Matière à débattre & décider

Agroecology

Research for the transition of agri-food systems and territories

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Foreword

Over the past decade, many national and international entities have become enthusiastic proponents of agroecology. In 2012, the French Ministry of Agriculture launched the "Agroecological project for France". This mobilizing project for all of French agriculture is aimed to produce differently by rethinking agricultural production systems and by making them part of collective dynamics, especially through Economic and Environmental Interest Groups, i.e. groups of farmers sharing the same agroecological perspectives (GIEE)[1]. The French Economic, Social and Environmental Council (CESE) took up the issue of agroecology and weighed in with an opinion in 2016. The Food and Agriculture Organization of the United Nations (FAO) organized the first "International Symposium on Agroecology for Food Security and Nutrition" in 2014. It subsequently organized meetings by world region and shared conclusions of these meetings at a second symposium in April 2018, where it launched the "Scaling up Agroecology Initiative". At the same time, the French Agricultural Research Centre for International Development (CIRAD) and the French National Research Institute for Agriculture, Food and Environment (INRAE) highlighted their convergence of views on agroecology in a joint note[2]. All of this activity not only stimulated national and international research efforts, but also led to better articulation between societal initiatives and the research systems of the countries of the Global North and the Global South.

Launched in 2011, INRAE's "agroecology" project is providing a new impetus to research. Agroecology is thus considered as a scientific discipline in its own right, located at the interface between ecology and agronomy. This first project makes it possible to amplify a systemic and ecological vision of research on agroecosystems, considering them as ecosystems managed no longer for the sole purpose of agricultural production, but, more broadly, for the provision of ecosystem services. The objectives of preserving natural resources (water, soil, biodiversity) and cultural heritage (landscape), and mitigating climate change are added to that of producing biomass.

Five research priorities have been identified: knowledge and use of biological interactions in agroecosystems; agroecology of the landscape; multi-criteria assessment of agroecosystems that includes biodiversity and the provision of ecosystem services; sustainable management of soil and water resources as a mechanism for agroecology; and the design of new agricultural systems through the mobilization of human and social sciences.

In 2012, this work led to the production of an overview[3] as well as the drafting of recommendations for INRAE. In 2013, a conference was organized by INRAE, under the

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1 See https://agriculture.gouv.fr/pres-de-10-000-agriculteurs-engages-dans-les-groupements-dinteret-economique-et-environnemental-giee.

2 Soussana J.-F., Côte F., 2016. *Agro-écologie : le positionnement des recherches de l'Inra et du Cirad*, 8 p. See https://www.cirad.fr/content/download/11293/132717/version/3/file/Agro-ecologie-Inra-CIRAD-note-longue.pdf.

3 See https://www6.inrae.fr/ciag/content/download/5608/42552/file/RevueIAvolume43.pdf.

aegis of the Ministry of Agriculture, bringing together researchers, decision makers and actors from the agricultural world. It was an occasion for exchanges and the insertion of agroecology into the agenda of the research community, of the agricultural world and, more generally, of civil society as a whole. The conference's deliberations were reported in the free online journal *Innovations agronomiques*[4].

The term "agroecology" soon started being increasingly used across INRAE – and in society in general – as a new paradigm for rethinking agroecosystems and agricultural activities. In 2014, the "New modelling challenges: agroecology"[5] seminar stimulated progress in the field of representation, prediction and management of agroecosystems. Since 2014, the EcoServ ("Services provided by ecosystems") metaprogramme has proposed an ecosystem approach to agroecosystems: agriculture is a provider of ecosystem services (and disservices) among which one seeks to leverage synergies and identify antagonisms. This holistic approach also improves agriculture by embracing a systemic vision. The AgriBio programme ("For and on organic farming"), launched in 2000, was supported by a specific research project in 2015. In 2019, it was adopted as an INRAE metaprogramme, Métabio "Scaling up organic farming". Organic farming is seen as a label based on agroecological principles. The study of the mechanisms that can amplify biological and ecological regulations in agroecosystems is now the basis of a new engineering discipline whose performance deserves to be assessed.

In 2016, with its "Inra2025"[6] orientation document, INRAE decided to intensify research in agroecology by choosing certain themes to study in depth and by widening the field of investigation, considering larger transformations, at the scales of agri-food chains and territories. Agroecology is not a simple or new way of seeing agronomy, but a redesign of agricultural production as part of a social process, with economic, sociological, food and environmental dimensions. This decision led to the launch by INRAE in 2017 of a forward-looking interdisciplinary discussion on the research necessary for agroecology, involving around 80 researchers and teacher-researchers.

This book presents the fruit of this collective reflection. The aim is to share this work and open it up to discussion internally, with our partners in the research community and the agricultural world, and with society at large.

The creation of INRAE as the result of the merger of INRA and IRSTEA in 2020, the expansion of skills, and the implementation of new interdisciplinary metaprogrammes and of "Territories of innovation" projects will help amplify research in agroecology, advance necessary knowledge frontiers, and put knowledge and co-construction at the heart of developments in agri-food chains and territories with the involvement of all actors.

Philippe Mauguin*, president and CEO, INRAE*

4 See https://www6.inrae.fr/ciag/Revue/Volumes-publies-en-2015/Volume-43-Mars-2015.
5 Garcia F., Gascuel-Odoux C., Soussana J.-F. (eds), 2014. *Colloque sur les nouveaux défis de la modélisation : l'agroécologie*, Synthèse, INRA, 49 p.
6 https://hal.archives-ouvertes.fr/hal-01607768/document

Introduction

Given the increasing world population, environmental and climatic challenges, and the growing scarcity of water and fossil fuel resources, an adaptation of, or even a complete break from, current agricultural production methods has become unavoidable. Agricultural systems will henceforth have to be designed not only to produce agricultural goods, but also to provide other ecosystem services. To this end, agricultural actors will need support from the research community and appropriate training.

