In general, field margins shelter higher abundances of natural enemies, although it depends on the plant composition of these habitats. There is less information as to whether this leads to higher abundances or activity of natural enemies in the adjacent crops.

Options at the landscape scale

Landscape level refers to the mosaic of crop and off-crop habitats resulting from the amount and spatial patterns of non-cultivated land (field boundaries, semi-natural habitats), the diversity of management at farm level and the fine interweaving of farm territories across the landscape. The resulting spatio-temporal pattern thus stems from the farmer's decision regarding land use allocation at the farm level and from the structuring of farm territories across the landscape, both factors being often constrained by environmental, socio-economic and agronomic factors (Thenail et al. 2009).

There is a consensus that the simplification of agricultural landscapes over the last decades has led to a significant decline in biodiversity, and in turn in the delivery of pest control services (Oliver et al. 2015). Several meta-analyses highlight the suppressive effect of landscape scale amounts of semi-natural areas on in-field pests: landscapes with higher proportions of semi-natural areas exhibit higher abundances of natural enemies, lower pest abundance or higher pest control in fields (Veres et al. 2013; Chaplin-Kramer et al. 2011). They also highlight the huge variability of these landscape effects, according to the type of crop and to the identity of the pest, predators or parasitoids that are considered. Variations of effects could partly stem from a general oversimple account of agricultural management in most landscape studies, i.e. a specific crop type is usually considered to be managed in the same way across a landscape, or at best, studies use dichotomy organic/conventional fields. There is now growing evidence that local field management can drastically affect in-field pest control processes (Petit et al. 2017; Ricci et al. 2019) which calls for a full account of the diversity of field management strategies that coexist within agricultural mosaics (Rusch et al. 2010; Vasseur et al. 2013). This calls for efforts to increase the functional representation of landscapes for the organism or the process under study (Fahrig et al. 2011). In some instances, it may require a spatial representation of cumulative single management practices or of combined management options implemented over years (cropping systems) at the landscape scale (Fig. 2E, F).

In addition, because of the large sampling effort required in comparative landscape studies, surveys are usually conducted during a single year and, as such, only provide a snapshot of processes occurring in one crop type across contrasted landscapes. Potential effects of the distribution of cropping systems in the landscape or issues such as the stability of pest control, within and between years cannot be documented. Finally, ecologists who have devoted efforts to landscape comparative research agree that identifying the ecological mechanisms underlying the observed landscape effects on biocontrol remains challenging but needs to be addressed in order to provide landscape management guidelines (Tscharntke et al. 2016; Karp et al. 2018).

Landscape-scale research approaches to assess or test biodiversity-based systems

The previous section has described common existing approaches that have advanced our understanding of the pest control service in agricultural landscapes and has also highlighted some of their limitations. In this section, we propose two distinct but complementary landscape approaches that could enhance our ability to design landscapes delivering services to agriculture (Table 1). The first approach consists in the set-up of long-term monitoring landscape networks (LMN). Here, the goal is to address the temporal dimensions of ecological and managerial processes with enhanced integration of ecological and agronomic knowledge, while preserving the generic value of findings derived from landscape comparative methods. The second approach is the set-up of agroecological system experiments (ASE), which addresses the current critical need to test multiple-scale land management design concepts in real situations and to document the dynamics of ecological mechanisms in response to the implementation of landscape designs.

