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Towards sustainable and multifunctional agriculture in farmland landscapes: Lessons from the integrative approach of a French LTSER platform

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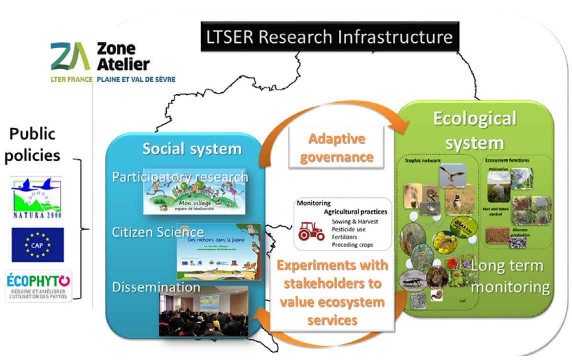
HIGHLIGHTS

- The "*ZA Plaine & Val de Sèvre*" is a Long-Term Socio-Ecological Research platform.
- This LTSER seeks agroecological solutions for sustainable agriculture.
- The land use and biodiversity have been monitored intensively since 1994.
- Innovative experimental investigation of ecosystem services on working farms.
- Participatory research, citizen science and dissemination to local stakeholders

GRAPHICAL ABSTRACT



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ABSTRACT

Agriculture is currently facing unprecedented challenges: ensuring food, fiber and energy production in the face of global change, maintaining the economic performance of farmers and preserving natural resources such as biodiversity and associated key ecosystem services for sustainable agriculture. Addressing these challenges requires innovative landscape scale farming systems that account for changing economic and environmental targets. These novel agricultural systems need to be recognized, accepted and promoted by all stakeholders, including local residents, and supported by public policies. Agroecosystems should be considered as socio-ecological systems and alternative farming systems should be based on ecological principles while taking societal needs into account. This requires an in-depth knowledge of the multiple interactions between sociological and ecological dynamics. Long Term Socio-Ecological Research platforms (LTSER) are ideal for acquiring this knowledge as they (i) are not constrained by traditional disciplinary boundaries, (ii) operate at a large spatial scale involving

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Socio-ecological system
Stakeholders

all stakeholders, and (iii) use systemic approaches to investigate biodiversity and ecosystem services. This study presents the socio-ecological research strategy from the LTSER “Zone Atelier Plaine & Val de Sèvre” (ZA PVS), a large study area where data has been sampled since 1994. Its global aim is to identify effective solutions for agricultural development and the conservation of biodiversity in farmlands. Three main objectives are targeted by the ZAPVS. The first objective is intensive monitoring of landscape features, the main taxa present and agricultural practices. The second objective is the experimental investigation, in real fields with local farmers, of important ecosystem functions and services, in relation to pesticide use, crop production and farming socio-economic value. The third aim is to involve stakeholders through participatory research, citizen science and the dissemination of scientific results. This paper underlines the relevance of LTSERs for addressing agricultural challenges, while acknowledging that there are some yet unsolved key challenges.

1. Introduction

Humanity's global footprint on the Earth's ecosystems, as measured by land use changes, has increased by a factor of ten over the past three centuries (Ellis et al., 2010), throwing us into the Anthropocene epoch (Corlett, 2015). Human activity has transformed the global environment by profoundly altering land and water use, biogeochemical cycles and atmospheric chemistry on a planetary scale (Chapin et al., 2000; Geiger et al., 2010; Robinson and Sutherland, 2002; Vitousek et al., 1997). Land-use changes and the direct exploitation of natural resources are the determining factors of the current biodiversity crisis (Maxwell et al., 2016), threatening biodiversity and the essential ecosystem functions and services that underpin human wellbeing (Newbold et al., 2016). Agriculture is the principal land use, occupying almost 40% of the earth's surface (Foley et al., 2011). Intensive farming – a mode of agriculture dependent on chemical inputs (fertilizers and pesticides) and mechanization – dominates agricultural farming systems in Europe, North America, part of Asia and Australia (Tilman et al., 2002). Agricultural intensification has succeeded in fulfilling the global demand for food production at the expense of biodiversity, threatening key ecosystem services and ecosystem resilience (Tilman et al., 2002). The benefits of agricultural intensification may have reached its limits since yields are no longer increasing for many crops (Ray et al., 2012) and the response to the use of pesticides is saturating (Gaba et al., 2016; Lechenet et al., 2014). Intensive agriculture is recognized as unsustainable from both environmental and economic perspectives (Tittonell, 2014) and there is increasing recognition by farmers, citizens, non-governmental organizations and policy-makers of the need for radical changes in our agricultural systems. In the future, agriculture is faced with three challenges: (i) maintain food production to feed a growing world population with new needs, (ii) limit or reduce damage caused by farming systems to the environment, and (iii) control the increase in atmospheric CO_2 by promoting carbon sequestration in the soil. A fundamental paradigm shift in agricultural knowledge, science and technology is required to meet sustainability, production and profitability goals (Vanloqueren and Baret, 2009) while making agriculture more respectful of natural resources and resilient to global change.

Several alternatives to intensive farming systems have been proposed, ranging from smart agriculture which involves “high-tech” farming, using drones, satellites and robots (Bac et al., 2014; Wang et al., 2006), ecologically intensive agriculture (Godfray, 2015), or agroecology (Altieri, 1989). Agroecology considers biodiversity and ecological processes to be at the heart of the agro-ecosystem functioning, through the provision of ecosystem services, and has great potential for developing innovative and sustainable agricultural production methods (Altieri, 1989; Tittonell et al., 2016). However, controlling complex ecological processes to manage ecosystem services in real agricultural landscapes is challenging since the services are not fully understood and interact with each other (Bennett et al., 2009). Many ecosystem functions and services act over very different spatial and temporal scales with largely unknown relationships between local field-scale diversity and ecosystem functions operating at the landscape scale: for example, pollination and biological pest control rely on semi-natural habitats in the surrounding landscape (Chaplin-Kramer et al., 2013; Garibaldi et al., 2011). In addition, the production of ecosystem services results from the interplay between social and ecological systems (Reyers et al., 2013), but little is known about the combinations of the social and ecological contributions required to produce these services, their resilience and their sustainability over time (Bennett et al., 2015). Finally, ecological and social processes may act at different spatial and temporal scales, resulting in scale mismatches (Cumming et al., 2013). For example, social organizations are often too spatially limited to be able to manage global environmental problems such as depleting oceanic fisheries and maintain their resilience. In contrast, global or national regulations that make sense at a broad scale may have unfortunate consequences at finer scales (Cumming et al., 2006).

2. Socio-ecological framework and long-term social-ecological research platforms

The environmental crisis results from the interaction between social, economic, and ecological drivers. Systemic (and wicked) problems, such as the environmental sustainability target, have complex causes and consequences (Görg et al., 2014), and beg for a new scientific paradigm: accounting for heterogeneous and diverging viewpoints, involving stakeholder knowledge, aiming at cooperation between science and society, and shifting from mono-disciplinary approaches to transdisciplinary research (Folke, 2006; Ostrom, 2009; Jahn et al., 2012; Spangenberg et al., 2015). While sustainability sciences used to consider human activities as disturbance to natural ecosystems, human activities are now embedded within the framework of environmental sciences, together with research moving from site-based to broader, regional approaches. Socio-ecological research couples social and ecological systems (Collins et al., 2011; Haberl et al., 2006), and roots its research agenda onto inter-, as well as transdisciplinary approaches, to analyze systems that loop into co-occurring complex dynamics (Holling, 2001), involve cross scale dynamics (Levin, 1999), and are adaptive (Folke et al., 2005).

There is, therefore, an urgent need for research that considers both social and ecological systems at various spatial scales, from field to farm to landscape, and various temporal scales to understand (i) the role of biodiversity in sustaining multiple functions, (ii) how socio-ecological processes interact, either in synergy or opposition, in provisioning multiple services, (iii) the motivations and preferences of the diverse stakeholders for a given bundle of services, and (iv) how to generalize nature-based solutions and propose these to policy makers. This requires that we build up our knowledge of the fundamental processes that underpin the economic and environmental performance of agricultural systems.