In industrialized temperate-zone countries, improvements in productivity of agriculture and its economic competitiveness since the 1950s have been made possible by a modernization process which has resulted in specialization of production systems, expansion of farms and increased reliance on synthetic inputs, agricultural machinery, and plant varieties and animal breeds with high productive potential. The specialization of systems and the alteration and homogenization of environments have made economies of scale possible, both in terms of production and agri-food processing to more standardized food products that better meet the needs of processing sectors and agri-food industries.

During this period, the agricultural sector organized itself by creating frames of reference and advisory structures. Natural environments were considered to be largely abiotic and homogenized through land consolidation and drainage, while agriculture-friendly biotic interactions in the soil and ecosystems were ignored. Advice provided to farms was aimed to optimize production. Agriculture became industrialized. This industrialization generated externalities considered to be positive ("sanitized" environments, without pests and with high productivity), but also negative externalities (soil, water, and air pollution; greenhouse gas emissions; biodiversity loss), whose consequences have led to crucial questions being asked in recent decades. The conclusions by IPBES[7] in its global assessment of biodiversity and ecosystem services are clear: through changes in land use and the use of inputs, agriculture, including animal production, is one of the main drivers of biodiversity loss (IPBES, 2019).

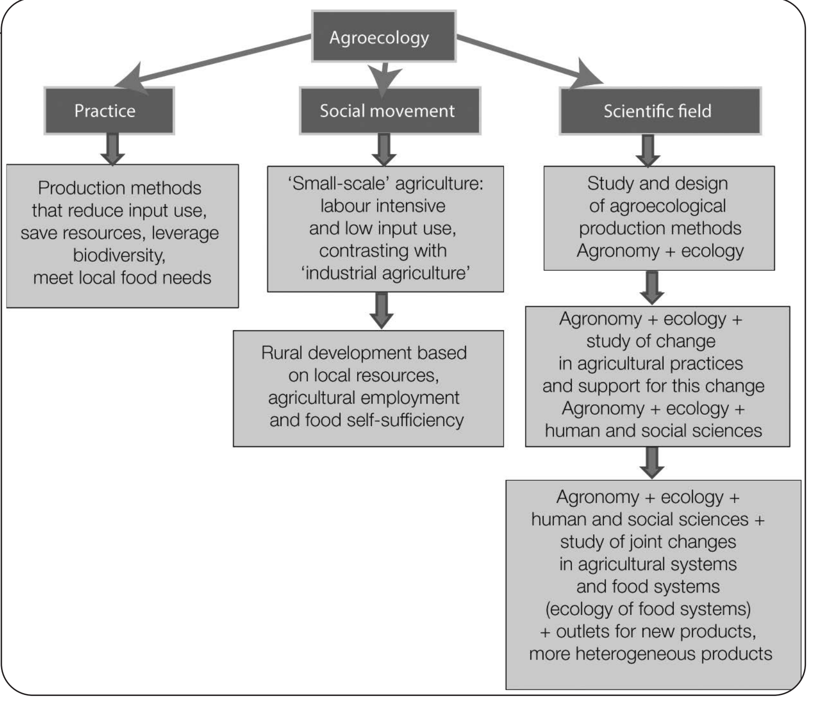
A better compromise between agriculture and the environment has been sought by improving the efficiency of inputs, decreasing discharges of waste into the environment, and even completely redesigning agricultural systems. Several movements (organic farming, conservation agriculture, and eco-farming at the international level; "reasoned" agriculture, high environmental performance agriculture in France, etc.) have proposed terms and advocated concepts to better combine and reconcile the economic, social, environmental and health performances of agriculture. Agroecology appears, including in this context of industrialized countries, as the essential, inclusive and principled way to contribute to the development of sustainable and resilient agriculture.

7 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

Founding principles

Agroecology is at the same time a scientific field, a practice and a social movement (Wezel *et al.*, 2009), as shown in Figure 1. Various definitions of agroecology have been developed, associating ecology to varying degrees with other disciplines (agronomy, genetics, sociology, etc.) or with local or traditional knowledge, in pursuit of the sustainability of production or food systems and the preservation and use of biodiversity (Wezel *et al.*, 2018). Interdisciplinarity, the interaction between disciplines, and transdisciplinarity, the interaction between the research community and society, are both key aspects of agroecology.

Figure 1. Agroecology is at the same time a practice, a social movement and a scientific field (based on Wezel *et al.*, 2009).



One objective: leveraging biological processes

Agroecology is above all a new paradigm that aims to leverage biological processes to meet expectations for agrosystems: agricultural production, of course, but also ecosystem services (protecting resources, mitigating climate change, preserving habitats and cultural heritage). A corollary is to consider agroecology as an aim so that, through agricultural systems and adopted practices, agrosystems integrate the ecological functions that guarantee their own sustainability, especially in terms of replenishing nutrient stocks and maintaining productive potential.

From this first paradigm stems a second: leveraging biological processes means accepting and accounting for increased diversity in agroecosystems, which leads to a greater diversity of agricultural products as well as a greater heterogeneity of each product that will have to be processed and included in food products, even in new diets.