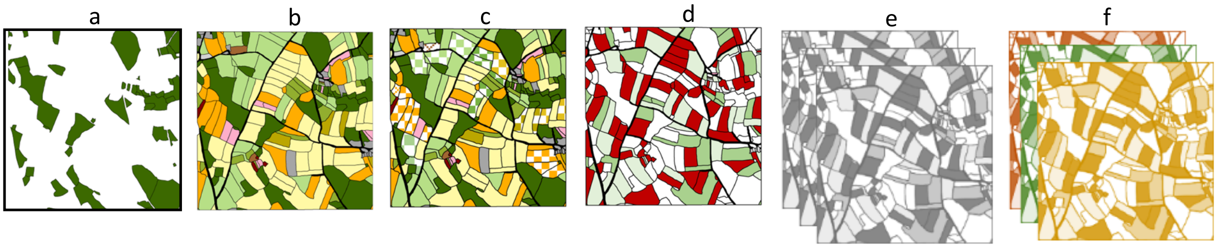

Fig. 2 Evolution in the representation of the spatio-temporal heterogeneity of landscape mosaics. **A** spatially implicit representation i.e semi-natural habitats and a neutral matrix; **B** land cover in the agricultural mosaics; **C** land cover and management with organic farming in dots; **D** gradient of management practices, e.g. levels of pesticide use; **E** single management practice cumulated over years; **F** spatial representation of cropping systems

Setting up a long-term landscape monitoring network

Principle

There is a long history of long-term ecological research worldwide as exemplified by the set-up of numerous LTER (long-term ecological research) and associated platforms worldwide. The general aim of LTER is to identify drivers of ecosystem change across environmental gradients using harmonised parameters and methods. Variable emphasis is put on stakeholders and some LTER specifically focus on agricultural landscapes and their sustainability (Bretagnolle et al. 2018). A similar philosophy could be developed to focus on the landscape dimension of agricultural systems where managerial and ecological processes are monitored in a network of replicated landscapes over time (LMN). The spatial extent of the network should allow to consider a wide range of pedoclimatic and socio-economic contexts as this is crucial to detect potential generic signals for landscape effects on ecological processes. The survey of local field management should allow to assess possible interactive effects of local and landscape-scale factors. The long-term dimension of the network (pluri-annual studies rather than the common snapshot approach) would provide the capacity to address key questions that are to date poorly documented. In arable agriculture, investigating the effect of cropping systems on ecological processes during the successive crop covers grown during a crop rotation is still in its infancy. The pluri-annual dimension also allows to assess the temporal stability of ecological processes and of the resulting ecosystem services. These new questions raise challenges in terms of data acquisition and data analyses that are comparable to those met in classical LTER platforms, and notably dealing with multi-annual variations. LMN also has its specific challenges and notably the integration of biophysical and management information at multiple spatial scales and across pedoclimatic and socio-economic contexts. The development of generic but informative indicators, or the standardisation of information across contexts is a key issue.

Example of Implementation: the SEBIOPAG network

In France, the national monitoring network SEBIOPAG (http://sebiopag.inra.fr) was set up in 2013 to monitor pest control services and their dynamic in 80 fields located in 4 regions of France and run by four research teams (Fig. 3, Avignon, Dijon, Rennes, Toulouse). The four regions differ in terms of pedoclimatic conditions and landscape (bocage, openfield, orchards) as well as on agricultural production systems.

The originality of this set-up is that the same 80 fields (and surrounding landscapes) are monitored over the years. As 75% of fields are arable annual crops and conducted in crop rotation, the types of crop surveyed has increased over the years and include winter cereals, oilseed rape, legume crops, cereal-legume associations, maize, lucerne, other temporary grasslands. Fields that constitute the network were initially selected along gradients of in-field level of pesticide use and properties of the landscape surrounding the field that are likely to affect pest control. Pesticide use is estimated annually with the treatment frequency index (TFI), i.e. the number of recommended doses applied to each hectare (Gravesen 2003). Pesticide use relatively to a standard for the considered crop per region for 2014 is presented in Fig. 4. Landscape properties are estimated with (i) the proportion cover of target crop, i.e. of crop similar to that grown in the focal surveyed field that year (ii) the heterogeneity of the landscape and (iii) the density (length per ha) of interface between cropped habitats

Table 1 Characteristics and objectives of landscape monitoring networks (LMN) and agroecological system experiments

