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REVIEW ARTICLE

Designing agroecological transitions; A review

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Abstract Concerns about the negative impacts of productivist agriculture have led to the emergence of two forms of ecological modernisation of agriculture. The first, efficiency-substitution agriculture, aims to improve input use efficiency and to minimise environmental impacts of modern farming systems. It is currently the dominant modernisation pathway. The second, biodiversity-based agriculture, aims to develop ecosystem services provided by biological diversity. It currently exists only as a niche. Here we review challenges of implementing biodiversity-based agriculture: managing, at the local level, a consistent transition within and among farming systems, supply chains and natural resource management. We discuss the strengths and weaknesses of existing conceptual frameworks developed to analyse farming, social-ecological and socio-technical systems. Then we present an integrative framework tailored for structuring analysis of agriculture from the perspective of developing a territorial biodiversity-based agriculture. In addition, we propose a participatory methodology to design this agroecological transition at the local level. This design methodology was developed to support a multi-stakeholder arena in analysing the current situation, identifying future exogenous changes and designing (1) targeted territorial biodiversity-based agriculture, (2) the pathway of the transition and (3) the required adaptive governance structures and management strategies. We conclude by analysing key challenges of designing such a complex transition, developing multi-actor and multi-domain approaches based on a combination of scientific and experiential knowledge and on building suitable boundary objects (computer-based and conceptual models, indicators, etc.) to assess innovative systems designed by stakeholders.

Keywords Adaptive management · Agroecology · Ecosystem services · Farming system · Social-ecological system · Social learning · Socio-technical system · Transdisciplinarity

Contents

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1 Introduction

In developed countries, the production-oriented or productivist model of agriculture developed greatly after World War II. It is based on the use of "off-the-shelf" technologies (e.g. synthetic inputs, genetics) to try to overcome environmental heterogeneity and, more particularly, effects of limiting and reducing production factors (van Ittersum and Rabbinge 1997; Caron et al. 2014). This model contributed to a specialisation of territories based on their suitability for specific land uses (Foley et al. 2005). It also led to standardisation of production methods and, as a consequence, a decrease in the place-based cognitive resources necessary to implement them. The desire to increase the health safety of agricultural production and its standardisation, even normalisation, prolonged and strengthened this process (Horlings and Marsden 2011; Lamine 2011). Since the 1980s, realisation has emerged about the negative effects of this production model on biodiversity, ecosystem functioning and climate change, as well as on product quality, human health and the increasing scarcity of fossil resources, water and natural phosphate deposits (MAE 2005, IAASTD 2009). At the same time, development of the concepts of sustainability, multi-functionality and ecosystem services challenged the monolithic logic of this model (Huang et al. 2015). Evaluation of environmental impacts of agriculture, social awareness of these issues linked to media coverage, redefinition of the objectives of agriculture in agricultural policies and, more recently, the worsening of the food security issue have promoted new ways to address limitations of this model of agriculture and of the "green revolution" (Godfray et al. 2010).

Horlings and Marsden (2011) distinguish two forms of ecological modernisation of agriculture that address these limitations. The first, in continuity with production-oriented agriculture, is based on increasing resource use efficiency (e.g. fertiliser, pesticides and water), recycling waste or by-products of one subsystem in another (Kuisma et al. 2013) and applying sound agricultural practices (Ingram 2008) or precision-agriculture technologies (Rains et al. 2011). It is also based on replacing chemical inputs with organic inputs (Singh et al. 2011) or genetically modified organisms (Godfray et al. 2010). Its main objectives are to reduce negative environmental impacts and raise production limits of production-oriented agriculture. Due to the levers of action it is based on, we call it "efficiency/substitution-based agriculture", while others call it "ecological intensification" (e.g. Hochman et al. 2011).

The second form aims to enhance ecosystem services provided by biodiversity (Le Roux et al. 2008; Zhang et al. 2007). These ecosystem services depend on the degree of (agro)biodiversity at field, farm and landscape levels (Kremen et al. 2012). Still focusing on the main lever of action, we called it biodiversity-based agriculture, while other authors call it "ecologically intensive agriculture" (Kremen et al. 2012) or "eco-functional intensification" (Levidow et al. 2012a, b). Extreme forms of these two forms of agriculture (Table 1, top) must be considered as two ends of a continuum. Importantly, in biodiversity-based agriculture, practices increasing resource use efficiency and recycling are also implemented, if necessary.

Some authors address production-oriented agriculture issues without distinguishing between the two forms of ecological modernisation (Godfray et al. 2010; Wezel et al. 2013). In line with Horlings and Marsden (2011), we argue that this is problematic for at least two main reasons. First, biodiversity-based agriculture introduces a paradigm shift in the vision of agricultural innovations and systems, especially in their objectives and expected performances of agriculture (Caron et al. 2014) and in how to apprehend and manage interactions between the environment and production (Levidow et al. 2012a, b). Efficiency/substitution-based agriculture usually consists of incrementally modifying practices in specialised systems to comply with environmental regulations, e.g. EU directives (Duru and Therond 2014). In contrast, biodiversity-based agriculture seeks to develop diversified cropping and farming systems (Fig. 1a, b) and landscapes (Fig. 1c) to develop ecosystem services and, in turn, drastically reduce the use of anthropogenic inputs (Duru et al. 2015). Second, biodiversity-based agriculture requires "adopt[ing] a more creative eco-economy paradigm which replaces, and indeed relocates, agriculture and its policies into the heart of regional and local systems of ecological, economic and community development" (Marsden 2012). Accordingly, developing this type of agriculture requires implementing multi-level and multi-domain approaches at the local level (Caron et al. 2014; Horlings and Marsden 2011; Lin 2011; Marsden 2012; Stassart et al. 2012).

In recent decades, research has generated knowledge about key interactions between biotic and abiotic components of agricultural ecosystems (e.g. Lin 2011) and between biodiversity, ecosystem functions and services (Cardinale et al. 2012). However, this knowledge is too general to be used directly to support design and management of diversified farming systems and landscapes promoting ecosystem services. Methods

Table 1 Features of the two paradigms of ecological modernisation of agriculture that represent the two extremes of a continuum

Feature	Efficiency/substitution-based agriculture	Biodiversity-based agriculture
Main aim	Reducing negative environmental impact; "ecological intensification" of agriculture	Producing ecosystem services for conserving resources; "ecologically intensive agriculture"
Paradigms	In continuity with the productivist agriculture paradigm: bio-economy and economy of scale	Breaks with the productivist agriculture paradigm: eco-economy and economy of scope
	Agriculture is considered as a separate and independent sector	Agriculture is considered as highly interdependent and integrated in the local human, cultural and ecological rural system
	Environment is considered through concerns about resource scarcity, waste and pollution	Environment is considered through its natural and cultural dimension (e.g., craftsmanship, stewardship, farming style)
	Competitiveness is in the global market	Competitiveness through sustainability and valorisation of natural resources
Innovation nature	Generic techno-science solutions ("one-size-fits-all") to improve efficiency of inputs based on genetics, organic inputs, mechanisation, precision farming and recycling (industrial ecology)	Place- and space-based diversified practices and farming systems based on ad hoc spatial and temporal "planned" and "associated" biodiversity and local knowledge systems
Public policy	Top-down steering and regulation	Adaptive governance based on local stakeholder participation and facilitating local network/consortia development, knowledge sharing and collaboration
Analysis from the angle of farming systems	Standardised practices and specialised farming systems with a small number of crops based on use of external inputs; linear top-down transfer of standardised technologies	Place- and space-based farming practices and systems based on agroecological principles, with diversified crop or livestock interactions, allowing greatly reduced use of external inputs; farm practices also defined according to objectives at the landscape level; collaborative innovation
Analysis from the angle of social-ecological systems	Farming systems consume many natural resources (NR); decoupled management of agricultural systems and NR leading to conflicts between agriculture and other resource users and protectors of the environment (including institutions)	Farming systems manage natural resources (NR); adaptive governance and management of NR including "associated" biodiversity for improving biological regulation at the landscape level
Analysis from the angle of socio-technical systems	Globalised and export- and component-based market; industrialisation; private and public food safety regulations and globalised standards creating lock-ins (e.g. regulatory barriers) to place-based products; highly sensitive to exogenous changes; power concentrated in large retailers; "free-trade"	Local-scale food system based on "tight feedback loops" linking producers, consumers and ecological effects, resilient to exogenous changes, with high sovereignty and autonomy; power in local agri-food networks allowing creation of space for agents to build alternative production (promotion of niches); "fair trade" and production of regional specialities

are still needed to manage the context-dependent features of biodiversity-based management practices (Duru et al. 2015). In parallel, social sciences, focusing mainly on economic sectors (e.g. transport, energy), provided frameworks to analyse, a posteriori, socio-technical transitions (e.g. Geels 2002, 2005) and methodological frameworks for "transition management", i.e. to steer transition towards a normative goal, such as sustainability (Loorbach 2010; Rotmans et al. 2001). These frameworks were not developed, however, to address characteristics of the agroecological transition on farms and to reconnect agriculture to local ecological and socio-economic systems (Sutherlan et al. 2015; see Sections 2 and 3 for details). Accordingly, research is still needed to develop salient and legitimate methodologies that allow stakeholders to design the "agroecological transition" that is, here, the transition from productivist or efficiency/substitution-based to biodiversity-based agriculture (Caron et al. 2014; Kremen and Miles 2012).

This paper proposes a transdisciplinary and multi-level conceptual and methodological framework to analyse conditions of and design the transition towards biodiversity-based agriculture at the local level. In Section 2, we define the main characteristics of biodiversity-based agriculture and key challenges of the agroecological transition and explain why it must be managed at the local level. In Section 3, we analyse the strengths and weaknesses of conceptual frameworks of farming, social-ecological and socio-technical systems to structure analysis when implementing the agroecological transition. We present an integrative analytical framework that connects and enriches the previous three frameworks and describes the nature of the local (territorial) system concerned by this agroecological transition. In Section 4, we present a participatory methodology that uses this conceptual framework to support stakeholders designing the agroecological transition at the local level. In Section 5, we conclude by examining key issues for researchers and stakeholders when implementing our

Fig. 1 Developing a **a** diversified cropping system, **b** farming system and **c** landscape that strongly increase provision of ecosystem services requires adaptation in supply chains or in local natural resource management. **a** Intercropping can be problematic for separating grains of cultivated species at harvest or in the factory; this logistical problem limits adoption of such cropping systems. **b** Agroforestry, based on growing woody vegetation within and/or around fields, requires specific management practices and materials; its development can require using local processing chains for wood-based products. **c** Hedgerows in an agricultural landscape can help limit soil erosion, improve water quality, and provide habitats for natural pest enemies and pollinators. It is estimated that nearly 70 % of the 2 million km of hedgerows likely present in France in the early twentieth century have been destroyed. Coordination among stakeholders is necessary to ensure development of landscapes adapted to deliver expected ecosystem services, such as biological regulation and water provision

methodology and offer suggestions for further research. Throughout the text, efficiency/substitution and biodiversity-based agricultures are compared to highlight the changes necessary to implement the latter.

2 Biodiversity-based agriculture: foundations and challenges

2.1 Foundations of biodiversity-based agriculture

Biodiversity-based agriculture seeks to develop diversity in cultivated species and genotypes at multiple spatial and temporal levels to favour functional complementarities in resource use and biological regulation (Caron et al. 2014; Duru et al. 2015; Kremen et al. 2012; Ostergard et al. 2001). This "planned" diversity and the landscape-matrix heterogeneity promotes the beneficial "associated" diversity (Altieri 1999; Duru et al. 2015; Kassam et al. 2012; Power 2010). These three forms of biodiversity determine the levels at which ecosystem services are provided to the agroecosystem (e.g. soil fertility, pollination, biological regulations) and to society, whether marketed (plant and animal production) or non-marketed (carbon storage, control of the water cycle) (Zhang et al. 2007). The level of agroecosystem's internal regulations depends on maintaining biological diversity and thus the integrity of agroecosystems (Drinkwater 2009; Koohafkan et al. 2011). Accordingly, when implementing biodiversity-based agriculture, the challenge for farmers lies in designing, implementing and managing consistently diversified cropping and farming systems and landscape structures that promote high levels of ecosystem services.

Such changes in agricultural practices and increased diversity in agricultural production involve multiple and interdependent adaptations to managing the whole agroecosystem (Caron et al. 2014; Lin 2011). Here, like other authors, we consider an agroecosystem to be composed of an ecosystem managed with the intention of producing, distributing and consuming food, fuel and fibre and of the resources, infrastructure, markets, institutions and people involved in these functions. It thus "encompasses all the complexity a social-ecological system can have" (Cabell and Oelofse 2012; Koohafkan et al. 2011; Marsden 2012; Pretty 2008).