This definition makes it possible to clarify what is expected from the research community. Thus, under the terms "smart agriculture" or "sustainable agriculture", there exists a body of mainly technologically oriented studies on the best possible use of resources. This model of agriculture corresponds to "weak" agroecology, which maintains continuity with current systems, neither advocating for a qualitative leap in the efficiency of the use of inputs, nor explicitly calling to replace them with biological processes (Duru *et al.*, 2014). Weak agroecology contrasts with "strong" agroecology, defined by its pursuit of consistency and sustainability and by the mobilization of biological processes (Duru *et al.*, 2014). This strong agroecology requires in-depth transformation of agricultural production systems. It is this more comprehensive agroecology that is INRAE's goal, because getting there will require a significant commitment to research, as all agricultural production is concerned and all academic disciplines are involved. This should not be seen as a desire to oppose what currently exists, but should be perceived for what it is: an ambition to rethink the mobilization of biological processes at all levels (species, breed/variety, animal and plant physiology, feed and fertility, animal production methods and cropping practices, future of products and co-products, connections to resources, to forms of energy, to soil and water, location, etc.).

Towards the redesign of cropping systems

The desire to "leverage biological processes", the underlying principle of building agroecological systems, usually requires redesigning cropping systems, involving changes in, for example, rotations, genotypes used or agricultural practices adopted, articulations between plant and animal production, connections to distribution methods and consumption patterns, organization of landscapes, etc. The field of agroecology is not restricted to plant production alone; indeed, animal production is a major pillar of biological processes given its complementarities with plant production. The monitoring of processes and flows maintained in a dynamic balance from the field to the landscape, which allows for the exploitation and reconstitution of organic and mineral stocks and the development of soil life, lies at the heart of this redesign. Strong agroecology therefore involves going beyond the mere optimization of agricultural systems.

From a very integrative viewpoint, agroecology cannot develop without a demand from society, consistent with the needs of food consumption and their organization into agri-food chains and territories. Some authors therefore incorporate the dimension of food systems into agroecology (Francis *et al.*, 2003; Gliessman, 2006). The in-depth redesign of agroecosystems, and that of agri-food chains and their organization into territories, in line with consumption needs, is an adaptive process that is built while moving forward along a trajectory that cannot be mapped in advance: the transition phase itself therefore becomes a subject of research.

This redesign is based on using principles of ecology. One motivation is to strengthen the resilience of agroecosystems, defined as their ability to adapt to disturbances or to return to equilibrium in a changing context. In the face of uncertainties arising from climate change, societal changes and the volatility of agricultural and food prices, the biological diversity of agroecosystems can constitute a factor of resilience that helps dampen the effects of disturbances. The vulnerability of agrosystems, at one time compensated for by short-term uses of inputs, is now assessed through their resilience and a greater stability of production types whose biological diversity is a key factor.

Figure 2. The trajectory of agricultural systems: from a specialization phase to a redesign of diversified systems based on the principles of agroecology (based on Tittonell, 2014).

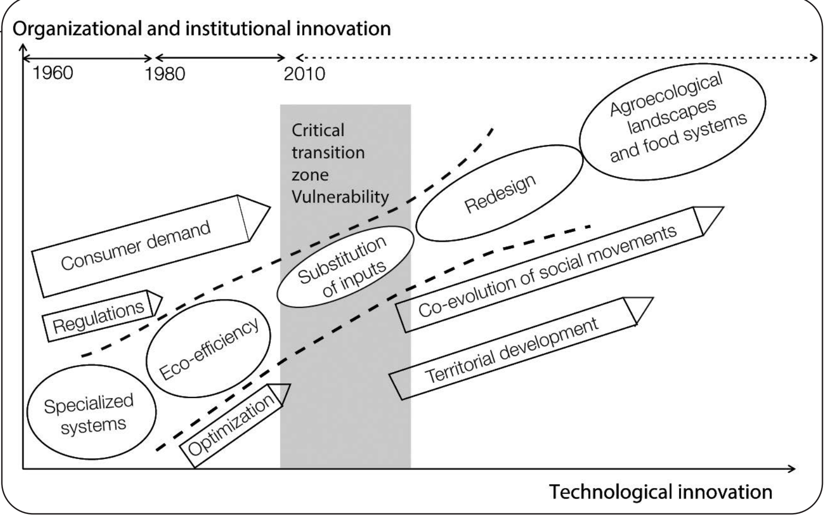


Figure 2 illustrates the fact that, in past decades, agricultural systems became specialized and were optimized according to eco-efficiency principles. The agroecological transition, which aims to replace inputs with biological processes, makes agricultural systems temporarily more vulnerable but eventually leads to more diverse systems, better adapted to environments and societal expectations, more resilient, and based on ecological principles.

Agroecology rubs shoulders with the concept of the circular economy, in the sense that both are part of the framework of sustainable development. Furthermore, they are both inspired in particular by the concepts of the green economy, collaborative economy, and even industrial ecology, based on recycling, while closing biogeochemical cycles as much as possible and avoiding the "waste" stage, thereby decreasing the consumption of raw materials and energy. Agroecology shares with the bioeconomy the goal of replacing the use of non-renewable resources and products of fossil origin with their partial recycling and with the processing of renewable resources (photosynthesis, soil biology) into food, organic fertilisers, materials, chemical bases and various forms of bioenergy. While agroecology shares with the circular economy and bioeconomy the goal of a sustainable agriculture that uses resources frugally, it distinguishes itself by the central role it accords to deriving value from the diversity of living organisms.

National and international societal expectations

The field of agroecology has experienced significant growth since the 2000s, with the pursuit of a coexistence of several visions, whether in academic terms, research methods or practices. This is why its scope and definition remain unclear. It is not an end in itself; instead, it embodies principles to support transitions that put ecological processes at the heart of the design and management of agroecosystems. Agroecology is part of a promising national and international societal context, as illustrated by the following two examples.