	Landscape monitoring networks (LMN)	Agroecological system experiments (ASE)
Principles	Long-term monitoring of ecological and managerial processes within sets of landscapes located in contrasted pedoclimatic and socio-economic contexts	Design and assessment of land management options at multiple embedded spatial scales (spatial organisation of cropping systems and semi-natural habitats)
Objective	• Detect generic signals • Disentangle local and landscape-scale factors and their interactions • Assess the stability and resilience of ecological services • Document the evolution of farming systems in time	• Design innovative landscape-scale systems • Test the feasibility and assess performances of agroecological landscapes • Document underpinning ecological mechanisms
Spatial characteristics	Monitoring of target fields and their surroundings along landscape gradients	Experimental spatial arrangement within a continuous landscape
Agronomy	Describe cropping systems and SNH at the landscape scale	Experiment innovative cropping systems implementing agroecological principles and their spatio-temporal organisation
Ecological processes	Statistical analysis of the relationships between landscape-scale management and services	• Monitoring the evolution of services following the implementation • Analytical studies of targeted underpinning ecological mechanisms
Links with local stakeholders	• Communication to land managers of ecological processes at play, • Provision of guidelines for landscape design in specific situations	• Co-design of ASE with local farmers and stakeholders, • Demonstration platform for visitors

and semi-natural habitats. The gradient covered by the SEBIOPAG sites for these three metrics is presented in Fig. 4.

Annual monitoring includes the census of management practices in the focal field, the description of land use in the 1 km^2 surrounding the focal field and in-field measurement of pest control. The latter is estimated by exposing 4 types of sentinel prey on predation cards, namely weed seeds *Viola arvensis* on the ground (Trichard et al. 2013), aphids *Acyrthosiphon pisum* on the ground and on the growing crop plant (Östman 2004) and lepidopteran eggs (*Ephestia kuehniella*) on the crop plant (Sigsgaard and Jacobsen 2017). Measurements are conducted in ten plots along two transects and pooled to get a field estimate of pest control. Two measures are conducted annually, the first during the crop vegetative growth period and the second at time of fruit, ears or pods maturation.

This network has enabled to assess the variations in pest control along a double gradient of pesticide use intensity (local field–scale intensification of agricultural practices) and landscape simplification (landscape-scale intensification). Results suggest a consistent negative effect of pesticide use and landscape simplification on the intensity of pest control, with interactive effects of both factors for all prey types (Ricci et al. 2019). The results have been presented to local land managers in each region and triggered discussions on potential options to use landscape-scale factors such as crop diversity or pesticide pressure to enhance biological pest control. Spatial models simulating the impact of landscape properties on pest control are under development and will be run using landscape scenarii designed by local farmers.

Setting up agroecological system landscape-scale experiments

Principle and definition

For a long time, agronomists have designed and tested cropping systems on long-term cropping system experiments (CSE). These CSE, in contrast to factorial experiments testing one or few practices, aim to test cropping systems as a functional entity whose complexity is more than the sum of its parts (Drinkwater 2002). Many of CSE have explored integrated pest management with a high diversity of experimental designs (Lechenet et al. 2017). Following the same philosophy, ASE adopt a systemic approach, but comprises the design of the