Biggs et al. (2012), through their thorough review of scientific literature and expert knowledge about conditions that increase production and resilience of ecosystem services, identify three properties of the social-ecological system to manage and four principles for its governance. The three key properties are diversity-redundancy, connectivity and state of slow variables.

- Diversity (taxonomic and functional) of biological (e.g. genes, species, ecosystems, spatial heterogeneity) and social (e.g. individual, social groups, networks, institutions) entities and their levels of redundancy define the potential for ecosystem services provision and adaptation. Functional redundancy determines the degree to which replacing one set of components with another can meet a biological or social function. Even though diversity and redundancy are required to provide ecosystem services, a threshold exists above which diversity can lead to a system whose functioning is cumbersome, complicated and less efficient and has low adaptation capacity.
- Connectivity between biophysical entities as well as social entities determines circulation of materials, energies and information and thus the system's performance. Too much connectivity can favour massive propagation of initially local perturbations or individualist behaviour harmful to the system. For the biophysical dimension of agroecosystems, connectivity mainly describes the spatial relationships between landscape elements (e.g. patches). They determine species dispersion abilities between habitats (Tscharntke et al. 2005). For the social dimension, connectivity encompasses the multiple dimensions of social networks.

- The state of slow variables (e.g. soil organic matter, water resources, management agencies, social values) determines dynamics of fast variables (e.g. field management, water withdrawals, authorisation to access resources) in complex systems. The manner of middle- or long-term management of slow variables thus determines day-to-day, year-to-year and long-term system functioning.

Four governance principles may favour adapted management of these three system properties:

- Understand the social-ecological system as a "complex adaptive system" characterised by emergent and non-linear behaviour, a high capacity for self-organisation and adaptation based on past experiences, distributed control and ontological uncertainties linked to incomplete knowledge of managers. Such envisioning of the system to manage may help stakeholders to consider adaptive governance and management (next section) as structurally necessary.
- Encourage learning and experimentation as a process for acquiring new knowledge, behaviour, skills, values or preferences at the individual or collective levels, which ultimately determines decisions and actions in situations of uncertainty and thus methods for managing the system. Experimentation, particularly within the framework of adaptive management, is a powerful tool for generating such learning.
- Develop participation: the participation of stakeholders in governance and management processes facilitates collective action, as does the relevance, transparency, legitimacy and, ultimately, acceptability of social organisations, decisions and actions. It also allows actors to respond more quickly to internal or external changes and promotes construction of shared representations and strategies.
- Promote polycentric subsystems of governance that structure debate and decision-making among different types of stakeholders, at different levels of organisation, and in different forms (e.g. bureaucratic, collective, associative, informal). The basic principle of polycentric governance is to organise governance systems at the spatial scale at which the problems to manage, or objectives to achieve, emerge. This can increase the system's ability to produce the expected ecosystem services as well as its flexibility and responsiveness. This organisation promotes organisational diversity, redundancy and connectivity of decision and action centres.

2.2 Challenges of the transition to biodiversity-based agriculture and its design

Key challenges at different levels arise when applying the above principles to promote development of biodiversity-based agriculture. At the farm level, diversified cropping and farming systems that increase provision of ecosystem services must be strongly adapted to a wide diversity of production situations (soil-climate-biodiversity at field and landscape levels, constraints of natural resource management). In other words, they must be site-, space- and time-specific (Caporali 2011; Caron et al. 2014; Duru et al. 2015; Douthwaite et al. 2002; Godfray et al. 2010; Koohafkan et al. 2011; Power 2010). Uncertainties about the nature and performances of agroecological practices in each farming system, even within each production situation of farming systems, may lead to strong risk aversion by farmers (Fig. 1a, b). To support farmers in reducing and managing these uncertainties, complementary research is required to fill in the gap between generic scientific knowledge and local knowledge. This need renews the way researchers can contribute to locally adapted agricultural innovations (Caron et al. 2014; Duru et al. 2015).

At the landscape level, natural resource management, e.g. management of the landscape structure to promote beneficial associated diversity (Fig. 1c), requires coordination between stakeholders with different interests and adapted institutions (Brewer and Goodell 2010; Caron et al. 2014; Darnhofer 2015; Duru et al. 2015). The need to anticipate and manage cascade effects between organisational levels makes these landscape-level practices complex to implement (Duru et al. 2015; Galloway et al. 2008; Walker and Meyers 2004).

At the supply chain level, development of new farming systems based on crop and animal diversity (e.g. crop associations or intercropping, multi-animal species and breeds) and a decrease in farming system inputs may cause economic, technological and organisational problems for supply chains, particularly during collection, processing and marketing phases (Fig. 1a; Fares et al. 2011).

Furthermore, developing the four principles of governance suggested by Biggs et al. (2012) may require profound changes in local institutions, i.e. rules of the social game, such as formal rules (including public policies), informal agreements and ways of doing things that structure human interactions and activity (North 2005 in Darnhofer 2015). Fostering biodiversity-based agriculture will require dealing better with the intricacy between agriculture and local socio-economical dynamics (Caron et al. 2014; Marsden 2012). Accordingly, to develop biodiversity-based agriculture, innovations cannot be only technological and technical, but also must be social, economic and institutional. They cannot exist only at the farm level but also at the levels of local supply chains and natural resource management institutions. Thus, implementing the agroecological transition requires considering and integrating interconnected processes and organisational levels in ecological systems, for example, from populations and communities to the landscape

(Rabbinge and de Wit 1989), as well as in entire human-technology-environment (or social-ecological) systems (Pahl-Wostl et al. 2010).

Due to the nature and level of necessary changes, the development of biodiversity-based agriculture cannot resort to simple incremental agronomic innovations such as increasing the efficiency of production factors. It requires extensive redefinition of agricultural performances leading to breakthrough (radical) innovations and extensive redesign of the agroecosystem (Caron et al. 2014; Duru et al. 2015; Hill 1998; Meynard et al. 2012). To meet the challenge of developing an agroecosystem adapted to and interconnected with the local ecological, socio-economical and institutional systems, the process of innovation must be conducted in a "local agricultural system of innovation" including a network of interacting institutions, businesses and individuals (Klerkx and Leeuwis 2008). This "territorial" implementation of the innovation process is also necessary for it to be legitimate to the social and cultural networks' values and traditions (Caron et al. 2014; Darnhofer 2015).

As efficiency-substitution agriculture is strongly supported by current institutions and dominant socio-technical regimes (next section), biodiversity-based agriculture has few opportunities to develop strongly through emergent transition, i.e. not planned and managed (Darnhofer 2015; Horlings and Marsden 2011; Kremen and Miles 2012; Levidow et al. 2012a, b; Vanloqueren and Baret 2009). Accordingly, if stakeholders seek to develop this form of agriculture at the local level, they may have to develop "transition management", i.e. a process of governance that seeks to steer or modulate the dynamics of transitions through interactive and iterative processes among networks of stakeholders (Darnhofer 2015; Foxon 2011; Foxon et al. 2009). The challenge is then to manage a "purposive transition", i.e. "deliberately intended and pursued…to reflect an explicit set of societal expectations or interests" (Geels and Schot 2007). A key element of this process is the "transition arena": a relatively small group of innovation-oriented stakeholders that reached consensus about the need and opportunity for systemic changes and engage in a process of social learning about future possibilities and opportunities (Foxon et al. 2009). Here, mutual understanding and collective development of shared goals and visions of the expected future and potential pathways to reach it are particularly at stake (Kemp and Rotmans 2005 in Darnhofer 2015; Loorbach 2010). Transition management is seen as a form of participatory policy-making based on complex systems thinking (Foxon et al. 2009). In agriculture, the term "transition" is used to indicate a reconfiguration of activities within the farm (Wilson 2008; Lamine 2011) but also as a radical change in agriculture or sub-sectors most often at national or higher levels and, more recently, at local to regional levels. Such transitions may take place in a middle- to long-term time span (Darnhofer 2015). When dealing with agroecological transitions, the challenge is then to design multi-domain and multi-level and middle- to long-term changes in local agriculture.

One of the great challenges for research is to develop operational knowledge that supports stakeholders in structuring the design of an agroecological transition from productivist or efficiency/substitution-based to biodiversity-based agriculture at the local level. This knowledge should enable the development of capacities of local heterogeneous stakeholders for designing and steering such transitions (Caron et al. 2014; Darnhofer 2015; Duru et al. 2015).

To reach this objective, research should develop transdisciplinary and multi-stakeholder approaches integrating contextualised scientific knowledge and local knowledge to analyse the current organisation of local agriculture and to design the one that is anticipated (Caron et al. 2014; Darnhofer 2015). To participate in this scientific challenge, this paper proposes both an integrative conceptual framework that allows stakeholders to analyse the multi-dimensional characteristics and issues of local agriculture (Section 3) and a participatory methodology to support local stakeholders in designing a local agroecological transition and its governance (Section 4).

3 An integrative analytical framework for analysing agriculture at the local level

3.1 Strengths and weaknesses of three existing analytical frameworks

Considering the key challenges of the agroecological transition presented above, we identified three conceptual frameworks that consider the organisational levels and domains in which the necessary changes must occur: (i) the farming system framework, to structure analysis of the organisation and dynamics of farm production systems; (ii) the social-ecological system framework, to analyse natural resource management; and (iii) the socio-technical system framework, to analyse the dynamics of agricultural innovations. In this subsection, we present the main characteristics of these three frameworks and identify their shortcomings in dealing with agroecological transition issues.

3.1.1 Farming systems and associated innovation systems

In recent decades, many analytical approaches of farming systems were developed (Darnhofer et al. 2012). Approaches of Hendrickson et al. (2008) and Darnhofer et al. (2010) describe well the two polar forms of farming systems that implement efficiency/substitution-based and biodiversity-based agriculture according to the number and level of integration of production subsystems as well as their performance levels and capacities to adapt to changes in contexts or objectives.

Most farming systems with production-oriented agriculture that implement efficiency/substitution-based practices are specialised and tend to have few crops and pre-planned management, which in some situations generates environmental issues (e.g. erosion, nitrate leaching, high pesticide use). Their dynamics are based on genetically improved plants and animals and the acquisition of high-performance equipment (machinery, buildings). Innovation on such farms is mostly linear and top-down, from research to farmers. This type of innovation process, most popular in the 1960s, is still adapted to the linear transfer of standardised technologies such as precision agriculture or the implementation of genetically modified organisms (Table 1). In contrast, production systems that implement biodiversity-based agriculture are based on multiple crops and/or enterprises that interact dynamically in space and time (e.g. crop diversification, crop-livestock interaction). It allows them to benefit from multiple synergies made possible by interactions between components (Sanderson et al. 2013). Their high level of diversity can reduce impacts of variability in prices or climate (Darnhofer et al. 2010). These production systems are managed dynamically by performing annual or seasonal adjustments to make best use of the opportunities that present themselves. They are based on activities that (i) exploit the existing potential of the farming system to adjust efficiently to short-term objectives and hazards and (ii) provide the ability to respond to new opportunities in the middle and long terms. This mode of management allows systems to adapt more easily to a constantly changing environment. Innovation on such farms is generally collaborative (Klerkx et al. 2012). It is based on coordinated networks of stakeholders that seek to co-produce knowledge and technologies, possibly assisted by participatory and transdisciplinary research (Knickel et al. 2009).

Due to the central focus on the farm level, analytical frameworks of farming systems have two main limits in dealing with agroecological transition issues. First, in most analyses, the social system considered is often reduced to farmers and sometimes their direct advisors, so that social interactions between the farmer and other stakeholders of natural resource management or supply chains are generally not considered, or if they are, it is disconnected from ecological processes that sustain management practices (Lamine et al. 2012). Second, interactions among farming systems, the landscape matrix and natural resource management are barely assessed (Benoît et al. 2012).