The French government's Agroecology Project

The Agroecology Project of the French Ministry of Agriculture was designed to encourage production methods that have high economic and environmental performance, and to promote a joint approach to the different dimensions of farms and, even further, those of agri-food chains and territories. Its aim is to produce differently by rethinking production systems. While this implies changing agricultural practices, it also represents another way of thinking, a gradual and profound change that emphasizes the systemic dimension of agricultural activity, across large spatial scales and over long periods. It now constitutes a mobilizing framework for French agriculture to rethink agricultural training and advice. As the first article of the Rural Code has emphasized since adoption of the law on the future of agriculture, food, and forestry of 13 October 2014, "public policies aim to promote and sustain agroecological production systems, including organic production methods, which combine high economic and social performance, in particular through a high level of social, environmental and health protections. These systems focus on improving farm competitiveness while maintaining or improving economic profitability".

The French Economic, Social and Environmental Council (CESE), as a multi-actor and social expression organization, has this to say about agroecology: "A scientific discipline at the crossroads of agronomy and ecology, agroecology can, through the practices that it promotes, help meet environmental and socio-economic challenges by transforming agriculture to move towards more sustainable food systems. Based on analysis of the obstacles to and mechanisms for its development, the CESE has formulated a set of recommendations concerning research, training, adaptation of agri-food chains, and reorientation of public policies to support farmers in the agroecological transition" (Claveirole, 2016).

FAO: priorities for agroecology

In 2014, the Food and Agriculture Organization of the United Nations (FAO) organized the first International Symposium on Agroecology for Food Security and Nutrition[8] with the intention of promoting agroecological systems at the international level. It was an opportunity to share experiences and put together an agroecology knowledge base, and it helped build a consensus on priorities for agroecology. Above all, it validated FAO's role in the implementation and promotion of agroecological approaches. The farmers of countries in the Global South had already expressed interest in such approaches for a long time, seeing them as an alternative to the dominant and intensive production systems because they led to lower dependence on inputs, higher productivity due to plant associations that used soil resources better, and lower sensitivity to pests. The 2014 symposium showed that agroecology can also be a way of rethinking agricultural systems in both developing and industrialized countries. The FAO later organized meetings by world region, including one for Europe, the conclusions of which were shared at a second symposium, in April 2018. The "Scaling Up Agroecology Initiative" was launched on this occasion[9]. This initiative has the goal of encouraging a process of transition of agricultural and food systems to a more inclusive and holistic agroecology by using knowledge-sharing tools, in particular by establishing an agroecology knowledge platform[10]. Criteria for characterizing agroecological systems were defined, and methodological work to analyse their performance is in progress.

Research based on new paradigms and new approaches

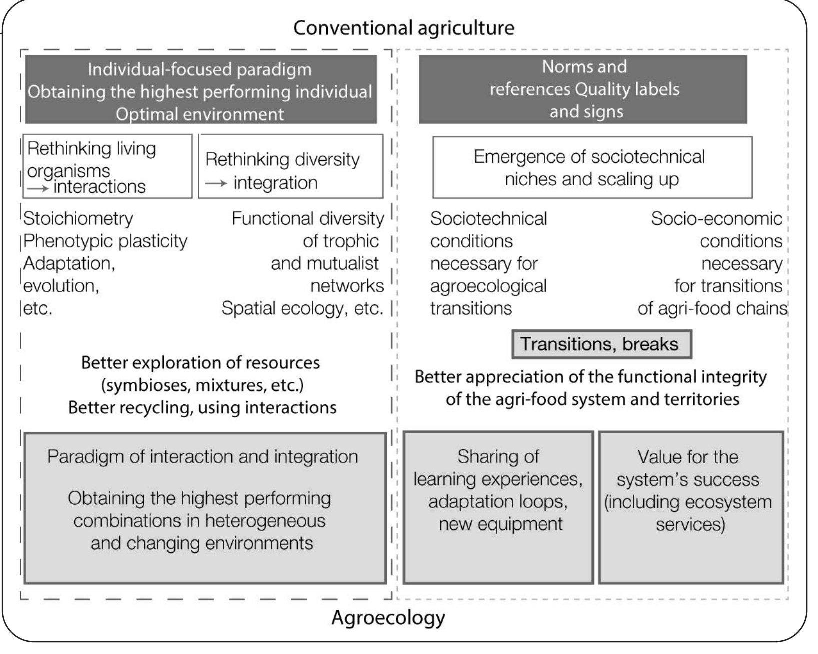
Figure 3 illustrates the research objectives and fields involved in moving from conventional systems to agroecology-based systems.

Agroecology's first ambition is a paradigm change, moving from a paradigm based on the "ideal individual", which aims to obtain the animal or plant individual with the highest performance in an environment made optimal and which underpins current agricultural systems, to a new paradigm based on "ideal interactions between individuals and their integration into ecosystems", whether at the field or landscape scale. The underlying

8 See http://www.fao.org/3/a-i4327e.pdf.
9 See http://www.fao.org/3/I9049EN/i9049en.pdf.
10 See http://www.fao.org/agroecology/home/en/.

assumption is that a diversity of individuals, varieties/breeds or species will be better adapted to heterogeneous and changing environments due to the continuous interactions between them. Their arrangements in time and space may also prove to be more efficient, because they are not only more seek out water and mineral resources better, but are also more resilient to disturbances because of their very diversity. The research community thus has reason to focus on functional properties, which provide ecosystem functions and services (supply of biomass; regulation of the water cycle, soil, and climate; landscape resources; etc.).

Figure 3. The challenges and paradigms of conventional agriculture (dark grey boxes) and of agroecology (light grey boxes).