This is the main purpose of the *Zone Atelier* network of Long-Term Socio-Ecological research (LTSER) platforms. LTSER platforms focus on socio-ecological systems (Redman et al., 2004; Mirtl et al., 2013; Singh et al., 2013). They consist in multi-scale and multi-level platforms with systemic interdisciplinary research approach, and produce long-term and large spatial scale data (Mirtl et al., 2013). LTSER can therefore be seen as a nexus between Socio-ecological research and more traditional LTER approaches (Dick et al., 2018), that emerged more or less simultaneously in Europe and the US (Mauz et al., 2012; Ohl et al., 2010). The concept of LTSER platform has gained much audience over the last decade (Haberl et al., 2006), with 35 LTSER claimed sites in Europe (Mollenhauer et al., 2018). However several caveat remain: first, though the socioecological paradigm is endorsed within LTSER sites, most LTSER still collect data on ecological processes (Dick et al., 2018). Second, in its European form, LTSER usually consist of a geographic region that encompass one or more traditional LTER sites where ecological research is conducted, while socioeconomic and cultural drivers are studied at a larger geographic scale (Mirtl et al., 2013), a nested design that may not necessarily favor the integration between social and ecological disciplines (see Dick et al., 2018). Third, governance issues and stakeholder involvement are still at their infancy in LTSER sites, despite participatory science may promote investment by citizens in bottom-up approaches and enable stakeholders to work together to generate innovative ideas for sustainable landscapes (Berthet et al., in press).

The "*Zone Atelier Plaine & Val de Sèvre*" (ZA PVS) fits with the LTSER concept: it covers a large study area (ca. 435 km^2) where socioeconomic and ecological data have been collected continuously since 1994. Focusing on agroecology as an alternative agricultural model, the LTSER aims at promoting nature-based solutions that integrate agricultural development and biodiversity conservation within resilient multifunctional landscapes. Besides data collection, the ZA PVS has been used to carry out experiments in real world conditions at various spatial scales, from fine scale (~1 m^2), to habitats (crops) and landscapes (e.g. by manipulating the proportion of meadows or hedges using NATURA 2000 (European Union) protected sites and agri-environmental measures). Three main objectives guide the ZA PVS research project. The first is long-term data collection through intensive monitoring of the socio-ecological system, including its ecology (the whole the trophic chain: plants, insects, spiders, small mammals and birds), landscape (configuration and composition, distribution of semi-natural habitats), and social aspects, such as land use, farmers' agricultural practices and public policies. The second objective is the experimental investigation of particular ecosystem services within an agro-ecological framework, e.g. experimental manipulation of pollination and biological pest control in relation to crop production and the socio-economic value of farming. The third objective is to identify solutions to improve the sustainability of the socio-ecological system management, exploring participatory science, action research and drawing up environmental public policies.

3. The study site, the *Zone Atelier Plaine & Val de Sèvre* (ZA PVS)

The study site, covering 435 km^2 (Fig. 1), has been designated a *Zone Atelier* (Lévêque et al., 2000) since 2008, though data collection started in 1994. *Zones Ateliers* are managed by the CNRS Institute of Ecology and Environment (INEE). The "Zone Atelier *Plaine & Val de Sèvre*" (ZA PVS) is located south of the city of Niort, in the *Deux-Sèvres* department in the *Nouvelle-Aquitaine* Region in, south-west France (Fig. 1). The area has open landscapes, it is relatively flat and the altitude is 60 to 160 MAMSL. It is a typical rural area with a temperate Atlantic oceanic climate, sparsely populated (62 ind/km^2) and managed almost exclusively for arable and mixed farming; the ZA PVS exclude the Forest of Chizé. There are 24 administrative *communes* inside the ZA PVS and 8 others (including the Niort urban district) partially within the ZA PVS. The total human population of the ZA PVS is ~29,000 inhabitants (excluding Niort). More than half of the study site was designated as a NATURA 2000 site in 2003 (NATURA 2000 code FR5412007).

3.1. Biophysical description

The region has a warm temperate climate with 820 mm annual precipitation and a mean annual temperature of 12.0 °C. The ZA PVS is an intensive farming area with mainly winter cereals (average 2009–2016: 41.5%). The most common crops are wheat (33.8%), corn (9.6%),

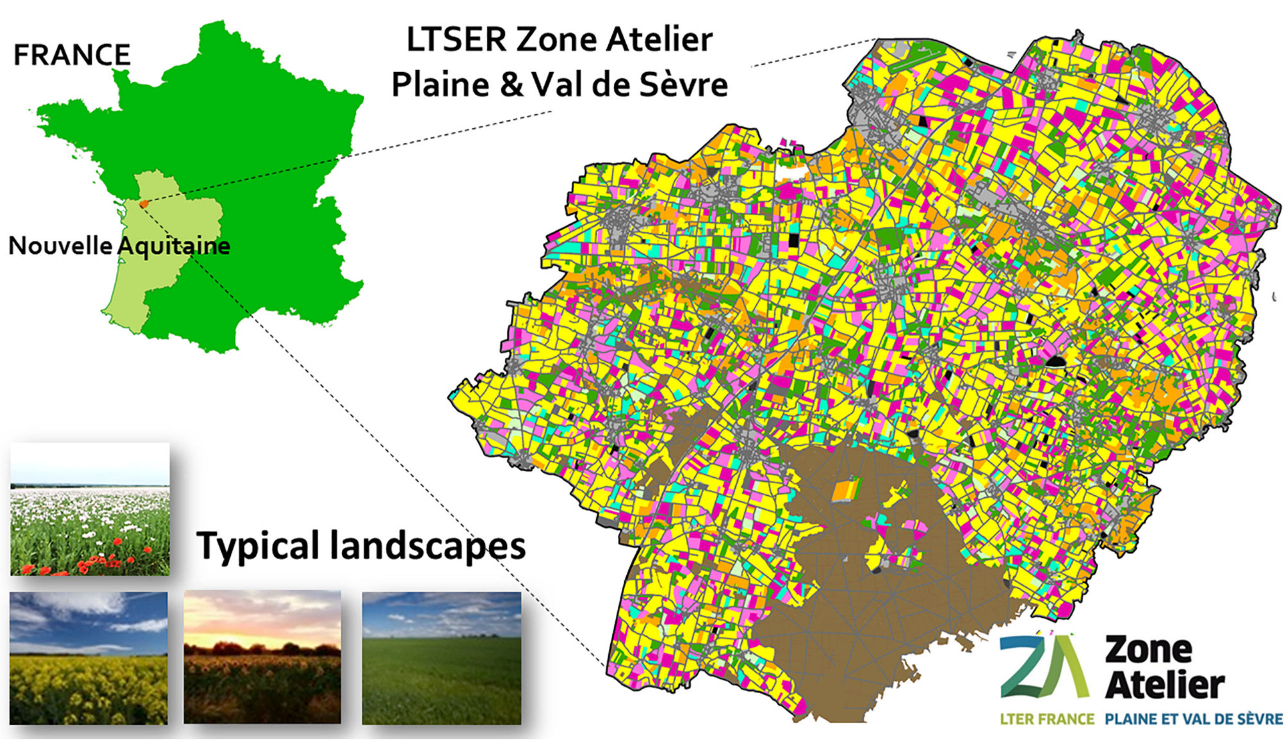

Fig. 1. Map of the ZA PVS in south-west France in the Nouvelle Aquitaine Region. Land use in the ZA PVS is represented by different colors e.g. winter cereals in yellow, woods in brown and urban areas in gray. Four typical landscapes of the areas are shown at the bottom left of the figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sunflower (10.4%), oilseed rape (8.3%), pea (2%) and meadows (13.5%), including both permanent grasslands and temporary hay (such as alfalfa). The fields are medium sized (4–5 ha). Meadow cover has strongly decreased, both in the long term (60% in 1970 down to 15% in 2016) and recently with a 30% decrease since 2007 with the abandoning of set asides in the European Union common agricultural policy (CAP). 9.8% of the area is urbanized and 2.9% of the area is in deciduous forest fragments. Livestock (cattle, goat) is still farmed but in steep decline. In the center of the ZA PVS, the "Forest of Chizé" (which is a NATURA 2000 protected site) is the largest forest in the region. The ZA PVS is crossed by a motorway that was built in 1981 which may act as a barrier to dispersal of many organisms (Gauffre et al., 2008).

The geological formation is dominated by a karst landscape with calcareous rocks ("brie") creating poor or very poor alkaline soils ("*terres de groies*") with rather low water retention and basic pH (pH >7), often <30 cm deep. The karst does not act as a watershed and the water flows have not yet been modeled. The ZA PVS is bordered by the *Marais Poitevin*, an important marshland that has been largely drained (Duncan et al., 1999), the Sèvre and Lambon rivers on the northern side and by the Boutonne river and a mosaic of natural wet meadows, riparian forest fragments and poplar cultivation on the eastern and south-eastern sides. The ZA PVS is crossed by a temporary stream (La Guirande), but surface water is a scarce resource, subject to multiple uses (tapwater, water for agriculture and industry), threatened by contaminants (especially nitrogen but also some pesticides). The entire ZA PVS is within a drinking water protected area.