3.1.2 Social-ecological systems

The management of natural resources at the local level (e.g. landscape or watershed) implies a social system composed of users, managers and governance institutions using technologies and infrastructures to manage artificial and natural resources, as well as a complex ecological system generating these natural resources. Conceptual frameworks produced to analyse or model such social-ecological systems (Anderies et al. 2004; Ostrom 2009; Sibertin-Blanc et al. 2011) allow the complexity of social, ecological and social-ecological interactions occurring in these systems to be encompassed. Analysing the dynamics of these complex systems is based on the concepts of resilience, adaptation and transformation of system structure and/or functions (Folke et al. 2002, 2011; Folke 2006; Holling 2001; Walker et al. 2006). In many situations, natural resource management problems are associated with a failure in governance (Table 1). This failure is often linked to underestimating the changing nature and complexity of the social-ecological system concerned (Folke et al. 2011; Pahl-Wostl 2009; Pahl-Wostl et al. 2010). The challenge is therefore twofold. On the one hand, it consists of strengthening the adaptive capacities of governance systems, i.e. their ability to change their modes of action and, if necessary, to implement structural modifications to best address past or expected environmental or social changes. Analytical and methodological frameworks developed thus provide a support for analysing existing governance systems and for leading the transition to "adaptive governance systems" (e.g. Pahl-Wostl et al. 2010). On the other hand, it consists of implementing "adaptive management" that aims for continual improvement in policies and practices for management of natural resources. This management strategy is based on structured learning about the effects of management strategies throughout their implementation (Pahl-Wostl 2009). It is an adaptive, deliberate and iterative decision-making process whose objective is to consider and address (i) uncertainties in the functioning of ecological systems and effects of management practices, (ii) imperfections and limits in detecting variations in the state of the environment under the effect of ecological processes or management actions, (iii) the impossibility of controlling and monitoring all management actions within the social-ecological system and (iv) the intrinsically unpredictable character of certain ecological processes (Williams 2011). This adaptive management practice is often associated with social learning objectives: mutual understanding, viewpoint sharing, collective development of new adaptive management strategies for resources and establishment of "communities of practice" (Armitage et al. 2008; Newig et al. 2008; Pahl-Wostl and Hare 2004). Social-ecological system and adaptive management frameworks are particularly applied to deal with natural resource management problems (e.g. water: Pahl-Wostl 2007) or to collectively address environmental sustainability issues (e.g. erosion: Souchère et al. 2010; nitrogen emissions: Toderi et al. 2007). In most of these situations, they are used at the local level to support analysis or to (co-)design solutions for reducing the investigated problems. The social-ecological framework was also developed to analyse formal rules and informal agreements used by actors for natural resource management and their consequences on sustainability management issues (Ostrom 2005). It was adapted to deal with agroecosystem issues in which economic and social structures depend greatly on agricultural activities (e.g. Schouten et al. 2012). Beyond its many assets, it has weaknesses when dealing with agroecological transition issues. Mainly, it was not developed to account for (i) agronomic and organisational reasoning and constraints in farming systems or (ii) necessary changes in agricultural supply chains.

3.1.3 Socio-technical systems

The dynamics of technological innovations and ways of producing goods within economic sectors or supply chains are considered as the result of interactions among three levels of organisation: production niche, socio-technical regime and the landscape (Geels 2002). The former corresponds to formal and informal networks of actors in which radical innovations emerge and are nursed. Socio-technical regimes are relatively stable configurations of institutions, techniques and artefacts, as well as regulations, standards and norms of production, practices and actor networks. They support the evolution of the dominant forms of production. The "landscape", or global context, is the set of factors that frame interactions among actors, such as cultural values, political institutions and environmental problems. The socio-technical system integrates these three levels. Its dynamics are addressed by analysing the nurturing of new technologies into niches and transforming of the dominant socio-technical regimes under the pressure of niche developments, niche incentives and regulatory changes coming from the "landscape" (Geels 2002, 2005; Smith and Stirling 2010).

Currently in agriculture, the dominant socio-technical regime corresponds to models of historical production-oriented agriculture and its modernisation through the efficiency/substitution-based approach. Key resources of the dominant regimes, such as infrastructure, production norms and standards and main market institutions, are historically adapted to support these forms of agricultural production. This system is dominant due its ability to create technological, organisational and institutional lock-ins that ensure its persistence (Arthur 1989; David and Arthur 1985). The niches are alternative production models of varying structure, which coexist in a complementary or competitive manner. This is the case of models promoted by groups of farmers who defend alternative production methods or a specific ideology (e.g. Diaz et al. 2013), which can be associated with biodiversity-based agriculture experiences.

This framework favours identifying learning-by-doing constraints and farmers' risk aversion to adopting innovations (Blazy et al. 2011; Cowan and Gunby 1996), supply-chain lock-in effects (Fares et al. 2011; Lamine et al. 2012), public policy effects on variety selection and training and extension services to farmers (Vanloqueren and Baret 2009). It provides an analytical framework for determining ways to strengthen regimes when they are threatened or for identifying the obstacles that prevent regime change, even though obvious underperformance is observed (Schiere et al. 2012). It also represents a useful framework for identifying emergence and stabilisation conditions for niches or their access to the status of a regime (Geels 2010). In other words, it helps analyse how alternatives to the dominant socio-technical regimes may develop. However, when dealing with agroecological transition issues, it, like the social-ecological framework, does not account for (i) agronomic and organisational reasoning and constraints within farming systems or (ii) issues and constraints linked to local natural resource management. Furthermore, although the dynamics of niches are considered, in most socio-technical approaches, their governance is not analysed in depth.

3.2 An integrative analytical framework of the local agriculture

As seen above, one of the challenges of managing the agroecological transition is to design, in an integrated manner, technological, organisational and institutional (the rules of the social game) changes within farming systems, supply chains and natural resource management at the local level. As shown, considering each of the three frameworks presented above separately (Fig. 2a) does not deal with or support the design of necessary multi-domain and multi-level changes. The integrative conceptual framework presented below aims to structure analysis of the nature of the complex (adaptive) system concerned by the agroecological transition: local agriculture (Section 2.2). We developed this framework by hybridising and extending all three frameworks presented above, considering their strengths and weaknesses (Fig. 2). This hybridisation was guided by previous attempts: Smith and Stirling (2010) hybridised social-ecological and socio-technical approaches, and Darnhofer et al. (2010) hybridised farming systems and social-ecological approaches.

Given that in each of the three frameworks the system is considered to be composed of two main types of components, stakeholders and resources, we first conceptualise local agriculture as a complex system of interactions between them. After presenting the characteristics of the social system and its resources, we examine stakeholder's strategies and technologies for managing these resources and address the nature of interactions among the stakeholders of local agriculture.

Importantly, we consider that agricultural stakeholders involved in the management of farms, agricultural supply chains and natural resources are strongly interconnected. We conceptualise local agriculture as an entire system of actors (the social

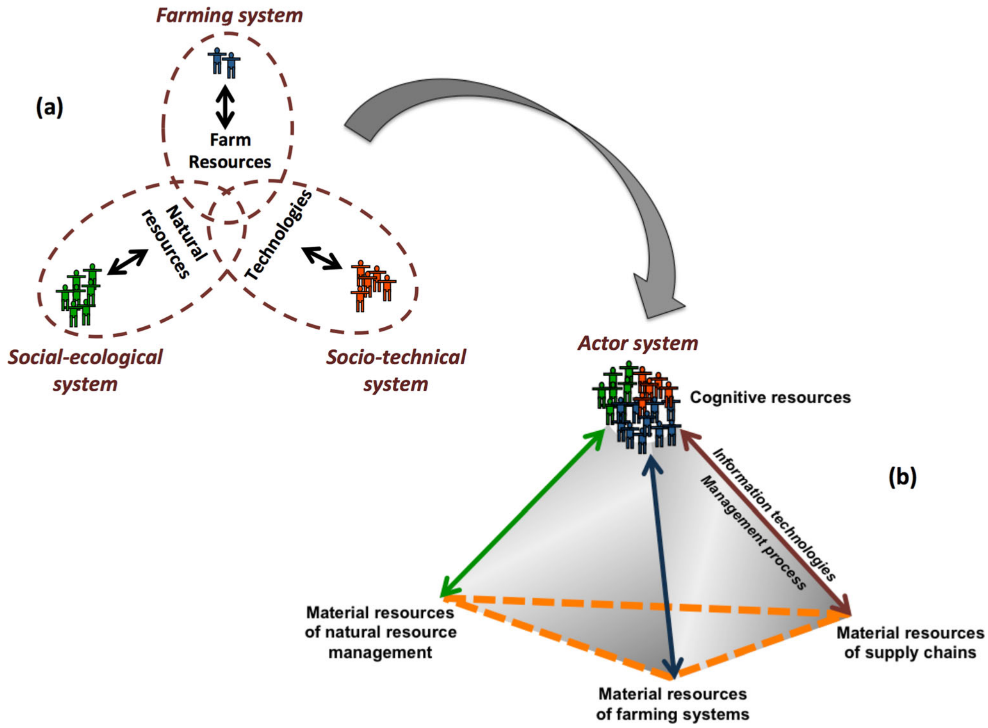

Fig. 2 From domain-based analytical frameworks to an integrated framework developed to structure analysis of local agriculture and design the agroecological transition at the local level. (a) Three key conceptual frameworks developed to analyse characteristics and dynamics of farming, social-ecological and socio-technical systems. When applied to agricultural issues, even though domains considered by these frameworks overlap, they focus on different system entities and dynamics: farm resource management, dynamics of technologies in supply chains and natural resource management. These three domains must be designed and managed as a whole to support development of a biodiversity-based agriculture. (b) Local agriculture as a system of actors managing three types of material resource systems through information technologies. The system of actors consists of farmers and other actors involved in supply chains and management of natural resources, with cognitive resources (e.g. beliefs, values, individual strategies) and whose behaviour is determined by informal norms and agreements (another type of cognitive resource) and formal rules. These actors manage material resources of farming systems (e.g. water, soil, biodiversity, infrastructure, material, formal rules, workforce), supply chains (e.g. products, infrastructure, human and financial resources, production standards and contracts, other formal rules) and natural resource management (e.g. water, soil, biodiversity, landscape, infrastructure, material, formal rules). Actors involved in agricultural teaching, advising, development and research also are part of this social system. The *tetrahedron* reflects that local agricultural development depends on interactions between its four dimensions. Each edge of the *tetrahedron* (*double arrows*) corresponds to a diversity of information technologies used to manage material resources and concrete management processes within a variety of farming systems, supply chains and natural resource management institutions. *Dotted lines* connecting the three material resource systems indicate that they are strongly connected and even interact

system) managing material resources of the farming systems, supply chains and natural resource management (Fig. 2b, top). Each stakeholder can be involved in only one of these management process types or, like many farmers, in two or three of them (Fig. 2b, top). In social-ecological and socio-technical systems approaches, the social system is recognised as a key factor. In the analysis of social-ecological systems, emphasis is placed on users of natural resources and governance organisations that regulate the use of natural resources. In the analysis of socio-technical systems in the agricultural domain, it is instead an issue of coordinating production and marketing systems within supply chains. In farming systems, the farmer represents the social dimension (ten Napel et al. 2011), but he/she is rarely considered as a socialised actor whose behaviour is determined by his/her social interactions. Here, we claim that the farmer, like all other actors, takes part in the social game and that his/her behaviour depends on the outcome of this social game (Greenberg 1990; Klerkx and Leeuwis 2008; Vanclay 2004). Actors involved in agricultural teaching, advising, development and research also take part in this social system; for example, this includes agricultural advisory services and agricultural development associations. Stakeholders' actions depend on their cognitive resources. They are intangible assets that correspond to knowledge (or beliefs), values, objectives (or desires), strategies (or intentions) and informal social agreements.

Management strategies of farms, agricultural supply chains and natural resources at the local level aim to conserve/restore/protect or produce/develop certain material resources. Considering the three key systems at hand, we distinguish three main systems of material resources (Fig. 2, bottom): (i) material resources of the farming system used by the farmer for agricultural activities; (ii) material resources used by stakeholders of the supply chain mainly for collecting, processing and marketing activities; and (iii) natural and artificial material resources involved in the management of the natural resources of local agriculture. We speak about the "system" of material resources as their components interact or are interconnected, such as:

(i) In the farming system: fields, planned biodiversity (crops, domestic animals), associated biodiversity, machinery, buildings, water resources and labour for the material resources of farming systems
(ii) In the supply chain: transportation, storage and processing equipment and roads for the material resources of supply chains
(iii) In natural resource management: water, soil and biodiversity (including associated) resources, landscape components (e.g. hedgerows, forests) and infrastructure (e.g. irrigation canals)

Formal rules (e.g. laws, regulations, contracts, public policies) negotiated locally or at higher levels, written on a physical medium (even a digital one) and used as a legal reference are included in these three material resource systems. They are part of the structure of local agriculture (North 2005 in Darnhofer 2015). They aim to regulate, define, finance or promote production methods within farms,[1] economic interactions between actors or production methods and agricultural products within supply chains,[2] and interactions between actors and natural resources (e.g. water laws). They also aim to organise the operating modes of formal organisations (e.g. farm, business, cooperative, public institution, association, formal arena for discussion). The three systems of material resources are interdependent, if not hierarchically nested. This interdependence can be direct or indirect. For example, irrigation water for the farm system is part of the system managed at the catchment level, and agricultural products from farms are collected, processed and marketed by supply chains.