This new paradigm draws on concepts from ecology, in particular functional ecology, which must be adapted to be useful for agroecosystems:

• stoichiometry is defined as the proportions of chemical elements, most often carbon, nitrogen and phosphorus, in organisms with trophic links. Applied to ecology, stoichiometry studies the propagation of these proportions due to a chain of reactions related to the needs of plants, the functioning of soils, and even transfers in catchments and aquatic ecosystems. Plant and animal associations can draw the most benefits from these proportions, create synergies between availability and various needs, and introduce adapted recycled resources.

• phenotypic plasticity of species is a property that allows them to adapt to various environmental conditions. The more "plastic" a species is, the more it will be able to adapt to varied and/or fluctuating conditions. When performing genetic selection of varieties or breeds for agricultural purposes, plasticity capacities may be preferable to optima designed for standard conditions, which may result in selection objectives based on phenotypic variances.
• trophic and mutualist networks define the links that species maintain with each other. These links can be food links (trophic) or simple relationships with reciprocal benefits (mutualist), such as symbioses.

Research in agroecology is therefore very much oriented towards analysis of living organisms, adaptability of varieties/breeds and species, the nature and importance of interactions between individuals, and their association effects at supra-individual scales in order to ultimately identify the best arrangements and combinations, help manage them and characterize the ecosystem functions and services that result from them. Although many different ecological processes have been studied in agroecosystems in recent years, integrating these processes at the design phase of agrosystems is a new challenge for the research community.

Agroecology's second ambition is to move away from a paradigm based on standards and benchmarks, which has allowed them to be used everywhere and in all circumstances (for advice, sales, etc.) and which has become the goal of agricultural-production support in recent years, to a socio-technical diversification paradigm, specific to a situation and leading to socio-technical trajectories and sectors, through processes of transition or even clean breaks with the past. To this end, two concepts must be used: (i) sharing of experiences and step-by-step learning, which accompany the transitions and adaptation of systems to their socio-technical context, and (ii) identification of possibilities and risks. Agroecology is a path based more on the use of processes and principles than on standards and labels.

Indicators will have to be created to describe these paths to accompany consumers. These systems will be characterized by values, in line with the concept of ecosystem services and human, economic and sociological dimensions that are accepted, recognized, or even encouraged, in the territory concerned. France's National Biodiversity Plan, unveiled in July 2018, recommended, for example, using organic or local products in institutional catering. This system of values, recognized by society, incites the evolution of the entire agri-food system.

Each of the six chapters in this volume sets out a different challenge:
• Integrating agroecology into agri-food systems. Agroecology favours a recourse to diversity, recycling of elements, and search for complementarities, thus shaking up the organization of existing agri-food chains and requiring the creation of new ones that involve producers as well as consumers or local authorities (short supply chains, agri-food chains based on quality labels, etc.).
• Promoting the agroecological transition of farms. This transition is fraught with uncertainties for farmers who commit to it. Managing them well involves identifying

their vulnerabilities and equipping the actors involved accordingly. A long-term view is necessary, and scientific knowledge must be combined with the actors' experiences.

- Leveraging ecological and hydrobiogeochemical processes in multifunctional landscapes. The landscape dimension, which includes the spatial distribution of landscape elements on and in the soil ("green infrastructure"), the spatio-temporal organization of rotations and the management of crops and livestock ("landscape of practices"), is an essential dimension of agroecology.
- Leveraging genetic diversity in plant and animal selection. Genetic diversity can contribute to the design of agroecological systems. Breeding schemes for plants and animals need to evolve to improve the provision of ecosystem services and resilience of agroecosystems.
- Modelling interactions between living organisms while considering environments and socio-economic contexts. It is a matter of better equipping researchers and actors in terms of representation, understanding and prediction of agroecosystem dynamics, in order to better identify and manage their strengths and vulnerabilities.
- Identifying agricultural equipment required for agroecology and the possible benefits of digital technology. This topic examines the specific and potential contribution that technology, sensors, equipment and services can make to the development of agroecology.

In each chapter, the outline and issues of the topic are first presented. The main scientific advances are then discussed. Detailed examination of examples of research projects follows, illustrating how the INRAE research community has constructed them and the results they have yielded. Finally, the main research priorities for developing agroecology are summarized.

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1. Integrating agroecology into agri-food systems

Agroecology relies on mobilizing diversity, whether genetic diversity (association of varieties, search for hardiness, etc.), species diversity (crop associations, etc.) or functional diversity (agroforestry, crop-livestock associations, etc.). It is based on recycling resources and searching for complementarities between types of production. Implementing these agroecological principles results in a greater diversity of agricultural products and a greater heterogeneity of each of them, which then can be intended for a larger number of sectors, consumers and users.

What are the consequences, throughout production, processing, marketing and consumption, of this increase in the diversity of products and in the heterogeneity of each of them? It is essential to understand changes in the entire system when moving towards a more diverse, heterogeneous world. The concept of agri-food “chains” is therefore much too restrictive, as it includes only those complementary activities which contribute, from upstream to downstream, to production of a food or bio-based product. We therefore prefer to speak instead of an agri-food “system”. What interests us here is the aim to connect all of the actors together and considering all dimensions of the end product, by:
- emphasizing the product’s heterogeneity, and no longer eliminating or homogenizing it;
- considering the entire agriculture-environment-food system, including all actors in this system and their interactions (producers, suppliers, processors, consumers, citizen associations, public policies);
- approaching transitions by focusing on actions aimed to efficiency, substitution and/or redesign according to Hill’s (1985) ESR[11] model.