3.2. The ZA PVS as a network of stakeholders

The ZA PVS is a collaborative platform where interdisciplinary research teams, with expertise in ecology, agronomy, environmental sciences, sociology, and economic sciences, interact with stakeholders. The site is managed by the *Centre d'Études Biologiques de Chizé* (CEBC) located at the center of the area (Fig. 1). Since the ZA PVS was designated in 1994, it has set up programs, involving local stakeholders, farmers, ordinary citizens and local authorities, to address key socio-economic challenges such as conservation of biodiversity, agricultural sustainability, quality of life and global change. Most programs bring together several local stakeholders, in transdisciplinary research projects, to evaluate their perception of various ecosystem services and identify potential social conflicts associated with particular ecosystem services (Görg et al., 2014).

The ZA PVS has a rather high diversity of agricultural strategies, with ~15 farms being managed using conservation agriculture, 45 farms using organic farming, and 350 conventional farms of which about 60% are mixed farms. About 200 farms were engaged in Agri-environmental scheme (AES) programs between 2004 and 2017, with a few dozen following precision agriculture guidelines. In addition, there are at least five major agricultural cooperatives currently operating in the ZA PVS. Since the designation of the Special Protection Area (NATURA 2000 network) in 2003, the ZA PVS principal investigator has been in charge of managing the AESs, being responsible for drawing them up as well as monitoring them, strengthening the links between research, farmers and local authorities. During the most recent campaign (2007–2014), 180 farms committed to an AES program, including measures towards farming extensification, replacement of arable land by meadows, management of low-intensity pasture systems, organic farming, and conservation of high-value habitats and their associated biodiversity. Nearly 10,000 ha were contracted in 2011 (up to 20% of the ZA PVS). AESs have been used for the ecological and socio-economic evaluation of the factors underlying farmers' commitment to the AESs as well as the environmental and economic consequences of this commitment at local and landscape scales. More recently, the links between scientists and farmers have evolved through innovative experiments in which they are directly involved (see Section 4).

Beekeepers are also important stakeholders involved in the ZA PVS research programs, since honey bees have been shown to increase oilseed rape and sunflower production (Bretagnolle and Gaba, 2015). French agricultural farmlands have traditionally been areas of high honey production, and the CAP has encouraged AESs for promoting floral resources for bees, such as floral fallows and field margins (Decourtye et al., 2010). In 2016 there were 164 declared beekeepers within the ZA PVS, with a total of about 20,000 hives, both permanent and transported from site to site. Finally, a large part of the research programs involve ordinary citizens and the local authorities in the ZA PVS. All of the 24 *communes* in the site participated in two main participatory science programs (presented in Section 5), one of which was directly aimed at schools.

3.3. Gently moving the research agenda from conservation to socio-ecological research

Originally, in 1994, the research project aimed at understanding the dynamic of endangered farmland birds (e.g., the little Bustard *Tetrax tetrax* or harriers *Circus spp.*), and consisted mainly in a conservation biology project. These top predator birds are however directly affected by changes at lower trophic levels (Furness et al., 1993), and eventually, the project consisted in studying the entire trophic network within which the top predators were embedded, a goal achieved before 2000. It then became apparent that the environmental changes induced by land use or agricultural practices indirectly affected the bird population dynamics through their prey. The study aims therefore moved to investigating the biotic, abiotic and human factors affecting the bird and prey dynamics alone and in interaction (Berthet et al., 2012). From the very beginning, researchers worked with farmers to protect bird nests, then to relate practices and biodiversity in the farmer's fields. In 2003, a Natura 2000 site was designated within the ZA PVS to protect 17 species of birds from the Bird Directive (Annex1 of the EU Birds Directive, 79/409/EEC), including the Little Bustard and the harriers. The ZA PVS principal investigator became the local manager the Agri-environmental contracts, which strongly contributed to reinforce links between research, farmers and local authorities. The designation of the protected area initiated transdisciplinary research gathering ecologists, economists and social scientists, to explore for instance the spatial allocation of the extensively managed grasslands (Bamière et al., 2011). A final step was launched in 2005, when citizen science projects (see Section 6) were deployed successfully, completing the LTSER mutation.

Although most of the funding of the ZA PVS comes from national research grants, the research agenda is guided by socio-economic issues or societal challenges such as the conservation of flagship species or the regulation of the use of pesticides. Indeed, the LTSER ZA PVS platform not only involves stakeholders in research projects and agro-ecological experiments, direct and frequent links with local and national authorities have also helped research results to have substantial consequences on public policies. Using the ECOBEE platform (Odoux et al., 2014), we investigated the relationships between honey bees and neonicotinoids, a class of systemic insecticides. In 2012 we demonstrated, for the first time, the effect of thiamethoxam (used for oilseed rape in France) on the survival of honey bees (Henry et al., 2012). Following these results, the agriculture ministry decided on a moratorium on rape seed treated with Cruiser (thiamethoxam) for three years, a decision followed in 2013 at European level by the EFSA. There was only a six month lag between the publication of the results and a public policy decision. In 2014, another trial at landscape scale was launched on the LTSER and confirmed the effect of Cruiser on beekeeping (Henry et al., 2014), and in 2015 another study showed the persistence of imidacloprid (another neonicotinoid) on cereals (Henry et al., 2015). This led to the ZA PVS principal investigator attending a hearing in the French National Assembly in January 2016 (see ZA PVS web portal) and to the publication of several articles in national media, which greatly contributed to the definitive ban on neonicotinoids in France from 2018 under the Biodiversity Law (July 2016).

4. Long-term, spatially explicit socio-ecological monitoring

Socio-ecological monitoring is one of the key activities of the ZA PVS. This covers key aspects of the trophic network, ecosystem functions and services, stakeholders and their activities as well as public policies (including. AESs, NATURA 2000). The monitoring strategy (i) analyzes the relationships between socio-technical data (agricultural practices and yield at the field scale using interviews with farmers) and biological data (biodiversity and ecosystem functioning), (ii) is spatially explicit with, since 2010, an experimental design based on 1 km^2 landscape windows selected to avoid cross-correlations between the landscape gradients being studied, (iii) is replicated every year to collect comparable data over the long term, for detecting trends due to global change. Below, we detail the three main features of our monitoring scheme.

4.1. Land use monitoring spatial design

The land cover has been monitored yearly at the field scale since 1994 (~19,000 fields/plots in 1996, ~13,000 in 2015, see Fig. 1). >30 categories of crop were recorded as well as all built up areas, roads/tracks, forest fragments (down to 0.1 ha), rivers and hedges. This therefore provides a very detailed, continuous description of the landscape that allows spatial analyses at any grain size from 1 ha to 45,000 ha. Agricultural fields/plots are defined according to their topology and land use, which is not the same as the land registry blocks or those in the graphical registry (RPG) updated every year and distributed by National Geographic Institute (IGN) (see (Levavasseur et al., 2016) for an example for the ZA PVS). Every year, land use and crops for each field and the shape of each field are surveyed exhaustively by fieldworkers driving cars slowly on every single track or road and recording land use and crop data in a GIS database. There are two surveys annually (March/April and June/July) to identify early and late sown crops. All information collected is then checked and stored on a server. There has been significant land cover change in the ZA PVS, with cereals in particular increasing by ~20% in 24 years. Conversely, meadows and other permanent components of the landscape (e.g. hedgerows) have declined, despite their critical role for the maintenance of biodiversity (Batáry et al., 2010; Bullock et al., 2002) and the provision of bundles of ecosystems services in intensive agro-ecosystems (Foley et al., 2011).

Detailed knowledge of land cover has been used for setting up tightly targeted spatial designs for biodiversity surveys and ecosystem function experiments (Fig. 2). Since 2010, 40 to 60 1 km^2 windows have been selected each year along landscape gradients that were chosen for particular research aims. These windows define the spatial limits within which biodiversity and ecosystem functions are sampled. The windows are selected using available land cover maps (crops, semi-natural habitats, forests and built up areas) to create statistically independent landscape gradients (Fahrig et al., 2011) for testing hypothesis relating biodiversity and ecosystem functions to local farming intensity and landscape heterogeneity. The independent gradients reflect variations in composition (crop diversity) and configuration (Pasher et al., 2013), as well as meadows, woodland and organic farming cover within the landscape window. Landscape windows are selected using an algorithm written in R that moves a window over the whole of the ZA PVS, iteratively selecting the windows to minimize inter-gradient correlations.