It is important to emphasise that we consider material resources as social constructs and not as intrinsic characteristics of biophysical objects that become resources for actors. The dimensions and properties that qualify a biophysical object as a resource depend directly on the management process considered. For example, the economic value and technological properties of the "wheat grain" resource for a farmer are not necessarily the same as those for other actors in the supply chain. The same kind of example could be applied to distinguish water resources managed for irrigation within farms and water resources managed by water managers acting at the catchment level.

Management strategies of farms, agricultural supply chains and natural resources are based on, and determined by, information technologies used to decide when and how to act upon the resource system concerned. Here, "information technology" is used in the general sense as "any kind of decision aid, whether or not computer-based, and whether the problem it purports to address is more or less well structured" (Cox 1996; Walker 2002). The nature of information technologies used and their application methods are determined by cognitive resources (e.g. assumptions, expectations and knowledge about information technology, procedural knowledge) and the governance structures that implement them (Cash et al. 2003; Jakku and Thorburn 2010). Information technologies (Fig. 2b, arrows linking the system of actors to the three material resource systems) determine the methods that characterise resources, the knowledge actors have about the state of material resources over time and consequently their actions for managing them in time and space, and finally, their ability to meet their performance objectives.

Formal rules, considered here as material resources, define the formal framework in which interactions among actors and between actors and the biophysical environment are established. Following New Institutional Economics (Ostrom 2005, 2009; Williamson 2002) and the Sociology of Organised Action[3] (Crozier and Friedberg 1977), we consider that these formal rules do not completely determine the behaviour of actors. Equipped with bounded rationality, actors have a certain degree of freedom and autonomy in their choices and actions. Like the Sociology of Organised Action, we emphasise that the boundaries between organisations are not impermeable. Particularly in agriculture, the boundaries of the system of actors are often difficult to identify. Actors may be involved in many interdependent organisations. For example, a farmer may belong to management-oriented agricultural groups (e.g. farmer associations to share equipment), to natural resource management groups (e.g. local water management committee) and to one or more cooperatives and supply chains (Fig. 2, top). Also, rather than examining organisations themselves, we consider it necessary to analyse relationships between individuals to understand the system of actors and

[1] For example, agricultural policies, agro-environmental measures for material resources.

[2] For example, production standards for material resources of supply chains, laws and regulations of the global socio-technical context.

[3] Both approaches focus on the central problem of cooperation between actors. However, they have their own conceptual and methodological frameworks for analysing social relationships. In Institutional Economics, the focus is more on "transactional costs", i.e. the economic aspects of relationships, such as contractual hazards and asset specificity. In contrast, in the Sociology of Organised Action, the focus is on the nature of exchanges between actors and on power issues. Both approaches are complementary since they shed light on different aspects of social relationships.

how individual actions produce, by "aggregation effects", a specific social order. This type of analysis helps determine the nature of exchanges between actors, i.e. informal norms and agreements that constitute powerful mechanisms for fulfilling agreements (Crozier and Friedberg 1977; Ostrom 2005, 2009; Williamson 2002). These informal norms and agreements are defined as cognitive resources. They can take the form of norms of behaviour representing specific and sometimes significant adaptation of formal rules.

This integrated representation of the complex adaptive system that is local agriculture (Fig. 2) sheds light on (i) the central role of the system of actors and the social game, (ii) the three main types of material resources managed by the system's actors and (iii) the role of information technologies at the interface between actors and material resources. At the local level, a wide diversity of farming systems and several supply chains co-exist, as well as different management strategies of natural resources. Accordingly, each edge of the tetrahedron in Fig. 2b corresponds to a wide diversity of concrete management strategies. Accordingly, Fig. 2b corresponds to a figurative, general and simplified representation of the conceptual framework presented in this section.

3.3 A local polycentric system of actors for promoting biodiversity-based agriculture

Productivist and efficiency/substitution-based agricultures are the current dominant regimes in developed countries (Levidow et al. 2012a, b). At the local level, they take the shape of many juxtaposed specialised farming systems embedded mostly within medium- to large-scale supply chains. Most exchanges between farming systems are performed via the market, at regional, national or international levels. In contrast, biodiversity-based agriculture is based on local interactions between farms seeking to develop adequate spatial distribution of agricultural and non-agricultural land use in the landscape fostering the ecosystem services. Locally, if developed, this form of agriculture takes the shape of a diversity of connected place- and space-based farming systems, adapted supply chains and organisations for collective management of natural resources in agriculture (e.g. water, crop patterns, semi-natural habitats). This local instance of biodiversity-based agriculture is called hereafter "territorial biodiversity-based agriculture".

Farming systems implementing biodiversity-based agriculture already exist in a strong minority in intensive agricultural areas (e.g. conservation agriculture- and agroforestry-based farming systems). They are usually geographically isolated but often highly interconnected via local, regional and national innovation networks (e.g. Moore 2011). They form niches with varying degrees of structure that often have little exchange with farming systems of the dominant regimes. The challenge of the agroecological transition, i.e. the development of territorial biodiversity-based agriculture, is to do an "about-face", i.e. to become the, or one of the, locally dominant forms of agriculture. Efficiency/substitution-based farming systems may persist locally but at a level that does not disturb biological regulations and social coordination. A key challenge is thus to organise and support local-level interactions between agricultural systems to take advantage of their complementarities, whether biophysical (e.g. best use of differing pedoclimatic characteristics and/or access to certain natural resources) and/or of their productions (e.g. crop-livestock interactions at the local level) (for examples see Moraine et al. 2014). As described in Section 2, this organisation of interactions between agricultural systems should be based on polycentric governance of diversity and connectivity. It may enable developing an economy of scope, also called an economy of diversity, which fosters the resilience, robustness and sovereignty of local agriculture in the face of external changes. Here, "sovereignty" refers to the right of people to healthy and culturally appropriate food, produced through ecologically sound and sustainable methods (Holt-Giménez and Altieri 2013). Organisation of interactions within and between agricultural systems should explicitly manage biophysical and social (institutions) slow variables to reach both the expected short- and long-term functioning of this form of agriculture. Carlisle (2014) highlights the importance of diversity at multiple relational scales in such local resilient agricultures.

4 A methodological framework for designing the agroecological transition of agriculture

4.1 The agroecological transition: a co-innovation process

The conceptual framework presented above leads us to consider the development of territorial biodiversity-based agriculture as an innovation process, based on interactions between actors involved in the management of farms, supply chains and natural resources at the local level. As such, like Klerkx et al. (2012), we consider this innovation process as a technological, social, economic and institutional co-evolution, which is supported by diverse actors with different interests and viewpoints but not necessarily with experience in negotiation or the exchange of viewpoints. The innovations within local agriculture thus result from changes as much in the functioning of the system of actors (e.g. informal norms and agreements) as in information technologies and the range of resources to be managed (e.g. planned or associated biodiversity), i.e. it concerns all components of local agriculture, as conceptualised in the previous section.

This approach requires transdisciplinary and holistic research that reconsiders agricultural systems by focusing particularly on (i) interactions between actors of farms, supply chains and natural resource management; (ii) infrastructures, policies and institutions in favour of innovation; and (iii) the local characteristics of agroecological systems, while also considering their complexity and the incompleteness of associated knowledge (Klerkx et al. 2012; Klerkx and Leeuwis 2008; Knickel et al. 2009).

To address the uncertainty and complexity associated with biodiversity-based agriculture, the design process must allow adaptive management to be developed within farming systems and supply chains (to manage annual variability in production) and for natural resources. It is a matter of defining innovative practices and agricultural systems as well as promoting social networks for facilitating learning (Moore 2011; Warner 2008). To reach agreement among actors, it is also a matter of designing and implementing adaptive governance in supply chains and for natural resource management (Klerkx et al. 2012; Pahl-Wostl 2009).

4.2 A participatory methodology for designing the agroecological transition of agriculture

The design methodology presented below aims to support local stakeholders in designing the agroecological transition of local agriculture. This design methodology is intended to be implemented in a transition arena (Section 2.2) where innovation-oriented stakeholders (i) question the limits of efficiency/substitution-based agriculture, (ii) would like to know in advance which activities they would have to change to promote biodiversity-based agriculture or (iii) would like to nurture already implemented biodiversity-based agricultural systems and associated innovations. The design methodology is managed by Participatory-Design Facilitator-Scientists. They do not necessarily have direct knowledge about the characteristics and functioning of the farming systems, supply chains and natural resource management concerned. They do, however, have the knowledge and methodological skills necessary to manage and facilitate the multi-actor design approach. The design process of the agroecological transition should take shape at the intersection of a local intention to change agriculture and the intention to perform research to manage a collective-design process. Here research takes the form of "research-oriented partnerships" or an "intervention-research" approach and is part of "Sciences of Design" (Hatchuel 2001). Research is in charge of developing boundary objects (Jakku and Thorburn 2010) and collective action processes enabling stakeholders to design the expected agroecological transition and the required governance structures and management strategies.

Participatory-Design Facilitator-Scientists must allow stakeholders of the transition arena to construct a shared understanding of the current and expected future functioning of farming systems, supply chains and natural resource management. Therefore, they must support social learning and establishment of communities of practices (Section 3.1.2). They must also support integration of knowledge of stakeholders and scientists about the functioning of local agriculture. Achieving this objective requires assembling the key innovation-oriented stakeholders of the management processes concerned and scientists with knowledge about the key social, biotechnical and ecological processes of local agriculture.

The stakeholders of the transition arena can be initially identified by the Participatory-Design Facilitator-Scientists by relying on the conceptual framework presented in the previous section and a classic stakeholder analysis (Grimble and Wellard 1997). The conceptual framework allows identification of the key agricultural systems and domains and so stakeholders that should be involved in the design process. Actors involved in agricultural teaching, advising, development and research are also concerned. Throughout the application of the design methodology, the participants can identify new stakeholders who should also participate in the design process. If this occurs, the newly identified stakeholders should be integrated into the design process as soon as possible (Bos et al. 2008). The multi-actor system developed by the Participatory-Design Facilitator-Scientists must consider asymmetries in power and relationships (e.g. knowledge, availability, hierarchy) between stakeholders to foster expression and consideration of the interests of all stakeholders involved in the design process (Voß et al. 2007). Grimble and Wellard (1997) and Barnaud and Van Paassen (2013) propose strategies and methods to address these power asymmetry issues.

Seeking to address challenges of managing the local agroecological transition (Section 2.2), we developed our participatory design methodology towards biodiversity-based agriculture by hybridising several existing methodological frameworks. We borrowed from the framework for strategic environmental management analysis (Mermet et al. 2005), which "repositions every situation of environmental management in an interpretation of the system of actors in which it is found, and where multiple components and relations, which are tied together in an organisation that must be clarified, emerge as much from a social characterisation (of actors, norms, issues) as from an ecological one (animals, plants, local environments, etc.)". We also borrowed from "reflexive interactive design" (Bos et al. 2008), which is dedicated to participatory design of farming systems that explicitly considers their positions and interactions within the socio-technical system. We integrated key elements of the "management and transition framework" that improve scientific understanding of system properties and give practical guidance for the implementation of transition processes towards more adaptive systems (Pahl-Wostl et al. 2010). We also relied on the work of Kajikawa (2008), who analysed and synthesised the methodological frameworks used in sustainability science. Kajikawa's review highlights basic components of sustainability science such as setting the goal (problem definition/structuring) and indicators (estimation of the distance to the goal), forecasting (construction of scenarios/visions to deal with uncertainty in future exogenous trends and identification of the goal) and backcasting (definition of pathways from the goal back to the present status). Importantly, these are the main components of the "transition management" framework (Rotmans et al. 2001). As in the principles of Biggs et al. (2012), the "management and transition framework", the "transition management" framework and the operational model for safeguarding ecosystem services (Cowling et al. 2008), our methodology explicitly deals with the key issues of designing adequate adaptive governance structures and management strategies. In more general terms, like "transition management", our methodology is a process-oriented and goal-seeking approach designed to deal with complexity and uncertainty.

When developing our methodology, the first challenge was to hybridise these methodological frameworks into a new one composed of relevant steps to support local stakeholders in designing the agroecological transition at the local level. The second challenge was to identify which methods, most of them participatory, to implement in these steps. We selected methods that are well documented and were applied to many sectors/domains, some of them in agriculture. When describing each step of the methodology in the new section, we provide references that describe the proposed method(s) and one or more examples of application. We actively apply most of them to a variety of agricultural issues.

4.3 A five-step methodology

Our participatory methodology is composed of five main steps: (i) analyse the current functioning of local agriculture, (ii) identify future exogenous changes that may determine its future (drivers), (iii) design local organisation of the expected territorial biodiversity-based agriculture (forecasting), (iv) design the major steps of the transition from the current situation to this new form of local agriculture (backcasting) and (v) design governance structures and management strategies adapted to guide the transition (Fig. 3). The conceptual framework presented in Section 3.1 is used to help participants to structure analysis of the complex nature of the system affected by the agroecological transition and to design the expected new form of local agriculture. The objectives and methods associated with these five main steps are presented below.