The implementation of agroecology must examine the agri-food system from different perspectives, which can be specified using game theory:
- products resulting from agroecology as pieces of the game:
  - what is a product resulting from agroecology?
  - what relationships exist between resources and products, in particular in terms of diversification and heterogeneity?
- the strategies of actors as players of the game:
  - consumer practices and preferences, what they are and how to change them,
  - the organization of markets, their evolution and the importance of norms and standards,
  - public action, in particular the European Common Agricultural Policy (CAP), but also more broadly the articulation between agricultural, environmental and health policies, in order to change the system;

11 ESR: efficiency, substitution, redesign.

• the spatial organization of markets and exogenous conditions as playing fields, by considering international trade and territorial constraints and opportunities;
• the system's dynamics, by considering all of the actors concerned and their approaches, the real and potential resources and products, the interactions between sub-systems (territorialized or others), and the impacts (positive and/or negative) in order to adapt strategies and their risks and benefits.

Products resulting from agroecology and their properties

Although this is a broad topic, the studies performed to date have focused mainly on analysing properties of products resulting from organic farming and from the diversity of forms of agriculture (Abecassis *et al.*, 2018). Effects of agroecological production methods on properties of processed products (specific qualities and features, existing and/or innovative market potential) have not been analysed in detail. All processing steps involved in defining a product's properties must be analysed: manufacturing processes, methods for stabilizing properties via packaging and storage, flexible distribution schemes for heterogeneous products, final preparation methods (cooked, ready-to-eat prepared meals, etc.) and recycling options.

Actors' strategies

Consumer practices

A connection can be established among product properties, consumer practices, consumers' willingness to pay, and instruments designed to encourage an increase in consumption of these products. In a meta-analysis, Dolgopolova and Teuber (2018) found a higher and fairly consistent willingness to pay for food products with "good for health" attributes. Sörqvist *et al.* (2013) showed that "green" or even eco-labelled products were perceived as having better organoleptic qualities. Risk aversion, loss aversion and inequality aversion (in which individuals are altruistic towards the less fortunate and envious of the more fortunate) are part of consumers' motivations for entering into local-agriculture contracts (Bougherara *et al.*, 2017). While some forms of diversification present in local-agriculture contracts do contribute value, this is not always the case.

Labelling is an important factor in consumer adoption, as shown by studies on organic farming (Asioli *et al.*, 2017; Drexler *et al.*, 2018). Environmental labelling, initiated as part of the Grenelle Environment Forum, is also an enabling factor. Finally, analysis of consumers' perception of non-food products such as biomaterials, biomolecules for pharmaceuticals, cosmetics, green chemistry, etc., and even bioenergy produced and used locally (biogas production, cities self-sufficient in energy, etc.) is also essential (Sijtsema *et al.*, 2016).

Organization of markets: norms and standards

The norms (set of rules legislated by an authorised body) and standards (set of recommendations developed by a group of users) established must promote and organize relationships among the various market actors.

Certification and specifications help build trust between actors – without, however, eliminating information asymmetries – when practices result in attributes that are difficult to verify before and after purchase (belief attributes), such as lower residues of inputs, more fibre, more vitamins, better texture or better taste. One way to reduce information asymmetry between producers and consumers is to use labelling (Bonroy and Constantatos, 2015).

Another dimension that must be considered is the organization of agri-food chains, in particular their length. Local-agriculture contracts, such as those promoted by AMAP (associations for the preservation of peasant agriculture), derive value from certain types of production and constitute tools for sharing risk between producers and consumers (Sproul *et al.*, 2015). In this context, the Ici.C.Local[12] research project analyses the organization of short supply chains and even registered a trademark in 2014 with the INPI (French National Institute of Industrial Property). This innovative and easy-to-use approach consists of labelling short-supply-chain products in retail outlets. It can be used by all economic actors involved in short supply chains: traders, craftspeople, independant workers, farmers, producers and processors.

There can be legal obstacles to marketing such products, in particular in the context of the European Union (EU)'s regulations for novel food and its laws on price negotiations (competition rules, etc.). Indeed, under EU regulations, marketing foods that were not consumed in significant quantities before May 1997 requires the compilation and examination of a complex dossier. Likewise, free-competition rules in the European Union can impact the positioning of products on the market.

Public policies

While certification matters fall under the purview of public action in general (and not only of public policies), introduction of new production methods in agri-chains can be supported by public policy instruments, in particular within the framework of the "greening" of the CAP and environmental policies (the EU's Water Framework Directive, for example).

Studies of payments for environmental services now called as "PES" are contributing to the debate (Tacconi, 2012; Duval *et al.*, 2016; Etrillard, 2015). It is a matter of:

- distinguishing services provided to farmers from services provided to society for which PES can be justified;
- defining the conditions and levels of PES above the opportunity cost of the action implemented;

12 e.g. "Here, it's local". See https://www.inrae.fr/actualites/iciclocal-valorise-circuits-courts-territoires; contact: Yuna Chiffoleau.

• choosing how to implement the forms of PES, via public support and/or via the market.

Finally, research by Agrimonde-Terra has shown the importance of reflecting on the issues of food security and sovereignty in a context in which agroecological practices become widespread. The impact on countries of the Global South deserves special attention.

Spatial organization of markets

Territorial and international dimensions

The organization of markets at different scales is approached through two themes:
• mechanisms for locating the links in the chain (production, processing, consumption), forms of concentration and dispersion according to market access constraints, and environmental constraints;
• consequences for developing countries of European decisions to encourage particular practices, especially agroecological ones (Boysen *et al.*, 2016).

More broadly, production contexts must be considered, in particular geographical, cultural, social and historical characteristics, in order to explain differences in the obstacles and mechanisms found under different local conditions.