4.2. Long term biodiversity monitoring

From 1994 onwards, biodiversity surveys have been carried out every year, starting with birds and small mammals since 1994, ground dwelling arthropods since 1995 and then other arthropods (grasshoppers since 2000, bees and hoverflies since 2009, spiders since 2013), plants since 2005 and soil organisms since 2016. Surveys are performed at field scale for most taxa, though for some threatened species of birds

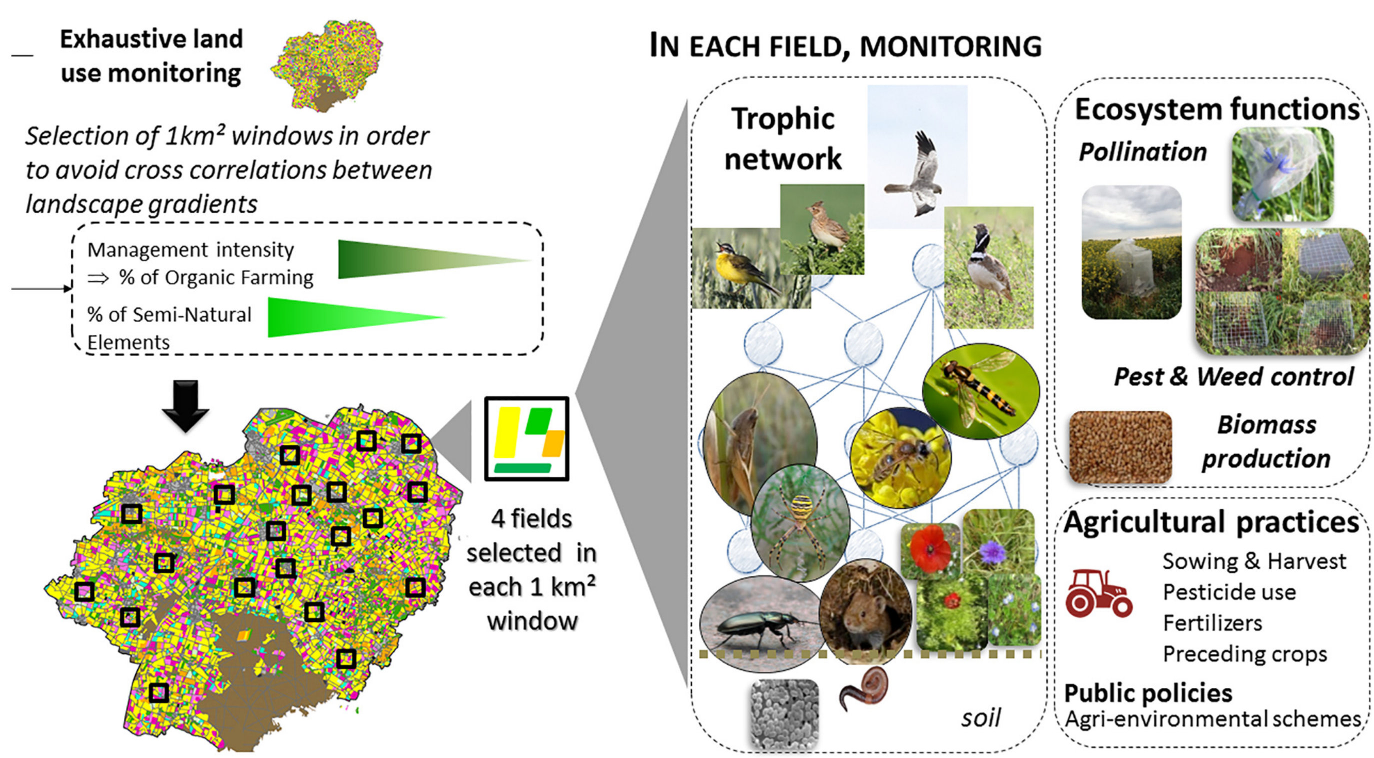

Fig. 2. The ZA PVS monitoring strategy applied since 2013. Based on the exhaustive land use knowledge, 41 km^2 windows are selected in order to avoid cross correlation between landscape gradients (here % of organic farming and % of semi-natural habitats). In each 1km^2 window, four fields are selected and biodiversity, ecosystem functions and agricultural practices are monitored in each of these fields.

Table 1
Sampling protocols used for monitoring biodiversity in the ZA PVS.

Taxa	Targeted group (s) or species	Targeted crops/habitats	First survey	Sampling technique	Variable	Landscape scale spatial design	Within field sampling design	Nb. of sessions per year	Survey period	Annuel survey effort	Main changes in the protocols over time	References
Plants	Weeds	major crops and borders	2005	Quadrats	Presence/Absence per m^2	2–3 fields within 40–60 $1km^2$ windows along landscape gradients	80 0.25 m^2 quadrats in field core and 20 0.25 m^2 in field margin	1	From April to July	100 to 250 arable fields	Quadrat area, within field sampling design and abundance scale	Gaba et al. (2010); Meiss et al. (2010); Perronne et al. (2015)
	Grassland plants	grasslands	2008	Quadrats	Presence/Absence and Abundance (cover) per m^2	1 grassland within 40–60 1 km^2 windows along landscape gradients	10 × 1 m^2 randomly located quadrats and 10 × 0.25 m^2	1	From April to July	60 to150 grasslands	Quadrat area, within field sampling design and abundance scale	
Arthropods	Ground dwelling arthropods (carabid beetles and spiders)	major crops, borders and grasslands	1995	Pitfall traps	Activity-Density per trap	3–4 fields within 40–60 1 km^2 windows along landscape gradients	2 traps in border and 2 traps within field	2	From April tu July (+irregular additional samplings)	20 to 400 fields	Trapping solution	Marrec et al. (2015); Caro et al. (2016)
	Honey bees	All	2008	Hive survey	Not relevant	Hives are randomly allocated to 10 grid cells out of a network of 50 grid cells with 3.3-km spacing	Not relevant	Twice a month	March to October	50 colonies assigned into 10 apiaries	not relevant	Odoux et al. (2014)
	Wild bees	Major crops, borders and grasslands	2010	Net captures	Abundance per meter	3–4 fields within 40–60 1 km^2 windows along landscape gradients						Rollin et al. (2013, 2015).
	Hoverflies, Wild bees	Major crops, borders and grasslands	2013	Pan traps	Abundance per trap	3–4 fields within 40–60 1 km^2 windows along landscape gradients	3 traps in border and 3 traps within field	2	From April tu July	From 100 to 400 fields		
	Butterflies, Honey bees, Hoverflies, Wild bees	Major crops, borders and grasslands	2013	Sweep nets	Abundance per meter							
	Grasshoppers	Grasslands	1999	1 m^2 cage sampler	Abundance per m^2	Grasslands randomly selected among all grasslands in ZA PVS	10 to 25 replicates per field	1	End of July	20 to 250 grasslands		Badenhausser et al. (2009); Badenhausser et al. (2009)
Birds	*Montagu's*, *Hen* and *Marsh harriers*, little bustard	Wheat, Ray grass (harriers) and Alfalfa (Little bustard)	1995	Nest searches	Abundance	Full coverage of the ZA oVS	Not relevant	3				Arroyo and Bretagnolle (1999); Jiguet and Ollivier (2002); Jiguet et al. (2000); Villers et al. (2010); Bretagnolle et al. (2011); (Millon et al., 2002)
	Montagu's, hen and marsh harriers	Not relevant	1995	Exhaustive count	Abundance	Full coverage of the ZA PVS	Not relevant	Continuous from April to September				
	Little owl, Scops owl and Stone Curlew	Not relevant	1999	Nocturnal point counts	Abundance							Génot (2005)
	Passerine	Not relevant	1995	Diurnal point counts	Abundance							Brodier et al. (2014); Bonthoux and Balent (2012)
Small mammals	Common vole, wood mouse, shrews	Major crops, borders and grasslands	1995	Trap line	Abundance per trap	1–2 fields within 3 to 4 1 km^2 windows along landscape gradients			April and June		Trapping methodology and design	Gauffre et al. (2008); Pinot et al. (2016)

and plants (e.g. cornflower), surveys are exhaustive and performed over all of the ZA PVS. The spatial sampling design at the field level has changed from year to year and depends on the target taxon, from total random sampling (e.g. grasshoppers), line transects across fields (e.g. small mammals), line transects within fields (pollinators, plants, small mammals) and point counts (birds) or point traps (carabids, spiders). A trait database has been built for all trophic groups including traits related to body size, resource acquisition and dispersal abilities (Deraison et al., 2015; Le Provost et al., 2017). Since 2013, the entire trophic network is monitored in three to four fields located within the 1 km^2 landscape windows. The sampling methods are summarized below and in Table 1.