Step 1 consists of setting up the transition arena involved in the design process and defining the "situation/problem" (Mermet et al. 2005). The situation/problem corresponds to the key management actors, called "effective management" (Mermet et al. 2005) and "causality chains" (Kajikawa 2008) involved. It is a matter of identifying the key actors, resources, human actions and ecological processes that have a decisive influence on the current functioning of farming systems, supply chains and natural resource management. To build this situation/problem representation, we perform two types of analysis. The first, performed by social scientists, analyses the system of actors involved in local agriculture and natural resource management, for example, by performing strategic analysis (Crozier and Friedberg 1977; e.g. Debril and Therond (2012) for strategic analysis of local water management situations). The aim is to highlight the nature of exchanges between considered stakeholders and the dominated and dominant actors, the latter having a vested interest in keeping the dominant socio-technical regime. This identifies the actors' activities, stakes, problems and strategies and highlights how the social game defines local agricultural issues and problems and, thus, the nature of solutions that stakeholders envision. The second type of analysis is performed through a participatory approach aiming to collectively construct conceptual representations of the functioning of farming systems, supply chains and natural resource management and their interactions. To perform this co-construction, we use methods for collective construction of cognitive maps, such as those representing farming system functioning (Gouttenoire et al. 2011), natural resource management at the local level (Etienne et al. 2008) and social-ecological system functioning (Sibertin-Blanc et al. 2011). The final objective of this step is to compare the social interactions that determine the functioning of local agriculture and natural resource management mapped by both approaches and, ultimately, for stakeholders and researchers to build them into a new shared representation.

This analysis of the current situation must help stakeholders understand (i) the diversity of farming systems, (ii) the organisation of dominant supply chains and agricultural niches in the territory (e.g. norms and production standards, formal and informal agreements) and (iii) the management strategies and organisations related to the key natural resources for local agriculture. More specifically, it must help them identify socio-technical barriers organised by the dominant agricultural regimes and natural resource management strategies that limit or foster the emergence or development of territorial biodiversity-based agriculture.

Step 2 consists of steering the stakeholders in the transition arena to construct possible "future images" (scenarios) of the context (external environment) of local agriculture (Bos et al. 2008; Kajikawa 2008). The objective is to allow stakeholders to address uncertainty in the future external environment of local agriculture (Walker et al. 2005). These scenarios correspond to the description of different sets of levels or trends of exogenous forces that can influence the future of local agriculture and natural resource management in the decades to come. These external forces are factors of change that the actors involved in local agriculture cannot control (Therond et al. 2009; Walker et al. 2002). These scenarios can integrate information produced by forecasting exercises performed at the supra-local level (regional, national, continental or global) that have been broken down or disaggregated locally. They may deal with social (e.g. demographics), economic (e.g. markets), biotechnical (e.g. available technology), political, institutional (e.g. governance) and environmental (e.g. climate) changes (Mahmoud et al. 2009; Therond et al. 2009). To construct these scenarios, we use the morphological approach of Godet (2006), which was used to analyse the future of the field-crop sector in the French Midi-Pyrenees region (Bergez et al. 2011). In this step, it is important to identify and integrate into scenarios the current and potential future characteristics of dominant regimes in the agricultural sectors (Section 3.1) that can act as constraints to or opportunities for the agroecological transition. The analysis of the situation/problem, and in particular the causality chains, performed in step 1 is used in this step to guide stakeholders in identifying exogenous forces.

This step should allow stakeholders and researchers to identify major exogenous changes that could modify the functioning of (i) farming systems (e.g. climate, technology, policies, inputs and outputs, prices, labour availability), (ii) supply chains (e.g. technology, regulations, prices of energy, inputs, and agricultural products; marketed services) and (iii) natural resource management (e.g. state and use of resources; management strategies, policies, regulations).

Step 3 aims to allow stakeholders in the transition arena to construct a shared vision of the organisation of territorial biodiversity-based agriculture that would address their local issues, both present and future, ensure a certain socio-economic control of local agriculture by local stakeholders, and be resilient in the face of future external changes (identified in step 2). We use the principles of Biggs et al. (2012; Section 2.1) as founding principles in this design step of biodiversity-based agriculture. To ensure that the development of agriculture is anchored in local ecological, socio-technical and social-ecological realities, stakeholders' work is based on iterative use and articulation of the conceptual framework presented in Section 3.1, the seven principles presented in Section 2.1 and the results of the two previous steps. This work can be performed with conceptual representations (e.g. texts, conceptual diagrams, cognitive maps, images of the future) alone or in combination with computer models (Voinov and Bousque 2010). These models are used to predict potential impacts of internal or external changes at the farm level (e.g. Martin et al. 2011, Le Gal et al. 2011), farm to local levels (e.g. Belhouchette et al. 2011) or e.g. at the catchment level for water management (e.g. Therond et al. 2014, Murgue et al. 2015). The design of the expected territorial biodiversity-based agriculture aims to determine the types of agroecological production and supply chains to develop locally and how they interact sustainably with the natural resources of the territory (Section 3.1.2).

Step 4 allows stakeholders in the transition arena to design the local agroecological transition from the current situation (specified in step 1) to the territorial biodiversity-based agriculture (designed in step 3). We use backcasting methods that help determine what should be done step-by-step in the short and middle terms to develop the expected form of local agriculture. They consist of defining detailed transition steps, the strategies associated with each step and the monitoring criteria (or indicators) to determine the successful completion of each step. Backcasting methods are now well-known and widely applied (Kajikawa 2008). We suggest, for example, using the approaches of Quist (2007) (see Vergragt and Quist (2011) for examples of application). The main point is to define realistic evolution strategies for the transition that will help overcome actors' resistance to changing the effective management system identified in step 1. In this step, stakeholders will also have to clearly identify the actors responsible for steering the transition, step-by-step. It is a matter of determining which individuals are able to embody the agents that will support changes in farming systems, supply chains and natural resource management.

By designing transition steps and their monitoring criteria, stakeholders identify the changes that need to occur to progressively build the territorial biodiversity-based agriculture envisioned and how to monitor them. The monitoring criteria may be indicators of adaptive management of the agroecological transition (next section). They should be part of information technologies that are developed to steer the transition.

Step 5 aims to help stakeholders in the transition arena to design adaptive governance structures and adaptive management strategies that will enable them to guide the agroecological transition designed in step 4. Based on the four attributes of the governance system proposed by Biggs et al. (2012), Section 2.1), it consists of defining the governance structures (i.e. multi-actor systems and their modes of coordination) that favour adaptive management of the agroecological transition. More precisely, the objective is to design formal rules and informal agreements that would promote the emergence and/or development of local niches that will act as a nursery for the agroecological transition, their coordination at the local level and then their transformation into the envisioned territorial biodiversity-based agriculture (designed in step 3). It also consists of designing adaptive management strategies: the information technologies necessary to monitor the practices implemented and changes in the state of the environment, and the way to redefine actions and

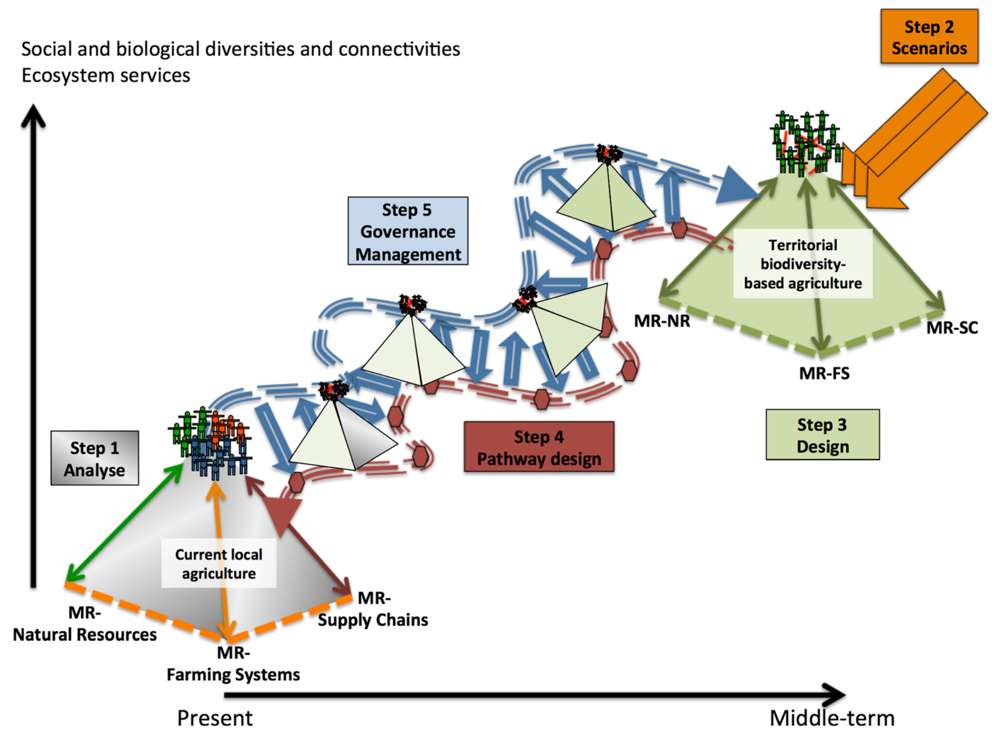

Fig. 3 Participatory design methodology of "territorial biodiversity-based agriculture" and the transition from the current situation to this new form of agriculture. This methodology is driven by Participatory-Design Facilitator-Scientists who manage and steer a multi-stakeholder group ("transition arena") that includes actors from the three management domains (farming systems, supply chains and natural resources) and researchers with key knowledge about the functioning of local agriculture. This participatory methodology is composed of five steps: (*1*) co-analysis of the current situation: the system of actors and their material resources (*MR*); (*2*) co-identification of future changes exogenous to local agriculture, which can determine its future; (*3*) co-design of the expected territorial biodiversity-based agriculture; (*4*) co-design of the transition (pathway) from the current situation to territorial biodiversity-based agriculture (the *reverse arrow* indicates a backcasting approach); and (*5*) co-design of governance structures and adaptive management strategies enabling stakeholders to guide the transition they designed. Each step must be performed by considering and integrating interactions between farming systems, supply chains and natural resource management

manage trade-offs between slow and fast variables (Section 2.1). The transition steps and their monitoring criteria identified in step 3 are the basic ingredients for designing the necessary adaptive management strategies. In this fifth step, the transition arena must also design connected networks of social learning involving farmers, their advisors and actors in the supply-chain and natural resource management that will steer these adaptive management strategies. Key issues are increasing capacity building and the management of uncertainty, power and marginality of participants involved in the learning process (Armitage et al. 2008). "Double-loop learning" or even "triple-loop learning" is a key challenge in such learning processes (Armitage et al. 2008; Pahl-Wostl et al. 2010). More specifically, the challenge for farmers is to share acquired knowledge about the effects of their practices and the risks taken. For the management of supply chains and natural resources, the challenge is to develop adaptive management strategies that consider the biotechnical realities of farms and ensure sustainability, sovereignty and resilience of the local territory.

5 Methodological issues and challenges

5.1 An iterative multi-level, multi-domain and multi-actor approach

In our participatory design methodology, each step should be conducted in several participatory workshops to focus on one of the three management domains of local agriculture (farming systems, supply chains and natural resource management) and on the interactions and consistency between them. In addition, although the approach was presented in a linear manner, each step raises questions about previous ones; thus, it may be necessary to organise them in iterative cycles.

Even though the design of the transition cannot be totally uncoupled from its implementation, one should see the former as the initial step of an iterative and cyclical redesign process of steps 2, 3, 4 and 5. In other words, scenarios of external forces, design of the expected territorial biodiversity-based agriculture, backcasting and design of the adaptive governance structures and management strategies are revised throughout the "confrontation" of the innovation process with actual changes in local agriculture and in its environment (exogenous driving factors).

A challenge when implementing our design methodology is to combine "hard and soft knowledge and analysis methods" (Pahl-Wostl 2007) and "formalised and non-formalised modelling and communication methods" (Newig et al. 2008) to address the complexity of the structure (static approach) and dynamics of complex adaptive systems (Gottschick 2008; Sinn 1998). This combination of different methods and tools must implement a systems approach that explicitly considers the diversity of stakeholder viewpoints and interests, their different types of knowledge and the different domains involved. Throughout the design process, it must favour the production and use of non-equivalent representations of the (components of the) territorial biodiversity-based agriculture produced by the different disciplines and stakeholder groups. This combination of non-equivalent representations is recognised as key for performing integrated and shared analysis of complex systems (Barreteau 2003; Giampietro 2002).