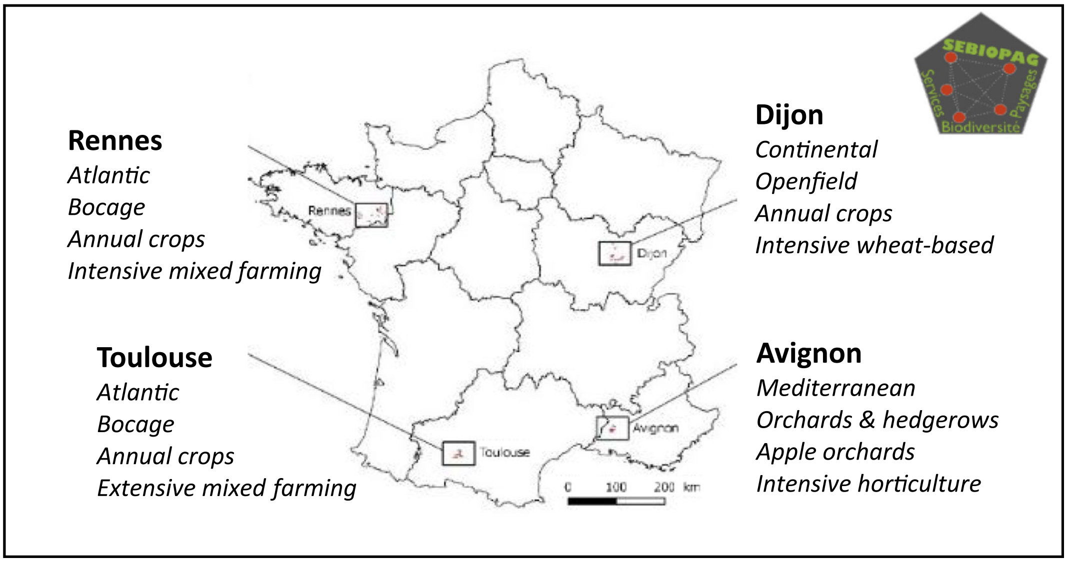

Fig. 3 The four regions of the SEBIOPAG landscape monitoring network

spatio-temporal arrangement and management of fields and semi-natural habitats at the farm level. Agroecological systems are thus a coherent landscape design strategy, a mosaic of adjacent fields with diverse cropping systems and a network of semi-natural habitats. As such, ASE considers and tests the combined effects of land management options implemented at multiple embedded spatial scales. The scientific focus is therefore not limited to the temporal dimension of cropping systems but also includes a spatial dimension that is highly relevant both ecologically (e.g. when tackling the issue of biological pest control) and agronomically, i.e. how

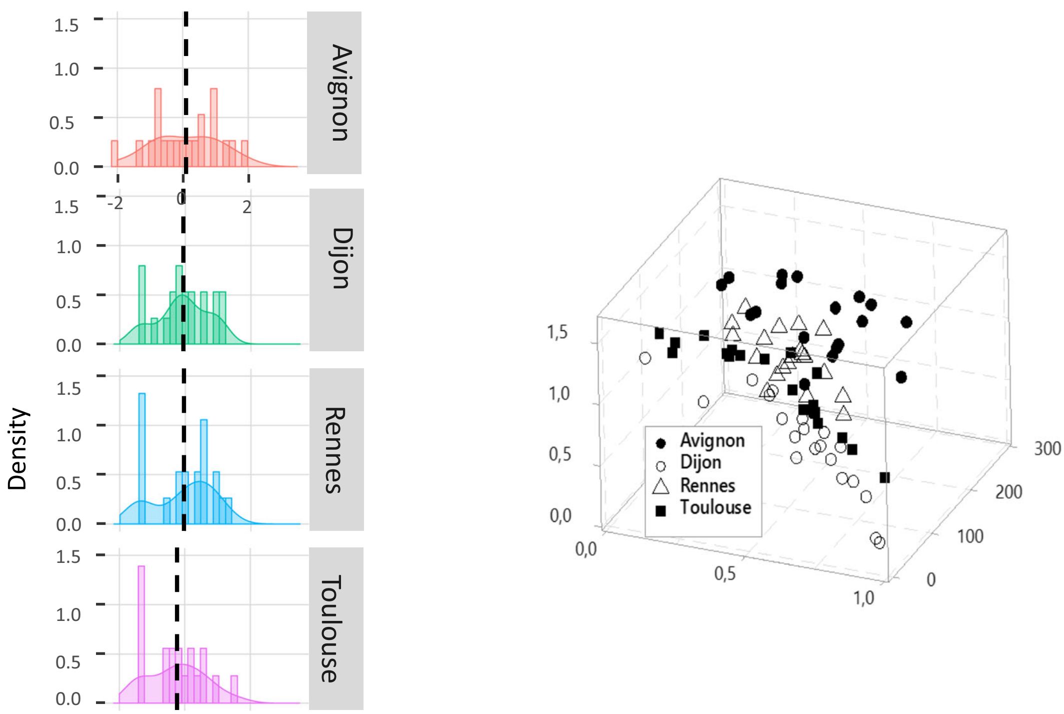

Fig. 4 The eighty SEBIOPAG fields. Left figure represents the gradient of pesticide use (2014 value standardised per crop type) in each region. Right figure presents the three landscape metrics for the 80 fields, per region