Quadrat surveys have been used since 2005 for weeds, i.e. the wild plants in farmland. Arable weeds have been monitored in 100 to 250 fields annually, including at least 100 winter wheat fields (the major crop on ZA PVS). Overall, the dataset currently contains about 3000 field surveys. In both annual crops and alfalfa, quadrats are spread along a transect within the field, but the margins are also surveyed. The occurrence and abundance of individual weed species are recorded in each quadrat (Gaba et al., 2010; Henckel et al., 2015). Seasonal variations have been included since 2015. Meadows have been monitored since 2011, either in artificial ones (sown with alfalfa <6 yr), temporary meadows (sown with grasses <6 yr) or permanent grasslands (age > 5 yr). Plant abundance is quantified by the percentage cover in each quadrat.

Point counts have been the main bird monitoring method, with nest searches and exhaustive counts for threatened flagship species (those that are targeted by NATURA 2000, such as the Little bustard *Tetrax tetrax* (Bretagnolle et al., 2011) and three species of harriers (Millon et al., 2002)). There have been two nocturnal point counts per breeding season for owls (using playbacks) and stone curlews (Gaget et al., in review) since 2000, and diurnal point counts for passerines and other birds. Passerine populations have been surveyed during the breeding season since 1995, using various survey designs one of which has been spatially constant since 1995 (Brodier et al., 2014).

Point traps have been the main insect monitoring method. The activity-density and species richness of ground dwelling arthropods (including spiders and carabid beetles) have been estimated since 1995 using pitfall traps (3 to 5 per field) in 30 to 300 fields and field margins of major crops: grassland, alfalfa, oilseed rape, wheat, maize and sunflower (Caro et al., 2016; Marrec et al., 2015). Grasshopper densities and diversity have been estimated annually since 2000, with 40–200 meadows surveyed every year at the end of July, the mature adult peak (Badenhausser et al., 2009). A 1 m^2 cage biocenometer was used and 10 to 30 samples per field were collected. Since, 2010 pollinators, i.e. honey bees, wild bees, hoverflies, moths and butterflies have been sampled by two complementary methods (see Westphal et al., 2008) on 120–240 fields per year: i) 12 colored pan-traps (plastic bowls 12 cm diameter and 10 cm deep painted fluorescent yellow or blue or left white), which catch mainly wild solitary bees, and ii) sweep netting along transects to survey all pollinators (Rollin et al., 2013).

Line transect surveys have been used for small mammal trapping since 1995 in 60 to 160 fields per year. Each major crop type has been represented in a sampling design uniformly covering the whole study area. Samples were taken in April and June/July while other months were sampled less regularly (Pinot et al., 2016).

These surveys have shown that the ZA PVS is very rich for biodiversity in general: weeds (~400 species out of 4500 in France), wild bees (over 250 out of the 960 species known in France), birds (~100 species out of 280 in France) and grasshoppers (25 species out of 123 in France, about 20%) (Table 2). There are also rare and very rare species in the ZA PVS such as *Paracinema tricolor* Thunberg (grasshopper).

Biodiversity surveys are all spatially explicit, with either random or stratified sampling, for drawing up distribution and abundance maps using geostatistical approaches or more flexible spatial generalized linear models. Fig. 3a shows the patterns of arable weed richness reflecting the large variability of agricultural practices and environmental factors. The dedicated spatial design of the surveys provides insights into, and quantification of, the effects of crop and meadow management, farming practices and landscape structure on biodiversity. We repeatedly found that landscape scale processes are as strong (or even stronger) than local scale processes in shaping communities, species assemblages and traits (Caro et al., 2016; Henckel et al., 2015; Le Provost et al., 2017). Annual surveys have also made it possible to build long time series for various biodiversity components, such as the cyclic common vole population (Fig. 3b).

4.3. Measuring ecological functions, ecosystem services, practices and policies

Recently, there have been experimental measurements of key ecosystem functions related to pest regulation, pollination and productivity. These have been carried out on the same fields as the biodiversity surveys.

Biological pest control has been quantified in 120–240 fields per year, since 2013, using predation cards. Cards include weed seeds (*Viola arvensis*), aphids (*Acyrthosiphon pisum* Harris) and moth eggs (*Ephestia kuehniella*). Since 2014, some of the cards have been caged, with small (<6 mm) and large mesh (13 mm) to differentiate predator guilds. As the fields surveyed for biological control are also surveyed for biodiversity, the predator communities can be compared to the predation rates.

Soil fertility was measured in 2015, either indirectly through earthworm sampling (Pelosi et al., 2013) or decomposition rate measurements using the tea bag index (Keuskamp et al., 2013).

Pollination by insects has been measured using phytometers and caged crop plants in fields. So far, four plant species have been used as phytometers in the ZA PVS, oilseed rape, sunflower, cornflower and radish (see also next section for crops).

Honey production has been monitored using standardized surveys of honey bee population dynamics with the ECOBEE long term honey bee experimental monitoring platform set up in 2008 (Odoux et al., 2014). The ECOBEE platform was set up to deal with the numerous concerns of professional beekeepers in modern agricultural environments and provides scientists with basic, accurate, long-term ecological data on honey bees under current beekeeping practices (Odoux et al., 2014).

Crop yield has also been monitored every year since 2006. Farmers have been interviewed using a very detailed questionnaire to collect information on selected farms in the ZA PVS (about 100 farms each year since 2009). We interview the owners of the fields in which the biodiversity and ecosystem functions have been monitored. The interviews provide allow accurate monitoring of the farmer's practices as well as yields and revenue. The questionnaire attempts to capture information on the variables that may explain the variation in gross revenue and yields, and to test for the effects of farmers' practices on biodiversity and ecosystem functions.

Public policies have been monitored, mainly agri-environmental policies such as NATURA 2000, AESs and the Nitrate directive (water quality) as well as species conservation policies. Both AESs and organic farming have been shown to be beneficial at both local and landscape scales for various taxa including plants (Henckel et al., 2015), carabid beetles (Caro et al., 2016), grasshoppers (Badenhausser and Cordeau, 2012; Julier et al., 2017) and birds (Bretagnolle et al., 2011). We have also assessed the effects of NATURA 2000 sites on birds (Brodier et al., 2014). Water and nitrogen pollution were evaluated at landscape scale, using innovative designs (Berthet et al., in review; Berthet et al., 2012). Finally, the ZA PVS is involved in national and international biodiversity conservation programs which focus on threatened bird species (Schlaich et al., 2017; Schlaich et al., 2016), with exhaustive monitoring since 1994 and the adoption of AESs, resulting in population recovery for some species such as the little bustard, (Bretagnolle et al., 2011), but not other species such as the stone curlew, (Gaget et al., in revision).

Table 2
Diversity of the main taxa monitored in the ZA PVS. The three values of diversity are: α-diversity (usually the field scale), γ-diversity (diversity in the ZA PVS) and diversity in France.