5.2 Development of useful scientific artefacts

In implementing our design methodology, one key challenge for scientists is to provide tools for steps 3 (design of a new form of agriculture resilient in the face of external forces) and 4 (define appropriate indicators for monitoring the transition), either by adapting existing tools or developing new ones.

For step 3, the challenge lies in the development and use of models that allow stakeholders to assess the extent to which the designed farming systems, natural resource management strategies and organisation of supply chains are resilient in the face of the external forces identified in step 2. Agricultural sciences are usually poorly equipped to support such integrated design methodology because they usually favour the development of disciplinary and mechanistic models requiring many input variables that are difficult to apply locally (due to lack of data and a complicated calibration-validation process) and that do not account for key constraints or processes of investigated activities and systems. Consequently, these models are rarely adapted for use in the framework of social learning (Bots and Daalen 2008). When the issue is about emergent properties from place-based interactions between human decisions and ecological processes at the landscape level, such as for management of spatially distributed resources (e.g. water resources) and processes (e.g. biological regulations), agent-based models are recognised as well adapted to simulate ex ante impacts of spatially explicit management strategies (An 2012; Bots and Daalen 2008; Bousquet and Le Page 2004; Voinov and Bousque 2010). Besides having modelling structures suitable for representing the dynamics at hand, they represent social-ecological system using concepts similar to those that stakeholders usually use and thus are relatively intuitive for stakeholders (Voinov and Bousque 2010). Berkel and Verburg (2012) used an agent-based model to help design participatory policy for a multi-functional landscape in combination with exploratory scenarios and participatory backcasting approaches. When the issue is limited to the design of farming systems, the use of biophysical models in the form of a game in participatory workshops allows actors to explore a wide range of material resource use modes (Martin et al. 2011). An important challenge for science is that these models need to consider the complexity and uncertainty associated with implementing biodiversity-based agriculture (Ingram 2008).

The definition of monitoring criteria is a key component in the backcasting approach (step 4). They must indicate whether actors' practices have the expected effects on the social system (e.g. nature and density of social networks) or the ecological system (e.g. level of ecosystem services). These criteria must be rendered into operational indicators of adaptive management. Based on a resilience framework of a rural social-ecological system, Cabell and Oelofse (2012) and Schouten et al. (2012) developed indicators of the state of ecological and social systems. Indicators for the ecological system include (i) diversity and heterogeneity of crops and landscapes, (ii) the state of resources (e.g. water and soil organic matter) and (iii) genetic resources adapted to characteristics of the local environment. Indicators for the social system relate to methods used for promoting knowledge exchange between actors in the territory and the level of sovereignty expected for resources, techniques and knowledge at the territory level.

5.3 Governance structures to support social learning

As already mentioned, in many situations, the problem of collective management of a resource is associated with a failure of governance (Folke et al. 2011; Pahl-Wostl et al. 2010). In the socio-technical (Smith et al. 2010) and social-ecological approaches (Ostrom 2009), the challenge consists of searching for adaptive multi-level governance that permits individual and collective activities to be coordinated with the respective aims of sustainable management of natural resources and of production and exchanges in marketing sectors. When one seeks to implement biodiversity-based agriculture, the challenge is to design and implement governance structures that promote the social learning process necessary to develop local-level coordination between the activities of farming systems, supply chains and natural resource management. Hargrove (2002) and Pahl-Wostl (2007) use the triple-loop learning concept for describing the nature of the learning process at hand. The first learning loop refers to incremental and standardised changes in practices, with the aim of meeting a predetermined goal. This first level of learning is typically applied by actors of the efficiency/substitution-based agriculture when adopting incremental innovations.

The second learning loop entails that the objective itself be reconsidered before searching for an optimal solution. The third learning loop refers to a profound change in knowledge, norms and values supporting the existing governance structure. Due to the objective of biodiversity-based agriculture, it is necessary to implement the last two learning loops to make necessary radical technological, social, economic and institutional innovations possible.

Ostrom (2005) and Pahl-Wostl (2009) show that the main types of governance structures vary in their support of these learning loops. While markets and bureaucracy (regulatory agencies) can manage the first learning loop, it becomes more expensive to resort to them when the learning process becomes more complex. Management costs of a second learning loop are often high in a bureaucracy. Coordination by a market governance structure encounters the same difficulty, even though the problem is less severe when redefinition of the objective is sustained by incentives for changing practices. When the process involves changes in norms and values, North (1990) and Ostrom (2009) show the effectiveness of hybrid networks of actors or informal institutions in which skills, knowledge and practices are discussed in informal forums or “collective choice arenas”. This type of hybrid governance structure, based on exchanging experiences with innovative practices within a network of actors, is adapted to the farm level but also to the supply chain and natural resource management (Fares, unpublished). These structures imply public-private co-regulation, in which traditional instruments and tools of public regulation (e.g. norms, standards, incentives via agro-environmental contracts) are combined with private tools built by local actors (e.g. contracts between firms and farms to manage groundwater problems).

6 Conclusion

Biodiversity-based agriculture is an alternative to the dominant efficiency/substitution-based agriculture. Its attractiveness and promise increases as social pressure increases for sustainable management of the environment and agriculture. It is particularly challenging in intensive production areas, such as intensive lowlands, mixed crop-livestock and livestock zones in developed countries and intensive agricultural zones in developing countries where agricultural development has been driven by the green revolution. It requires simultaneous implementation of agronomic innovations that enable the development of diversified farming systems and new modes of coordination between actors in supply chains and for natural resource management. Accordingly, its adoption and diffusion depends on an innovation process involving technological, social, economic and institutional changes performed by a variety of actors with different interests and viewpoints.

We developed a conceptual and methodological framework tailored to help local stakeholders design the agroecological transition towards a territorial biodiversity-based agriculture. It hybridised concepts and methods related to farming, social-ecological and socio-technical systems and transition management, design and sustainability science. It was framed to (i) structure identification and strong involvement of the many types of concerned stakeholders throughout the design process; (ii) be holistic, to consider interactions within and between the subsystems of local agriculture; (iii) consider the specific characteristics of different management strategies and the incompleteness of associated knowledge; and (iv) be transdisciplinary, to integrate the knowledge of researchers and stakeholders. As such, it participates in the development of “integration and implementation sciences” (Bammer 2005) since it (i) attempts to provide sound theoretical and methodological foundations to address societal issues characterised by complexity, uncertainty, change and imperfection; (ii) is based on systems and complex thinking, participatory methods and knowledge management and exchange; and (iii) is grounded in practical application and involves a large stakeholder panel.

The design methodology presented here aims to support local stakeholders in designing an expected and coordinated innovation process within farming systems, supply chains and natural resource management. It enables stakeholders, assisted by researchers, to define an action plan that includes adaptive governance structures and management strategies to steer the transition at the local level. This “action plan” specifies both the expected local agriculture to develop and the pathway and social organisations to establish. To effectively develop a territorial biodiversity-based agriculture, the design process must continue with effective transition management, which is an “on-the-go” decision process based on adaption to factual endogenous and exogenous changes and implies experimentation and individual and social learning. The challenge for effective transition management (vs transition design) is to manage iterative participatory design-assessment cycles and large collective “learn-by-doing” and “do-by-learning” processes about the agroecological transition. Transition management may be supported by iteratively implementing our methodological framework from the forecasting step to the design of adaptive governance and management step.

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References

Altieri M (1999) The ecological role of biodiversity in agroecosystems. Agric Ecosyst Environ 74:19–31. doi:10.1016/S0167-8809(99)00028-6

An L (2012) Modeling human decisions in coupled human and natural systems: review of agent-based models. Ecol Model 229:25–36. doi:10.1016/j.ecolmodel.2011.07.010

Anderies JM, Janssen MA, Ostrom E (2004) A framework to analyze the robustness of social-ecological systems from an institutional perspective. Ecol Soc 9(1):18, http://www.ecologyandsociety.org/vol9/iss1/art18/

Armitage D, Marschke M, Plummer R (2008) Adaptive co-management and the paradox of learning. Global Environ Chang 18:86–98

Arthur WB (1989) Competing technologies, increasing returns, and lock-in by historical events. Econ Jl 99:116–131, http://www.jstor.org/stable/2234208?origin=JSTOR-pdf

Bammer G (2005) Integration and implementation sciences : building a new specialization. Ecol Soc 18(2):21, http://www.ecologyandsociety.org/vol10/iss2/art6/

Barnaud C, van Paassen A (2013) Equity, power games, and legitimacy: dilemmas of participatory natural resource management. Ecol Soc 18(2):21. doi:10.5751/ES-05459-180221

Barreteau O (2003) The joint use of role-playing games and models regarding negotiation process: characterization of associations. J Artific Soc and Social Simul 6(2). http://jasss.soc.surrey.ac.uk/6/2/3.html

Belhouchette H, Louhichi K, Therond O, Mouratiadou I, Wery J, van Ittersum M, Flichman G (2011) Assessing the impact of the Nitrate Directive on farming systems using a bio-economic modelling chain. Agric Syst 104:135–145. doi:10.1016/j.agsy.2010.09.003

Benoît M, Rizzo D, Marraccini E, Moonen AC, Galli M, Lardon S, Rapey H, Thenail C, Bonari E (2012) Landscape agronomy: a new field for addressing agricultural landscape dynamics. Landsc Ecol 27:1385–1394. doi:10.1007/s10980-012-9802-8

Bergez JE, Carpy-Goulard F, Paradis S, Ridier A (2011) Participatory foresight analysis of the cash crop sector at regional level: case study for a southwestern region in France. Reg Environ Chang 11:951–961. doi:10.1007/s10113-011-0232-y

Berkel DB, Verburg PH (2012) Combining exploratory scenarios and participatory backcasting: using an agent-based model in participatory policy design for a multi-functional landscape. Landsc Ecol 27:641–658. doi:10.1007/s10980-012-9730-7

Biggs R, Schlüter M, Biggs D, Bohensky EL, BurnSilver S, Cundill G, Dakos V, Daw TM, Evans LS, Kotschy K, Leitch AM, Meek C, Quinlan A, Raudsepp-Hearne A, Robards MD, Schoon ML, Schultz L, West PC (2012) Toward principles for enhancing the resilience of ecosystem services. Annu Rev Environ Resour 37:421–448. doi:10.1146/annurev-environ-051211-123836

Blazy JM, Carpentier A, Thomas A (2011) The willingness to adopt agro-ecological innovations: application of choice modelling to Caribbean banana planters. Ecol Econ 72:140–150. doi:10.1016/j.ecolecon.2011.09.021

Bos B, Koerkmap PG, Gosselink J, Bokma S (2008) Reflexive interactive design and its application in a project on sustainable dairy husbandry systems. Outlook Agric 38:137–145. doi:10.5367/000000009788632386

Bots PWG, Daalen CE (2008) Participatory model construction and model use in natural resource management: a framework for reflection. Syst Pract Action Res 21:389–407

Bousquet F, Le Page C (2004) Multi-agent simulations and ecosystem management: a review. Ecol Model 176:313–332. doi:10.1016/j.ecolmodel.2004.01.011

Brewer MJ, Goodell PB (2010) Approaches and incentives to implement integrated pest management that addresses regional and environmental issues. Annu Rev Entomol 41–59 doi: 10.1146/annurev-ento-120709-144748

Cabell JF, Oelofse M (2012) An indicator framework for assessing agroecosystem resilience. Ecol Soc 17(1):18. doi:10.5751/ES-04666-170118

Caporali F (2011) Agroecology as a transdisciplinary science for a sustainable agriculture. In: Lichtfouse E (ed) Biodiversity, biofuels, agroforestry and conservation agriculture, Sustainable Agriculture Reviews 5, doi:10.1007/978-90-481-9513-8_1, © Springer Science+Business Media B.V. 2011 doi: 10.1007/978-90-481-9513-8

Cardinale BJ, Duffy JE, Gonzalez A et al (2012) Biodiversity loss and its impact on humanity. Nature 486:59–67. doi:10.1038/nature11148

Carlisle L (2014) Diversity, flexibility, and the resilience effect : lessons from a social-ecological case study of diversified farming in the northern Great Plains. Ecol Soc 19:3. doi:10.5751/ES-06736-190345

Caron P, Biénabe E, Hainzelin E (2014) Making transition towards ecological intensification of agriculture a reality: the gaps in and the role of scientific knowledge. Curr Opin Environ Sustain 8:44–52. doi:10.1016/j.cosust.2014.08.004