to organise a coherent farming strategy at the landscape scale. Compared to classical CSE, ASE will thus use existing and develop new indicators to account for spatial and functional relationships between management units and how this varies between seasons and between years.

Example of implementation: the CA-SYS platform

INRA has recently set up a landscape-scale ASE over one of its experimental farm, covering 125 ha near the Dijon area in Burgundy. This Co-designed Agroecological System experiment platform CA-SYS (www.inra.fr/plateforme-casys_eng) aims to design and evaluate new agroecological systems that maximise the use of biological processes (e.g. biological control of pests, improved nitrogen cycling, beneficial plant-microbe interactions) and reduce the use of inputs, i.e. nitrogen, water and pesticides (Cordeau et al. 2015b) with the aim of proposing multiperformant agricultural systems from an agronomic, economic, environmental and social point of view. The CA-SYS platform has been designed as pesticide-free ASE that uses (cropped and wild) biodiversity as mean to produce; it is expected that halting pesticide use and enhancing planned biodiversity within the fields and their margins will increase the service of pest control. One originality of this platform has been the active involvement of farmers and farmers' advisers of the surrounding area in the co-design of the ASE. More generally, stakeholders have shown a continuous and growing interest in the development of this ASE.

In terms of in-field crop management, CA-SYS tests four cropping systems combining a large diversity of farming technics (no-plowing and cover crop–based systems inspired from conservation agriculture, tillage and cover crop–based systems inspired from organic agriculture) which were co-designed with a vast array of actors (farmers, extensions, researchers). Conducting pesticide-free systems over the long term need to finely tune cropping systems (Fig. 5) comprising the use of hardy crop or less sensitive to pests (e.g. sunflower), the use of cultivars (e.g. in wheat or oilseed rape) or crop mixture (cereals–legumes) as much as possible, and the use of cover crop undersown (e.g. fababean in the oilseed rape to delude pest insects) or during the fallow period (e.g. to compete weeds).

In terms of landscape design, two aspects were integrated. First, the composition, spatial organisation and management of existing and recently established semi-natural habitats was also co-designed with a vast array of actors (extensions, researchers) during dedicated workshops or technical days dedicated to farmers. The aim of this design was to enhance or maintain the abundance of natural enemies that are known to contribute to the biological regulation of the major pest types likely to be encountered in the tested cropping systems. At this stage, expertise is required to identify pests known to occur in the studied area, expertise on the biology of pests and of their natural enemies as well as the effects of land organisation and management on both these pests and their natural enemies. As a result, a design of types and spatio-temporal arrangement of semi-natural habitats was included in CA-SYS, as presented in Fig. 6. Non-cropped habitats cover 14.11 ha (i.e. 40.44 linear km of about 3-m-wide habitats) and include 6.8 ha of grass strips, 2.69 ha of flower strips, 1.27 ha (3340 linear metres) of hedges, 5.07 ha of grassy pathways, and 1.43 ha of stony pathways bordered by grasses. This design is thus high both in terms of diversity of habitat types and plant composition and in terms of acreage over the farm. As such, it offers a valuable experimental set-up to study the contribution of a newly established dense network of semi-natural field boundaries to the population dynamics of natural enemies and pests and the resulting evolution of pest control through the coming years.