Taxa	Targeted group(s) or species	γ diversity	Mean α-richness (range)	Diversity in France	References
Plants	Weeds	429	17.85 (5–47)[a]	1262	Jauzein (1995)
	Grassland plants	239	5.89 ± 4[a]	>2000	Violle et al. (2015)
Arthropods	Carabid beetles	99	8.2[a]	1000	Dajoz (2002)
	Grasshoppers	25	4.3[a]	123	
	Spiders	208		1725	http://asfra.fr/Site/Main_public.html
	Hoverflies	68		>500	
	Wild bees	263		960	
Birds	Passerines	105		306	Issa and Muller (2015)
Small mammals		9	1.38	31	Quéré and Le Louarn (2011)

[a] At field scale

5. Experimental socio-ecological evaluation of the biodiversity/function/ecosystem service cascade

Empirical analysis of long-term monitoring data provides an overview of the responses of populations, species, trophic interactions and agro-ecosystem functioning to global change. To explore new approaches for agriculture, experiments are needed to understand the underlying mechanisms linking biodiversity, agricultural practices, the landscape and the provision of multiple services. Consequently, the long-term monitoring program has been supplemented by experiments in farm fields to identify and understand the processes underlying the spatiotemporal dynamics of biodiversity and associated functions, with particular focus on the effect of management changes (e.g. pesticide reduction) on the delivery of ecosystem services. Experiments in a working agroecosystem are challenging as the system is highly dynamic, changes depend on the interactions between social and ecological processes and there is a mismatch in the scales over which social and ecological processes act. In the ZA PVS, we have therefore developed innovative socio-ecological experiments in which the factors of interest are manipulated from small scales (1 m^2) to landscape scales at various biological (population, community, food web) and social (field, farm) organization levels. Below, we describe three types of experiment undertaken with farmers in their fields to evaluate important ecosystem services such as crop pollination and biological control, in relation to reduction in pesticide use, crop production and the socio-economic value of farming.

5.1. Estimating pollination service in real farm conditions

Pollination in farmland landscapes is a keystone function for the delivery of multiple ecosystem services: (i) it is directly involved in crop production (e.g., oilseed rape, sunflower) and is, therefore, a provisioning service for farmers (Klein et al., 2007), (ii) it directly supports economic activity through beekeeping and apiaries (Odoux et al., 2014),

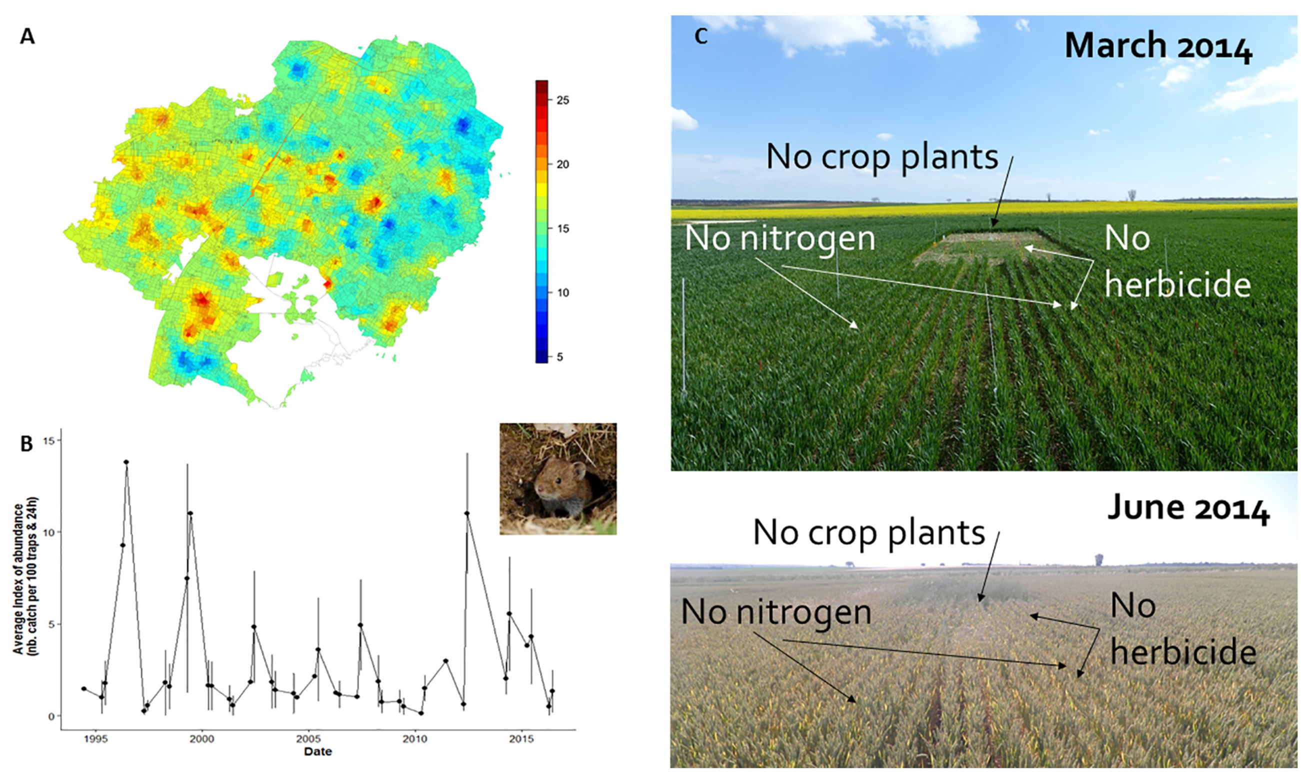

Fig. 3. a) Map of weed species richness in arable crops in the ZA PVS over the 10 past years. Black dots indicate fields in which weeds have been surveyed. Ordinary kriging was used on square-root transformed species richness and local random effect. Weed richness varied from less than five (blue) species to >25 species (red). b) Time series of common vole abundance in the ZA PVS based on April and June sampling campaigns from 1995 to 2016. Abundance is expressed in number of catches per 100 traps and 24 h averaged over the five major crop types (cereals, oilseed rape, alfalfa, meadows and spring crops). c) Pictures of the chemical input reduction experiment in winter wheat in one of the 56 farmers' fields used. The pictures show the experiment at two points in time: in March (top) and June (below) 2014. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(iii) it is a regulating service, being involved in the population regulation of many native plants and insects (Clough et al., 2014) that directly affect crop production (weeds and many insects that may be either pests or auxiliaries (Bretagnolle and Gaba, 2015; Rollin et al., 2013), and (iv) finally it is viewed as a cultural service because many species of bees are dependent on the conservation of habitats and pollinate rare plant species (Clough et al., 2014). Pollination, associated with wild and domestic bees (in addition to other insect pollinators such as hoverflies, moths and butterflies) in farmland landscapes is common to many services and sources of conflicts between stakeholders' aims.

Targeting this key regulating ecosystem service, we quantified the effect of insect-pollination on productivity (seed yields) of oilseed rape and sunflower crops as well as farm profitability. The effect of pollination by insects on yield quantity and quality has been quantified using pollinator exclusion (insect-proof bags around flowers) on selected oilseed rape plants in 30 farm fields per year since 2013. Farming practices and revenues have been assessed using interviews with farmers. The effects of landscape heterogeneity on the importance of pollination by insects has been assessed using phytometer experiments with oilseed rape plants grown in the lab and pollinator exclusion treatments. Phytometer experiments have been used to estimate seed production in a large number of fields (~200 each year), covering a diversity of landscapes along gradients (with increasing proportion of semi-natural habitats) exploiting the variability of landscape features in the ZA PVS.

5.2. Evaluating the effect of input reductions on ecological processes and agricultural performance, from plots to farms

Reducing the use of agrochemicals is one of the main challenges in agriculture. However, little is known on the consequences of such reductions on biodiversity as well as on farmers' productivity and profitability. Cropping systems are subject to wide variations in agricultural practices as they depend on farmers' attitudes, the pedoclimatic conditions and the interactions between these (Gaba et al., 2014; Gaba et al., 2016). We set up an experiment with farmers to address these questions, focusing on the use of herbicides and nitrogen inputs for winter cereals. Farms were selected to cover a wide range of farming intensity within the ZA PVS from organic farming to high-input conventional farming. A factorial approach was used to untangle the changes in weed diversity and crop production in response to reductions in weed control and nitrogen amendment alone and together. We also investigated the effect of presence of crops on weed diversity as a function of the inputs to quantify the potential regulatory effect of the crop on the weeds, i.e. the wild flora in fields. Each factor was binary, i.e. present or absent (Fig. 3c). The experiment was carried out by the farmers according to an experimental design provided by the scientists. Farmers were surveyed to characterize the cropping system with particular attention paid to the characterization of agricultural practices that might interact with the variables of interest. For instance, seedling density may affect the competition between the weeds and the crop. Both ecological and economic outputs were evaluated giving important insights for both fundamental and applied science (Catarino et al., in review). This was the first experiment in a move towards medium-term experiments on a wider spatial scale. In a six year experiment starting in 2015, nine farmers are testing innovative bee-friendly practices over 2 ha in each of 27 fields, consisting in reducing pesticide inputs to (i) increase weed resources for bees between the blooming periods for oilseed rape and sunflower and (ii) decrease the exposure of bees to insecticides. The experiment is being carried out in three main crops: oilseed rape, winter cereals and sunflower. A multi-criteria evaluation will assess whether these innovative bee friendly practices are sustainable for biodiversity, production and net farm revenues. To conclude, these experiments provide an opportunity to bring together farmers, beekeepers and scientists to discuss their own interpretations of the results, thus facilitating knowledge transfer.