Example of the Rebecca programme: Research on sugarcane biomass-energy in Capesterre (Guadeloupe)

To contribute to Guadeloupe's ambitious energy-transition goals, researchers from INRAE, CIRAD and Quadran (an industrial partner) performed a preliminary study on the potential size of a sustainable biomass-energy sector and on a pilot electricity-production unit in Guadeloupe. They also identified the conditions necessary for an agro-industrial sector to emerge for producing electricity from biomass from varieties of the fibrous sugarcane grown locally.

To enlighten the choices of regional policymakers, the study provided information on the following aspects: cultivation methods, conditions of payment and support for farmers, size and location of the power plant, and environmental performance. Based on territorial scenarios of the adoption of cropping systems adapted to climatic conditions, which incorporated all types of farms and territorial concerns (energy, water, waste), the project was able to meet the expectations of a wide variety of actors and sectors. A project to build a 12 MW power plant is currently being undertaken by the project's industrial partner.

Dynamics and coherence of the agri-food system

Any analysis of the system's dynamics must consider, among other things, all actors and their approaches, real and potential resources and products, interactions between territorialized sub-systems, impacts (positive and/or negative) of adapting strategies, and risks and benefits of the strategies. Furthermore, it is important to analyse relationships between the system's actors, in particular knowledge about the sources of value (economic, environmental, social) and of market powers, their evaluation and their distribution. Multi-criteria analyses of the sustainability of organic farming systems provide some answers.

Deriving value from the diversity and heterogeneity of resources generated by agriculture

Deriving value is a key subject, as many co-products and by-products are not currently used at all, or could be used better (Pöyry, 2011). This topic is prominent at several conferences.

The large volumes of co-products from field crops constitute an interesting avenue for deriving value because of their economic potential in terms of quantity and prices, which makes them competitive with fossil-based products. Several examples illustrate these possibilities:

- large-scale processes to derive value from plant-based proteins by the mutualized institute Improve[13];
- production of second- and third-generation bioenergy in the Futurol[14] project;
- different forms of biogas units installed in fields (Charnier *et al.*, 2017);
- innovative production and comprehensive derivation of value from Miscanthus by creating new value chains[15].

The co-products resulting from agroecological production will probably come in smaller quantities and be more diverse and heterogeneous. The challenge will be to capture the value that can be incorporated into niche products with specific characteristics. To this end, it will be crucial to develop competitive small-scale technologies, such as biorefining performed in the field itself (de Vries *et al.*, 2018). Business models and logistical concepts will have to be adapted. The seasonality of production and territorial characteristics will have to be considered. Some promising examples of deriving good value from locally produced products can also show the way for agroecological production schemes:

- the FUI Green Epoxy project aims to find a non-toxic alternative to epoxy resins by using tannins derived from agroforestry;
- the Mediterranean ArimNet2 project "Pyrodigest" derives value from biochar, an agricultural amendment available locally;
- the integrative and holistic NoAW (No Agricultural Waste)[16] EU project showcases examples of production of biogas, biodegradable polyesters and biofertilisers, and a typology of circular business models.

13 See http://www.improve-innov.com/en/.
14 See https://www.ifpenergiesnouvelles.com/article/2nd-generation-biofuels-industrial-first-french-futuroltm-technology.
15 See https://www.grace-bbi.eu/.
16 See https://noaw2020.eu/.

Agroecology and traditional products

In Europe, several major projects focused on traditional food products were launched in the 2000s. The first integrative EU project was "Traditional foods: from culture, ecology and diversity, to human health and potentials for exploitation" (TrueFood[17]). This project showed that a wide spectrum of innovations was possible, such as products with improved nutritional properties (local cheeses with a high level of bioactive peptides, raw and dry hams with substantially reduced salt levels, etc.). Other innovations concern protocols for monitoring potential pathogens and packaging of fresh products: active packaging to increase shelf life, and intelligent packaging to monitor product quality during transportation and storage (Cotillon *et al.*, 2013).

EU projects such as Trade-It[18] (Traditional Foods, Entrepreneurship, Innovation and Technology Transfer) and Trafoon[19] (Traditional Food Network to Improve the Transfer of Knowledge for Innovation) have built on results of the TrueFood project. The Trade-It project focused on traditional craftspeople in the milk, meat and baking sectors, with the objectives of sharing practical experiences within Europe and transferring knowledge to small- and medium-sized enterprises (SMEs) and micro-enterprises, including family businesses.

Within the European Union, SMEs in the agri-food sector are under increasing pressure from the opening up of new markets and increased consumer demand for standardized food products at competitive prices, in a context of significant growth in size and influence of large distributors and the need to comply with national and European regulations. The Trafoon project launched a knowledge-transfer network in 2013 to support traditional-food SMEs, and more specifically organic and local food products made from cereals, fish, fruits, olives, vegetables and mushrooms. This network brings together researchers, knowledge-transfer experts and SME associations from 14 European countries to promote the sustainable transfer of innovation and entrepreneurship in the agri-food sector for the benefit of European regions and their consumers. This project has led to a large increase in interactions among traditional-food SMEs, SME associations and research institutes, not only to increase knowledge transfers to SMEs, but also to identify new opportunities backed by interdisciplinary research to support agri-food SMEs. Through this project, the needs of SMEs across Europe were analysed, and the most recent innovations available, both technical and socio-economic, were the subject of specific demonstrations and training days, such as in the domain of durum wheat in Montpellier (Mandato *et al.*, 2018).

17 See Rossi, 2012; http://www.basefood-fp7.eu/www.basefood-fp7.eu/content/download/5952/55880/file/rossi.pdf.
18 See https://cordis.europa.eu/project/rcn/110709/factsheet/en.
19 See https://www.trafoon.org/.