A second aspect of the landscape design was the spatial organisation of the tested cropping systems over the farm. It is divided into 3 zones or blocks of fields, defined above as agroecological systems (Fig. 7A). These zones differ by the number and type of cropping systems they test. The first zone only includes tillage-based cropping systems, the second only no-plowing cover crop–based systems, and the last zone comprises a mix of fields conducted either with the tillage-based or no-plowing-based systems (Fig. 7B). The rationale of this design is to address the question of a potential complementarity between adjacent cropping systems. It is indeed expected that contrasting soil tillage regimes will lead to major differences in the capacity of fields to host natural enemies, during different periods of their life cycle. Assessments of the spatio-temporal distribution of organisms and its evolution both within and between years can shed some light on the ecological functioning of this land mosaic. Quantification of movements of natural enemies between fields under contrasting managements as well as between off-crop habitats and cropped fields will bring knowledge on

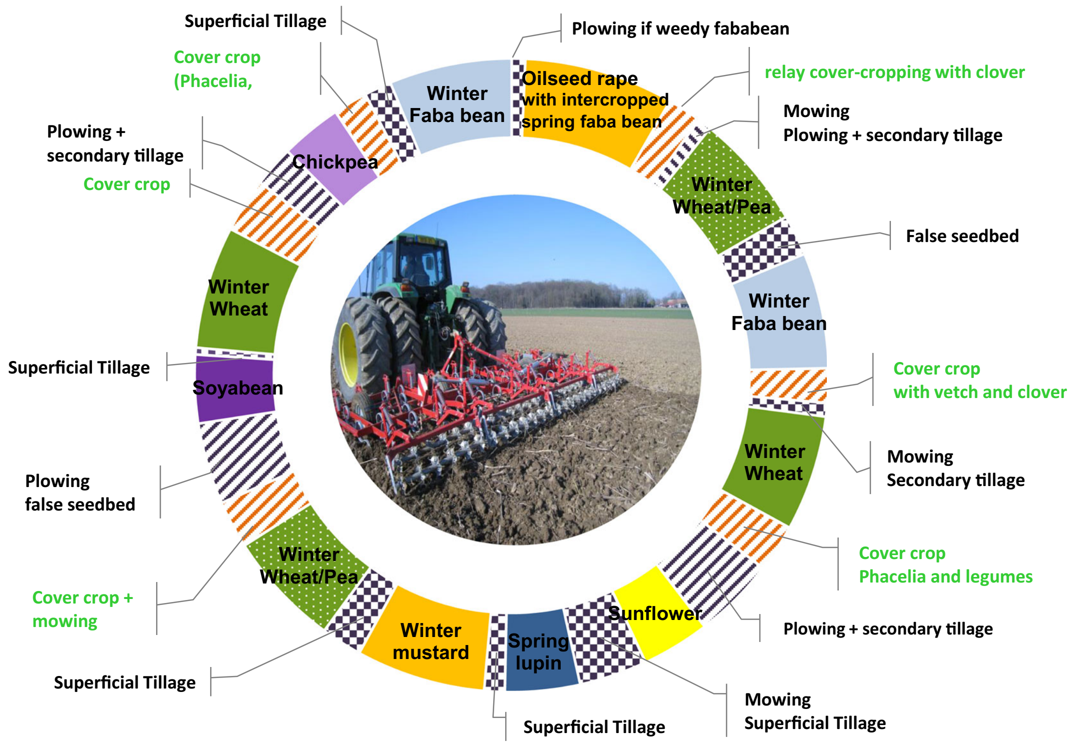

Fig. 5 Example of 12-year crop rotation for tillage-based system using no exogenous N fertilisation tested in the CA-SYS platform. Cover crops are indicated in green while tillage strategies are indicated in black. Certain crops were associated like winter wheat with winter pea or oilseed rape with companion faba bean. Superficial tillage refers to operations such as mechanical weeding. Brice Mosa and Violaine Deytieux © 2018

Fig. 6 Types and spatial arrangment of the semi-naturals habitats oft he CA-SYS platform. 3-m-wide flower strips were bordered by 3-m-wide grass strips to avoid seed dispersal into the field while permitting seed to shed into the flower strips for long-term maintainance oft he sown diversity. Rodolphe Hugard and Violaine Deytieux © 2018