6. From participatory research to adaptive governance of an agricultural area

Recent research has identified the need to foster less centralized, more participatory organizations that better take into account the diversity of agricultural production and ecological conditions (Prost et al., 2017; Spangenberg et al., 2015). Many studies have shown that involving local stakeholders in data collection and experiments speeds up decision making (Danielsen et al., 2010). Local stakeholders' participation may also lead to a better understanding of the socio-ecological system (Görg et al., 2014; Spangenberg et al., 2015), thereby improving decision making (Reed, 2008). For instance, participatory science may promote investment by ordinary citizens in protecting their local area since better knowledge improves place attachment (Pellow, 1992). However, bottom-up approaches raise difficult challenges for the management of agricultural innovation which needs to deal with many widespread, independent farmers as well as with other stakeholders (residents, agricultural extension agencies, naturalists, agribusinesses, local authorities, etc.) who often have diverging interests and complex relationships. Some important questions remain for agriculture policy, such as how to meaningfully involve different stakeholders in collaborative processes where historically there have conflicting points of view (Darly and Torre, 2013), and how to enable these stakeholders to work together to generate innovative ideas when agricultural lock-in effects are particularly strong (Vanloqueren and Baret, 2009). These questions call for new research on innovative cooperatives aiming to enhance agroecosystem sustainability, hereby opening new perspectives for agroecosystem governance. Rather than developing coercive or incentive policy instruments, this research could promote the emergence of local planning cooperatives. Two related bottom-up approaches have been implemented in the ZA PVS: the first involves citizens in participatory science programs and the second studies local governance processes at the local scale.

6.1. Involving citizens in participatory science programs

In the ZA PVS, we started participatory science programs with children with the aim of strengthening their link with nature and biodiversity, and then eventually enlarged citizen participation to parents and the rest of the rural and urban population. A first participatory project, "***Des nichoirs dans la Plaine***" ("Nest boxes in the plain"), started in 2008 and combined both experiential learning and dissemination of the scientific results. The project arose from conservation concerns for three species of bird (hoopoe, little owl and scops owl) whose populations are in decline all over Western Europe. The research part of the program consisted in testing the hypothesis that these bird populations were limited by the number of suitable nesting holes (all of them nest in holes). Suitable holes have become much rarer over the years through building construction and renovation and cutting old trees. We predicted that increasing the number of suitable holes could increase the populations. This program also aimed at raising children's awareness of scientific reasoning and ecosystem complexity by showing the extent to which these birds need not only nesting holes but also meadows around villages to forage for prey, highlighting the need for complementary habitats. From 2008 to 2010, 2200 nest boxes were installed in 1460 household gardens. The children used a web platform to compile their observations that we then recovered and analyzed. Nearly 10 years after the start of the program, the number of little owls has increased by 25% (unpublished data).

A second program, "*Mon Village, Espace de Biodiversité*" *(My village, a haven for biodiversity)*, started in 2012. This five-year educational program concerns various ecosystem services: pollination, biological pest control, organic matter recycling and socio-cultural services. Contrary to "*Nichoirs dans la Plaine*", "*Mon village, Espace de Biodiversité*" targeted all inhabitants of the villages in the ZA PVS, not just children. They were invited to collect data (for instance some of them buried tea bags in their gardens to quantify soil organic matter recycling), and to participate in forums, public conferences and adult education courses. Over the five years, 7600 people participated in the public conferences. But the most visible action of the project was the installation of communal hives in each village of the ZA PVS, a total of 23 hives. Villagers were invited to take care of the hives after a period of learning with professional beekeepers. They, together with public works staff responsible for green spaces, were also encouraged to improve flower richness, in both gardens and communal areas. At the end of the season, all villagers were invited to harvest the honey. Insect shelters were also installed in 1518 gardens (8% of the households in the ZA PVS) for wild bees. In parallel, scientists and NGO staff gave regular conferences about biodiversity, especially to 2236 school children in the 23 primary schools. As is normal for citizen science projects (Kullenberg and Kasperowski, 2016), this project did not produce scientific output in the form of academic peer-reviewed papers, but the participants increased their knowledge of both biodiversity and their own effect on ecosystem functioning. These two programs proved to be very successful, achieving their aim of bringing together citizens, scientists and local authorities to discuss the issues and enabling the local population to improve their understanding of ecosystem functioning. The very high level of participation (around 20% of all the inhabitants of the ZA PVS) is an indicator of the success of these projects.

6.2. From the study of local governance to adaptive governance

In addition to participatory science programs, we have recently developed programs with farmers and beekeepers to promote collective discussions on the design of multifunctional sustainable agricultural landscapes. A pilot study provided a typology of the mental models of a wide set of stakeholders (farmers, beekeepers, politicians, environmental associations, crop firms, pesticide firms) and identified the key points where a there was a lack of common understanding (Vuillot et al., 2016). A participatory research project led to a common representation of the functioning of the crop farming/beekeeping socio-ecological system in order to identify the challenges to be faced by the implementation of adaptive co-management. We used a companion modeling process adapted from the Commod method (Étienne, 2013), which relies on sharing knowledge as the primary method of advancing relationships between individuals, and between individuals and the resource. The collaborative workshops and the companion modeling process identified several options for changing the existing systems, including (i) involving beekeepers when designing the cropping system, (ii) joint monitoring of the impact of forage harvesting on grain, seed and honey production, and (iii) making crop agrochemical treatments compatible with apiary management. This transdisciplinary research program currently aims to investigate the decline in honey production and honey bee populations, trying to disentangle several possible causes, and their interactions in such intensive agricultural landscapes (Decourtye et al., 2010), such as pesticides (Henry et al., 2012), parasites and diseases (Rosenkranz et al., 2010), lack of floral resources (Requier et al., 2015) and the reduction in floral diversity in agricultural landscapes (Potts et al., 2010). A main challenge however remains. This is ensuring resilient co-evolution of two different types of agriculture (arable farming and beekeeping), that can be seen as two smaller scale interdependent socio-ecological systems overlapping in space and time. The ways these systems behave with multiple interrelated components, shared from field to landscape scale, suggest that they are interlinked in continual adaptive cycles with cross-scale effects (Bretagnolle and Gaba, 2015).

Within the ZA PVS, we have also analyzed local governance processes at the agroecosystem scale, first as part of the implementation of NATURA 2000 (Berthet et al., 2012), then during the setup of a local, environmentally-friendly alfalfa supply chain with a local agricultural cooperative (Berthet et al., 2016). The first study highlighted the advantages of applying local ecological knowledge to the design of conservation strategies and agri-environmental schemes (Berthet et al., in review; Berthet et al., 2012). In the second study, we supported the alfalfa supply chain project by setting up a collective design workshop, which involved about 30 local stakeholders, agricultural cooperative technicians and members, as well as ecologists and agronomists. This workshop used the KCP (knowledge, concepts, proposal) method (Hatchuel et al., 2009) and the main outputs were the identification of various acceptable landscape configurations for maintaining bird populations and the identification of gaps in our knowledge, which led to a research action project for the implementation of the alfalfa supply chain ("*Prairinnov project*", 2012–2014, which was run jointly by the CNRS/CEBC and the cooperative). It assessed the impacts of various strategies for the application of inputs and for mowing alfalfa on environmental processes. It also produced insights into the effect of the distribution and proportion of alfalfa in the landscape on the provision of various ecosystem services. Lastly, it explored the effects of the local alfalfa supply chain on both the farms involved and the cooperative handling it. This study also proposed that meadows should be considered as common goods and managed collectively as is traditional in many countries, relying on self-organization at a local scale, as an alternative to public funding, for increasing biodiversity in agricultural areas. This approach could be tested within the ZA PVS.

7. Improving data management efficiency

With long-term data gathered over large spatial scales (19,000 fields and over 550 farms in 1994), the total data collected for research over the past 23 years is not only voluminous, but also very heterogeneous as the databases used, the protocols and the sampling schemes have evolved over time. The datasets also require ethical reviews of the collection, storage and use of the data, including release of anonymized or pseudonymized data on land use and agricultural practices to external researchers. Although much effort has been devoted over the past years to improve data traceability and anonymization, as well as data access and storage, there are still important challenges. Below we list three main issues we had to deal with, i.e. data access, data interoperability and long-term data storage.