Cash DW, Clark W, Alcock F, Dickson NM, Eckley N, Guston DH, Mitchell RB (2003) Knowledge systems for sustainable development. PNAS 100:8086–8091. doi:10.1073/pnas.1231332100

Cowan R, Gunby P (1996) Sprayed to death: path dependence, lock-in and pest control strategies. Econ J 106:521–542. doi:10.2307/2235561

Cowling RM, Egoh B, Knight AT, Farrell PJO, Reyers B, Rouget M, Wilhelm-Rechman A (2008) An operational model for mainstreaming ecosystem services for implementation. PNAS 105(28):9483–9488. doi:10.1073/pnas.0706559105

Cox P (1996) Some issues in the design of agricultural decision support systems. Agric Syst 52:355–381. doi:10.1016/0308-521X(96)00063-7

Crozier M, Friedberg E (1977) L'acteur et le système. Seuil. Paris ISBN: 978–2020046770

Darnhofer I (2015) Socio-technical transitions in farming: key concepts. In: Sutherland AN, Darnhoffer I, Wilson GA, Zagata L (eds) Transition pathways towards sustainability in agriculture: case studies from Europe. 17–31. CABI, Wallingford. ISBN 978-1-78064-219-2

Darnhofer I, Bellon S, Dedieu B, Milestad R (2010) Adaptiveness to enhance the sustainability of farming systems. A review. Agron Sust Dev 30:545–555. doi:10.1051/agro/2009053

Darnhofer I, Gibbons D, Dedieu B (2012) Farming systems research: an approach to inquiry. In: Darnhofer I, Gibbons D, Dedieu B (eds) Farming systems research into the 21st century: the new dynamic. Springer, Dordrecht, pp 1–30, **ISBN: 978-94-007-4502-5**

David P, Arthur B (1985) Clio and economics of QWERTY. Am Econ Rev 75:337–349

Debril T, Therond O (2012) Les difficultés associées à la gestion quantitative de l'eau et à la mise en œuvre de la réforme des volumes

prélevables : le cas du bassin Adour-Garonne. Agron Environ Soc 2(10):127–138
Diaz M, Darnhofer I, Darrot C, Beuret J-E (2013) Green tides in Brittany: what can we learn about niche–regime interactions? Environ Innov Soc Transit 8:62–75. doi:10.1016/j.eist.2013.04.002
Douthwaite B, Manyong VM, Keatinge JDH, Chianu J (2002) The adoption of alley farming and Mucuna: lessons for research. Agrofor Syst 56:193–202
Drinkwater LE (2009) Ecological knowledge: foundation for sustainable organic agriculture in organic farming: the ecological system. Cornell University, Ithaca, **Ed Charles Francis, 353 pages**
Duru M, Therond O (2014) Livestock system sustainability and resilience in intensive production zones: which form of ecological modernization? Reg Environ Chang. doi:10.1007/s10113-014-0722-9
Duru M, Therond O, Martin G, Martin-Clouaire R, Magne MA, Justes E, Journet EP, Aubertot JN, Savary S, Bergez JE, Sarthou JP (2015) Challenges of implementing biodiversity-based agriculture to enhance ecosystem services. A review. Agronomy for Sustainable Development (in press)
Etienne M, Du Toit D, Pollard S (2008) ARDI: a co-construction method for participatory modelling in natural resources management, in proceedings of IEMSS Congress, Barcelona (Espagne), 2, 866–873
Fares M, Magrini MB, Triboulet P (2011) Transition agroécologique, innovation et effets de verrouillage: le rôle de la structure organisationnelle des filières. Le cas de la filière blé dur française. Cah Agric 21:34–45. doi:10.1684/agr.2014.0691
Foley JA, Defries R, Asner G-P, Barford C, Bonan G, Carpenter SR, … Snyder PK (2005) Global consequences of land use. Science 309: 570–575. doi: 10.1126/science.1111772
Folke C (2006) Resilience: the emergence of a perspective for social–ecological systems analyses. Global Environ Chang 16:253–267
Folke C, Carpenter S, Elmqvist T, Gunderson L, Holling CS, Walker B (2002) Resilience and sustainable development: building adaptive capacity in a world of transformations. Ambio 31:437–440
Folke C, Jansson Å, Rockström J, Olsson P, Carpenter SR, Chapin FS, Crépin A-S, Daily G, Danell K, Ebbesson J, Elmqvist T, Galaz V, Moberg F, Nilsson M, Österblom H, Ostrom E, Persson Å, Peterson G Polasky S, Steffen W, Walker B, Westley F (2011) Reconnecting to the biosphere. Ambio: 719–738. doi: 10.1016/j.gloenvcha.2006.04.002
Foxon T (2011) A coevolutionary framework for analysing a transition to a sustainable low carbon economy. Ecol Econ 70:2258–2267
Foxon TJ, Reed MS, Stringer LC (2009) Governing long-term social–ecological change: what can the adaptive management and transition management approaches learn from each other? Environ Pol Gov 20:3–20. doi:10.1002/eet.496
Galloway JN, Trends R, Townsend AR, Erisman JW, Bekunda M, Cai Z, Freney JR, Martinelli LA, Seitzinger SP, Sutton MA (2008) Transformation of the nitrogen cycle: potential solutions. Science 320:889–892. doi:10.1126/science.1136674
Geels F (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res Policy 31: 1257–1274, http://econpapers.repec.org/RePEc:eee:respol:v:31:y:2002:i:8–9:p:1257–1274
Geels F (2005) Processes and patterns in transitions and system innovations: refining the co-evolutionary multi-level perspective. Technol Forecast Soc Chang 72:681–696. doi:10.1016/j.techfore.2004.08.014
GeelS FW (2010) Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective. Res Policy 39(4):495–510. doi:10.1016/j.respol.2010.01.022
Geels F, Schot J (2007) Typology of sociotechnical transition pathways. Res Policy 36:399–417. doi:10.1016/j.respol.2007.01.003
Giampietro M (2002) Complexity and scales: the challenge for integrated assessment. Integr Ass 3(2–3):247–265
Godet M (2006) Le choc de 2006. Démographie, croissance, emploi. Pour une société de projets. Editions Odile Jacob. Paris. 300 p ISBN: 978-2-7381-1213-2
Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson L, Toulmin (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818. doi:10.1126/science.1185383, **New York, NY**
Gottschick M (2008) Participatory sustainability impact assessment: scientific policy advice as a social learning process. Syst Pract Action Res 21(6):479–495. doi:10.1007/s11213-008-9109-5
Gouttenoire L, Cournut S, Ingrand S (2011) Modelling as a tool to redesign livestock farming systems: a literature review. Animal 5:1957–1971. doi:10.1017/S175173111100111X
Greenberg J (1990) The theory of social situations: an alternative game-theoretic approach. Cambridge University Press, Cambridge
Grimble R, Wellard K (1997) Stakeholder methodologies in natural resource management: a review of concepts, contexts, experiences and opportunities. Agric Syst 55:173–193
Hargrove R (2002) Masterful coaching. Revised edition. Jossey-Bass/Pfeiffer, Wiley, **432 p**
Hatchuel A (2001) The two pillars of new management research. Br J Manag 12:33–39
Hendrickson JR, Liebig MA, Sassenrath G (2008) Environment and integrated agricultural systems. Renew Agric Food Syst 23:304–313
Hill SB (1998) Redesigning agroecosystems for environmental sustainability: a deep systems approach. Syst Res 15:391–402. doi:10.1002/(SICI)1099-1743(1998090)15:5<391::AID-SRES266>3.0.CO;2–0
Hochman Z, Carberry PS, Robertson MJ, Gaydond DS, Bellb LW, McIntoshe PC (2011) Prospects for ecological intensification of Australian agriculture. Eur J Agron. doi:10.1016/j.eja.2011.11.003
Holling CS (2001) Understanding the complexity of economic, ecological, and social systems. Ecosystems 4:390–405. doi:10.1007/s10021-00 -0101-5
Holt-Giménez E, Altieri MA (2013) Agroecology, food sovereignty and the new green revolution. J Sust Agric 37:93–102
Horlings LG, Marsden TK (2011) Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernization of agriculture that could "feed the world". Global Environ Chang 21:441–452. doi:10.1016/j.gloenvcha.2011.01.004
Huang J, Tichit M, Poulot M, Petit C, Darly S, Shuangcheng L, Aubry C (2015) Comparative review of multifunctionality and ecosystem services in sustainable agriculture. J Environ Manag 149:138–147. doi:10.1016/j.jenvman.2014.10.020
IAASTD (International Assessment of Agricultural Knowledge, Science and Technology for Development): Agriculture at a crossroads. In: MacIntyre BD, Herren HR, Wakhungu J, Watson RT (eds) Global report. Washington, DC: International Assessment of Agricultural Knowledge, Science and Technology for Development, Island Press. ISBN 978-1-59726-538-6
Ingram J (2008) Agronomist–farmer knowledge encounters: an analysis of knowledge exchange in the context of best management practices in England. Agric Hum Values 25:405–418. doi:10.1007/s10460-008-9134-0
Jakku E, Thorburn PJ (2010) A conceptual framework for guiding the participatory development of agricultural decision support systems. Agricult Syst 103:675–682. doi:10.1016/j.agsy.2010.08.007
Kajikawa Y (2008) Research core and framework of sustainability science. Sustain Sci 3:215–239. doi:10.1007/s11625-008-0053-1
Kassam A, Friedrich T, Derpsch R, Lahmar R, Mrabet R, Basch G, González-Sánchez EJ, Serraj R (2012) Conservation agriculture in the dry Mediterranean climate. Field Crops Res 132:7–17. doi:10.1016/j.fcr.2012.02.023
Kemp R, Rotmans J (2005) The management of the co-evolution of technical, environmental and social systems. In: Weber M,