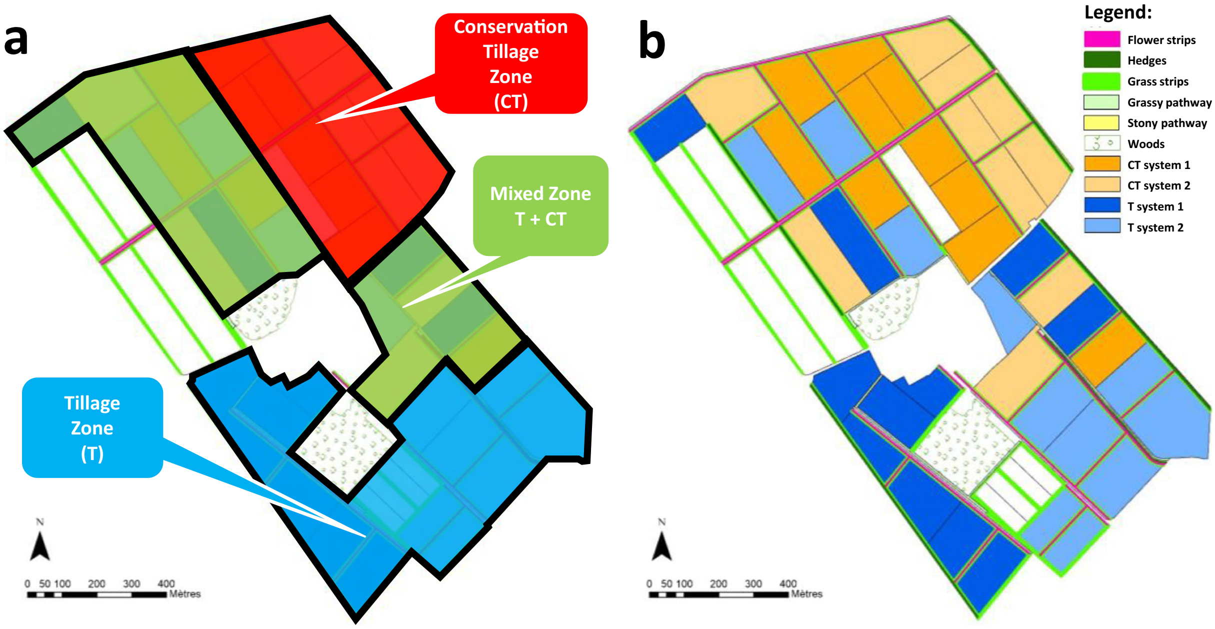

Fig. 7 Experimental design of the CA-SYS platform. **A** Three agroecological systems were co-designed with farmers, extensions and researchers. **B** Each agroecological system comprises two to four cropping systems embeded in a dense network of semi-natural habitats. Rodolphe Hugard and Violaine Deytieux © 2018

neighbouring and mass effects and thus provide useful guidelines on the spatio-temporal organisations that promote pest regulation.

Conclusion

Agriculture is facing the challenge to ensure global food security with minimal impacts on the environment. To meet this challenge, biodiversity-based options are currently being investigated that could represent alternative approaches for mainstream agriculture. The design of biodiversity-based system should fully consider the multiple embedded ecological and managerial scales at which processes take place, from the field to the landscape. This can only be addressed by a concerted effort of ecologists, agronomists and social scientists in a way that articulates the large body of relevant research within each discipline, with the common goal of designing sustainable and resilient agricultural landscapes. Here, we have illustrated how the articulation of agronomy and ecology can be relevant at different spatial scales, and we advocate combining monitoring and experimental landscape-scale approach to enhance the contribution of agroecological research to the design of agricultural landscapes. A critical issue for developing this avenue is to get policymakers and funding bodies to recognise the value and support long-term landscape-scale research programmes.

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