Open-data access is now expected under European legislation (PSI Directive 2013/37/EU and INSPIRE Directive 2007/2/EC) and FAIR (Findable Accessible Interoperable and Reusable data, (Wilkinson et al., 2016)) scientific ethics, requiring both high storage capacities and easy Internet access. One quick and easy method is to release metadata. This has been done for ZA PVS within the metadata portal available in DEIMS (see Mollenhauer et al., 2018). However, standards for metadata sometimes differ even within a discipline. In the field of ecology, for example, both the Ecological Metadata Language and ISO 19115 standards are used, with pros and cons (Moritz et al., 2011). Moreover, there are currently no established standards for interdisciplinary communication. Finally, metadata standards are not suited to the needs of all potential users, and metadata access may not necessarily ensure effective data reutilization. Another solution therefore consists in data publication, describing the datasets in detail, including any modifications to protocols and sampling schemes. We have started preparing data papers (e.g. Plumejeaud-Perreau et al., 2014 on weed monitoring), however, the number and diversity of data sets will require very large number of data papers.

Data heterogeneity (a combination of ecological and sociological data) creates a second issue in data management. Our strategy has focused on analysis rather than on conventional data management, i.e. data interoperability rather than standardization. We have created a spatio-temporal RDF ontology, so that a SPARQL end point can be used for querying data. This supports spatial reasoning and can be used as a semantic mediator to resolve the semantic inconsistencies between the various datasets (Tran et al., 2016).

Data set continuity and long-term data storage is the third issue. This arises from changes in data collection methods, software and file structures. Information technology is evolving very fast and software accordingly. For instance, since 1994, the land use and spatial organization of 19,000 agricultural parcels has been recorded in the field each year and stored in an ARCGIS/ACCESS database with >600,000 records. Due to the size of the data set, we eventually moved the base to a QGIS plugin/PostgreSQL DBMS (Plumejeaud-Perreau et al., 2014). However, the QGIS plugin was implemented using QGIS 1.8, using the Python API, but the API for QGIS 2.1, which is now used, is incompatible with the earlier version. Another continuity issue is that data storage is expected to last for decades while projects are funded for very short periods and hosting charges are paid monthly, not for decades.

8. Conclusions and future prospects

The ZA PVS is a unique consolidated LTSER platform that ranges from the study of changes in biodiversity with farming intensification and the conservation of biodiversity, through the design of new nature-based solutions for novel agricultural practices and multifunctional landscapes, to their implementation in working farms taking account of the many different stakeholders. Starting as a long-term ecological research site (LTER), the ZA PVS has moved towards involving non-scientists in research projects, first as the drivers of change in the ecological systems and then as key elements for biodiversity conservation and the design of effective policies.).

Including various stakeholders such as farmers, beekeepers and other local inhabitants not only has a socio-political effect, it also changes research perspectives by giving a systemic representation of each of the stakeholders' perceptions of their environment and their needs which may conflict (Fig. 4). The participation of a wider range of stakeholders is crucial for designing innovative sustainable agricultural systems based on agro-ecological principles, as it gathers a wider pool of knowledge and facilitates the formulation of research questions to meet their concerns. To date, few participatory and innovative design studies have been carried out at an agroecosystem scale which is the scale relevant to the management of ecological processes. There is a need to develop suitable design methods and tools, and an LTSER can be very useful in this approach as the research infrastructure can be used to facilitate collective design processes and monitor their long-term impacts. This also requires new approaches: socio-ecological experiments, statistical tools for analyzing participatory science data and building new bridges between scientists and local stakeholders in the form of involvement, rules of engagement and the dissemination of results and knowledge. In addition, it can facilitate the application of the most recent ecological knowledge to the design of innovative and sustainable agroecosystems.

Working with stakeholders, testing changes and leading participatory research projects is changing the way we learn about socio-ecological systems, shifting from a rather "positivist" (common in ecological research) to a more "constructivist" approach. Socio-ecological systems can no longer be considered as fixed objects, but should be considered as open ended as they can be designed and transformed and changes can be directed. This raises important issues of both observer effects and ethics (van Mierlo et al., 2010). Reflexivity must be allowed for by anticipating the effect of the research programs on the system functioning (interactions between species, between stakeholders, between stakeholders and species). Ethical issues must be dealt with by anticipating the impact of the research programs on local stakeholders' well-being.

In conclusion, the large and long-standing research platform, LTSER Zone Atelier "*Plaine & Val de Sèvre*", provides the scientific expertise, innovative research approaches and long-term datasets needed to record and analyze social and environmental changes in the local agroecosystem as well as to investigate and identify new agricultural and local governance practices. The LTSER research infrastructure is unique and is an essential tool for addressing the environmental, socio-economic and political issues we are currently facing. We hope

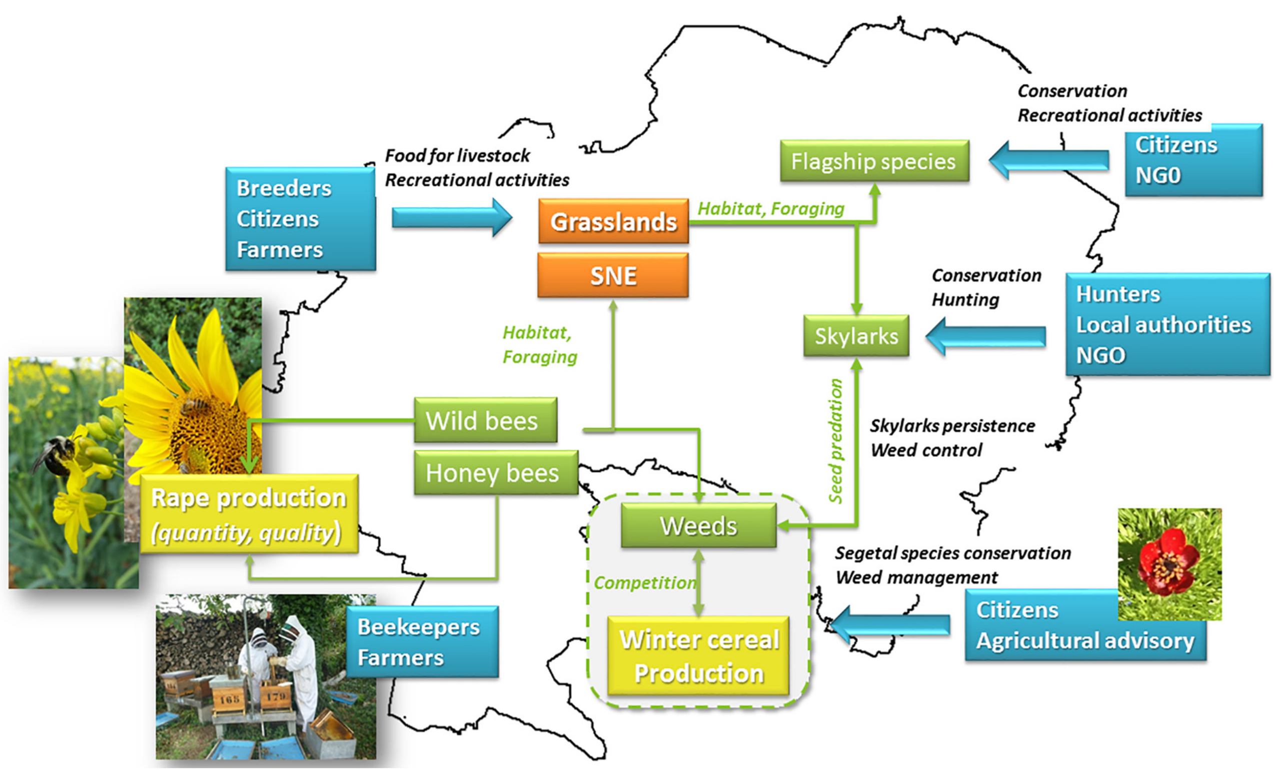

Fig. 4. Schematic representation of the systemic approach underlying the ZA PVS research program. Complex relationships between the ecological system (in green) and the social system (in blue) are shown. Ecological processes are indicated in green, and social goods in yellow. Semi-natural elements (such as edges) and grasslands are indicated in orange to emphasize their important role for biodiversity conservation in farmland. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

that the presentation of our socio-ecological research strategy will stimulate the development and networking of other LTSERs as is the case for the French Zones Atelier network.

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