Hemmelskamp J (eds) Towards environmental innovation systems. Springer, Berlin, pp 33–55
Klerkx L, Leeuwis C (2008) Balancing multiple interests: embedding innovation intermediation in the agricultural knowledge infrastructure. Technovation 28:364–378, **ISBN: 0166-4972**
Klerkx L, van Mierlo B, Leeuwis C (2012) Evolution of systems approaches to agricultural innovation: concepts, analysis and interventions. In: Darnhofer I, Gibbon D, Dedieu B (eds) Farming systems research into the 21st century: the new dynamic. Springer, Dordrecht, pp 359–385
Knickel K, Brunori G, Rand S (2009) Towards a better conceptual framework for innovation processes in agriculture and rural development: from linear models to systemic approaches. J Agric Educ Ext 15:37–41
Koohafkan P, Altieri M, Gimenez EH (2011) Green agriculture: foundations for biodiverse, resilient and productive agricultural systems. Int J Agric Sustain 1–13. doi: 10.1080/14735903.2011.610206
Kremen C, Miles A (2012) Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. Ecol Soc 17(4):40. doi:10.5751/ES-05035-170440
Kremen C, Iles A, Bacon C (2012) Diversified farmings: an agroecological, systems-based. Ecol Soc 17(4):44. doi:10.5751/ES-05103-170444
Kuisma M, Kahiluoto H, Havukainen J, Lehtonen E, Luoranen M, Myllymaa T, Grönroos J, Horttanainen M (2013) Understanding biorefining efficiency—the case of agrifood waste. Bioresour Technol 135:588–597. doi:10.1016/j.biortech.2012.11.038
Lamine C (2011) Transition pathways towards a robust ecologization of agriculture and the need for system redesign. Cases from organic farming and IPM. J Rural Stud 27:209–219. doi:10.1016/j.jrurstud.2011.02.00
Lamine C, Renting H, Rossi A, Wiskerke J S C, Brunori G (2012) Agri-food systems and territorial development: innovations, new dynamics and changing governance mechanisms. In: Darnhofer I, Gibbons D, Dedieu B (eds) Farming systems research into the 21st century: the new dynamic. Springer Dordrecht. pp. 229–255. doi:10.1007/978-94-007-4503-2_11
Le Gal P-Y, Dugué P, Faure G, Novak S (2011) How does research address the design of innovative agricultural production systems at the farm level? A review. Agric Syst 104:714–728. doi:10.1016/j.agsy.2011.07.007
Le Roux R, Barbault J, Baudry J, Burel F, Doussan I, Garnier E, Herzog F, Lavorel S, Lifran R, Roger-Estrade J, Sarthou JP, Trommetter M (éditeurs) (2008) Agriculture et biodiversité, valoriser les synergies. Expertise scientifique collective, synthèse du rapport, INRA. Paris, France: 738 pages
Levidow L, Birch K, Papaioannou T (2012) Divergent paradigms of european agro-food innovation: the knowledge-based bio-economy (KBBE) as an R&D agenda. Sci Technol Hum Value 0(00), 1–32. doi:10.1177/0162243912438143
Levidow L, Birch B, Papaioannou T (2012b) EU agri-innovation policy: two contending visions of the bio-economy. Crit Policy Stud 6:37–41. doi:10.1080/19460171.2012.659881
Lin BB (2011) Resilience in agriculture through crop diversification: adaptive management for environmental change. Bioscience 61:183–193. doi:10.1525/bio.2011.61.3.4
Loorbach (2010) Transition management for sustainable development: a prescriptive, complexity-based governance framework. Governance 23(1):161–183. doi:10.1111/j.1468-0491.2009.01471.x
Mahmoud M, Liu Y, Hartmann H, Stewart S, Wagener T, Semmense D, Stewart R, Gupta H, Dominguez D, Dominguez F, Hulse D, Letcher R, Rashleigh B, Smith C, Street R, Ticehurst J, Twery M, van Deldenp H, Waldick R, White D, Winter L (2009) A formal framework for scenario development in support of environmental decision-making. Environ Model Softw 24:798–808. doi:10.1016/j.envsoft.2008.11.010
Marsden T (2012) Towards a real sustainable agri-food security and food policy: beyond the ecological fallacies? Political Q 83:139–145. doi:10.1111/j.1467-923X.2012.02242.x
Martin G, Felten B, Duru M (2011) Forage rummy: a game to support the participatory design of adapted livestock systems. Environ Model Softw 26:1442–1453. doi:10.1016/j.envsoft.2011.08.013
Mermet L, Billé R, Leroy M, Narcy J-B, Poux X (2005) L'analyse stratégique de la gestion environnementale: un cadre théorique pour penser l'efficacité en matière d'environnement. Nat Sci Soc 13:127–137. doi:10.1051/nss:2005018
Meynard JM, Dedieu B, Bos B (2012) Re-design and co-design of farming systems: an overview of methods and practices. In: Darnhofer I, Gibbon D, Dedieu B (eds) Farming systems research into the 21st century: the new dynamic. Springer, Dordrecht, pp 407–431
Millennium Ecosystem Assessment (2005) Ecosystems and human well-being—synthesis. Island Press, Washington, **155pp**. ISBN 1-59726-040-1
Moore KM (2011) Global networks in local agriculture: a framework for negotiation. J Agric Food Inform 12:23–39
Moraine M, Duru M, Nicholas P, Leterme P, Therond O (2014) Farming system design for innovative crop-livestock integration in Europe. Animal: 1–14. doi:10.1017/S1751731114001189
Murgue C, Therond O, Leenhardt D (2015) Toward integrated water and agricultural land management: participatory design of agricultural landscapes. Land Use Policy 45:52–63. doi:10.1016/j.landusepol.2015.01.011
Newig J, Haberl H, Pahl-Wostl C, Rotman DS (2008) Formalise and non-formalised methods in resource management—knowledge and social learning in participatory processes: an introduction. Syst Pract Action Res 21:381–387
North D (1990) Institutions, institutional change and economic performance. Cambridge University Press, Cambridge. ISBN 9780521397346
North D (2005) Understanding the process of economic change. Princeton University Press, Princeton. ISBN 9781400829484
Ostergard JR, Robert L, Tubin M, Altman J (2001) Stealing from the past: globalisation, strategic formation and the use of indigenous intellectual property in the biotechnology industry. Third World Q 22:643–656. doi:10.1080/014365901200718
Ostrom E (2005) Understanding institutional diversity. Princeton University Press. pp 376 ISBN: 9780691122380
Ostrom E (2009) A general framework for analyzing sustainability of social-ecological systems. Science 325:419–422. doi:10.1126/science.1172133, **New York, NY**
Pahl-Wostl C (2007) Transitions towards adaptive management of water facing climate and global change. Water Resour Manag 21:49–62
Pahl-Wostl C (2009) A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. Global Environ Chang 18:354–365. doi:10.1016/j.gloenvcha.2009.06.001
Pahl-Wostl C, Hare M (2004) Processes of social learning in integrated resources management. J Appl Community Psychol 14:193–206
Pahl-Wostl C, Holtz G, Kastens B, Knieper C (2010) Analyzing complex water governance regimes: the management and transition framework. Environ Sci Policy 13:571–581. doi:10.1016/j.envsci.2010.08.006
Power AG (2010) Ecosystem services and agriculture: tradeoffs and synergies. Phil Trans R Soc B 365:2959–2971. doi:10.1098/rstb.2010.0143
Pretty J (2008) Agricultural sustainability: concepts, principles and evidence. Phil Trans R Soc London B 363:337–365. doi:10.1098/rstb.2007.2163
Quist J (2007) Backcasting for a sustainable future. The impact after 10 years. Eburon, Ootsburg, 284 pp ISBN 978-90-5972-175-3

Rabbinge R, De Wit CT (1989) Systems, models and simulation. In: Rabbinge R, Ward SA, Van Laar HH (eds) Simulation and systems management in crop protection. Pudoc, Wageningen, pp 3–15
Rains GC, Olson DM, Lewis WJ (2011) Redirecting technology to support sustainable farm management practices. Agric Syst 104:365–370. doi:10.1016/j.agsy.2010.12.008
Rotmans J, Kemp R, van Asselt M (2001) More evolution than revolution: transition management in public policy. Foresight 3:15–31
Sanderson MA, Archer D, Hendrickson J, Kronberg S, Liebig M, Nichol K, Schmer M, Tanaka D, Aguilar D (2013) Diversification and ecosystem services for conservation agriculture: outcomes from pastures and integrated crop–livestock systems. Renew Agric Food Syst 28:128–144. doi:10.1017/S1742170512000312
Schiere JB, Darnhofer I, Duru M (2012) Dynamics in farming systems: of changes and choices. In: Darnhofer I, Gibbon D, Dedieu B (eds) Farming systems research into the 21st century: the new dynamic. Springer, Dordrecht, pp 339–365
Schouten MAH, Van der Heide CM, Heijman WJM, Opdam PFM (2012) A resilience-based policy evaluation framework: application to European rural development policies. Ecol Econ 81:165–175
Sibertin-Blanc C, Therond O, Monteil C, Mazzega P (2011) Formal modeling of social-ecological systems. Proc. of the 7th European social simulation association conference, 19–23 September, Montpellier
Singh JS, Pandey VC, Singh DP (2011) Efficient soil microorganisms: a new dimension for sustainable agriculture and environmental development. Agric Ecosyst Environ 140:339–353. doi:10.1016/j.agee.2011.01.017
Sinn JS (1998) A comparison of interactive planning and soft systems methodology: enhancing the complementarist position. Syst Pract Action Res 11:435–453. doi:10.1023/A:1023098025076
Smith A, Stirling A (2010) The politics of social-ecological resilience and sustainable socio-technical transitions. Ecol Soc 15(1):11, http://www.ecologyandsociety.org/vol15/iss1/art11/
Smith A, Voß J-P, Grin J (2010) Innovation studies and sustainability transitions: the allure of the multi-level perspective and its challenges. Res Policy 39:435–448. doi:10.1016/j.respol.2010.01.023
Souchère V, Millair L, Echeverria J, Bousquet F, Le Page C, Etienne M (2010) Co-constructing with stakeholders a role-playing game to initiate collective management of erosive runoff risks at the watershed scale. Environ Model Softw 25:1359–1370. doi:10.1016/j.envsoft.2009.03.002
Stassart PM Baret P, Grégoire JC, Hance T, Mormont M, Reheul D, Vanloqueren G, Visser M (2012) Trajectoire et potentiel de l'agroécologie, pour une transition vers des systèmes alimentaires durables. In: Van Dam D, Streith M, Nizet J, Stassart P.M (dir.) Agroécologie. Entre pratiques et sciences sociales. Educagri éditions, 2012, Paris, pp. 25–51
Sutherlan LA, Zagata L, Wilson G (2015) Conclusions. In: Sutherland AN, Darnhoffer I, Wilson GA Zagata L (eds) Transition pathways towards sustainability in agriculture: case studies from Europe. CABI, 189–204
ten Napel J, Van der Veen AA, Oosting SJ, Koerkamp PWGG (2011) A conceptual approach to design livestock production systems for robustness to enhance sustainability. Livest Sci 139:150–169
Therond O, Belhouchette H, Janssen S, Louhichi K, Ewert F, Bergez JE, Wery J, Heckelei T, Alkan Olsson J, Leenhardt D, van Ittersum MK (2009) Methodology to translate policy assessment problems into scenarios: the example of the SEAMLESS Integrated Framework. Environ Sci Policy 12:619–630. doi:10.1016/j.envsci.2009.01.013
Therond O, Sibertin-Blanc C, Lardy R, Gaudou B, Balestrat M, Hong Y, Louail T, Nguyen VB, Panzoli D, Sanchez-Perez JM, Sauvage S, Taillandier P, Vavasseur M, Mazzega P (2014) Integrated modelling of social-ecological systems: the MAELIA high-resolution multi-agent platform to deal with water scarcity problems. Intern. Env. Modelling and Software Society (iEMSs) 7th Intern. Congr. on Env; Modelling and Software. San Diego, CA (USA), D. P. Ames N, Quinn WT, Rizzoli AE (eds) http://www.iemss.org/society/index.php/iemss-2014-proceedings
Toderi M, Powell N, Seddaiu G, Roggero P, Gibbon D (2007) Combining social learning with agro-ecological research practice for more effective management of nitrate pollution. Environ Sci Policy 10:551–563
Tscharntke T, Klein AM, Kruess A et al (2005) Landscape perspectives on agricultural intensification and biodiversity—ecosystem service management. Ecol Lett 8:857–874. doi:10.1111/j.1461-0248.2005.00782.x
van Ittersum MK, Rabbinge R (1997) Concepts in production ecology for analysis and quantification of agricultural input–output combinations. Field Crops Res 52:197–208. doi:10.1016/S0378-4290(97)00037-3
Vanclay F (2004) Social principles for agricultural extension to assist in the promotion of natural resource management. Aust J Exp Agric 44:213–223
Vanloqueren G, Baret PV (2009) How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. Res Policy 38:971–983. doi:10.1016/j.respol.2009.02.008
Vergragt PJ, Quist J (2011) Backcasting for sustainability: introduction to the special issue. Technol Forecast Soc Chang 78:747–755. doi:10.1016/j.techfore.2011.03.010
Voinov A, Bousque F (2010) Modelling with stakeholders. Environ Model Softw 25:1268–1281. doi:10.1016/j.envsoft.2010.03.007
Voß J-P, Newig J, Kastens B, Monstadt J, Nölting B (2007) Steering for sustainable development—a typology of empirical contexts and theories based on ambivalence, uncertainty and distributed power. J Environ Policy Plan 9
Walker DH (2002) Decision support, learning and rural resource management. Agric Syst 73:113–127
Walker B, Meyers JA (2004) Thresholds in ecological and social–ecological systems : a developing database. Ecol Soc 9(2):3, http://www.ecologyandsociety.org/vol9/iss2/art3
Walker W, Harremoes P, Rotmans J, Van Der Sluijs J, Van Asselt M, Janssen P, Krayer Von Krauss M (2005) Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. Integr Assess 4:5–17, **1389-5176/03/040**
Walker B, Gunderson L, Kinzig A, Folke C, Carpenter S, Schultz L (2006) A handful of heuristics and some propositions for understanding resilience in social-ecological systems. Ecol Soc 11(1):13, http://www.ecologyandsociety.org/vol11/iss1/art13/
Walker B, Carpenter S, Anderies J, Abel N, Cumming G, Janssen M, Lebel L, Norberg J, Peterson GD, Pritchard R (2002) Resilience management in social-ecological systems: a working hypothesis for a participatory approach. Conserv Ecol 6(1):14, http://www.consecol.org/vol6/iss1/art14
Warner KD (2008) Agroecology as participatory science emerging alternatives to technology transfer extension practice introduction: the travail of extension. Sci Technol Human values 6:754–777
Wezel A, Casagrande M, Celette F et al (2013) Agroecological practices for sustainable agriculture. A review. Agron Sustain Dev 34:1–20. doi:10.1007/s13593-013-0180-7
Williams BK (2011) Adaptive management of natural resources—framework and issues. J Environ Manag 92:1336–1353
Williamson O (2002) The theory of the firm as governance structure: from choice to contract. J Econ Perspect 16:171–195
Wilson G (2008) From “weak” to “strong” multifunctionality: conceptualising farm-level multifunctional transitional pathways. J Rural Stud 24(3):367–383. doi:10.1016/j.jrurstud.2007.12.010
Zhang W, Ricketts TH, Kremen C, Carney K, Swinton SM (2007) Ecosystem services and dis-services to agriculture. Ecol Econ 64:253–260