Research questions

Analysing properties of products resulting from agroecology

The properties of products resulting from agroecology need to be analysed to answer the following questions:
- can products within agri-food systems be identified as being "agroecological"?
- what impacts do agroecological practices have on products?
- what consequences do they have for processing phases?

These questions can be broken down into a set of more specific questions:
- what is referred to when describing products "resulting from" agroecology? What impacts do agroecological practices have on products, in particular on their nutritional characteristics? What indicators are used to qualify them?
- what properties do products at the production and processing phases have, and what consequences does the degree of processing (unprocessed, different compositions, stored, packaged) have?
- what new technological approaches are necessary for these products?
- should these products be mixed to homogenize them or, on the contrary, optimized for new added-value products (product characteristics, production context, etc.)?
- how should co-products be considered from the integrative-bioeconomy viewpoint of optimal use of renewable resources?

The qualification of products based on the principles of agroecology and the processing issues associated with these products form a vast area of study. Questions can be asked about co-products and the relationships between agroecology and the bioeconomy, including the circular economy, in particular about reusing products that are partially consumed or used. Some of these issues have already been addressed in studies on organic farming and, more broadly, on the diversity of forms of agriculture.

Analysing consumer practices and their evolution

Once consequences of agroecological practices for products are identified, the products can be related to consumer practices:
- do certain product characteristics related to agroecology (environmental, local or non-local production, packaging) make consumers willing to pay for them, and why? What motivates consumers to enter into "agroecological" local-agriculture contracts? What role do consumers play in the development of agroecological approaches?
- what communication methods are necessary to encourage consumers to adopt these products? What type of labelling should be used (see studies on nutrition labelling[20])?
- how should products be positioned (a minimum standard, a brand, etc.) to promote acceptance of their increased diversity and a preference for more heterogeneous products?

20 See https://alimentation-sante.org/wp-content/uploads/2017/03/Rapport-CS-de%CC%81finitif-14-mars.pdf.

• how would consumers perceive non-food products resulting from agroecology (biomaterials for construction, natural fibres, cosmetics, etc.)?

The questions raised pertain, among other aspects, to the labels to develop and the methods of communication and training to use to raise awareness among consumers[21].

Studies on organic farming products, marketed under the Bleu-Blanc-Coeur brand or in different contexts (local products, with an "environmental" or "good for health" content), provide some answers and suggest avenues for future work. Work on nutritional labelling and on environmental impacts (life cycle assessment (LCA) approach, Agribalyse[22] database) could also prove useful. Reflections undertaken in Territoires d'Innovation projects, such as the Agroecology-Dijon project, the Terres de Sources project for the Rennes Basin, and the Ouesterel project on animal welfare, and their reflections on labelling and consumers' willingness to pay can also be mobilized.

Organization of markets: the importance of norms and standards

Organic farming studies on these topics are also useful: organic farming certification is, in practice, a tool to impart value. However, agroecology is not a "downgrading" of organic farming; it is instead a new conceptual pathway. It is therefore important to determine clearly the benefits of certification and agroecological standards for the co-evolution of the variety of models by considering all activities, from production to consumption and use of the final products. This is one avenue pursued by INRAE's "Metabio métaprogramme"[23] for scaling up organic farming.

Public policies

The challenges of "greening" the CAP are of particular interest to the INRAE working group dedicated to the future of this European Union policy and its French implementation. Agroecological practices occupy a key place in this effort, as much through cross-compliance measures as through agro-environmental and climate measures. Work is continuing, in particular on different forms of payments for environmental services, a tool that could promote implementation of agroecological practices.

More work needs to be done on relationships between agricultural policy and food and health issues, as well as between agricultural policy and the tools available to it. The results of circular economy approaches may be useful for showing how to reuse resources intelligently, either locally or more globally. The spatial and temporal dimensions of material flows merit reflection to understand the advantages and disadvantages of using products or co-products resulting from agroecology.

21 For example, see https://www.hohenlohe.de/Typisch/Naturparadies-Hohenlohe/Gruener-Sueden/Bioenergiedoerfer-in-Hohenlohe.html.
22 See https://ecolab.ademe.fr/agribalyse
23 https://www6.inrae.fr/comite_agriculture_biologique/Accueil/Actualites/METABIO

Territorial and international dimensions of the organization of markets

The main issues pertain to the environmental impacts of the location of various activities.

What effects does the rise in agroecological practices or localized circular-economy approaches have? Can they lead to reorganization of sectors or markets? This indirectly shows the importance of systemic reflection, much like for the bioeconomy.

What potential implications do the options for developing agroecology in France have for other countries, via the markets? Of particular concern is the concept of "leakage", in which relocating types of production that emit large amounts of greenhouse gases to countries with less restrictive legislation ultimately leads to an overall increase in their emissions. This mechanism is covered extensively in climate change literature.

Finally, what implications does the multi-use of products and co-products have for various markets? The underlying idea is to understand clearly interactions between the organization of activities at the regional and international scales.

Coherence of the system

Multi-criteria analyses make it possible to study a system's sustainability along different dimensions (economic, environmental, social, etc.) and to understand the system's coherence clearly. In addition, it is necessary to study how agroecological systems will work together with conventional systems, which themselves will evolve, and with organic farming systems. The issues to address concern both the distribution of the respective efforts and the organization of their interrelationships. Thus, which actor(s) assume responsibility for reducing pressure on the environment? As farmers cannot be expected to do so on their own, all other actors, in a circular approach, must be concerned and involved in finding relevant solutions. To this end, the forms of organization upstream and downstream of production must be analysed to understand their impact on the adoption of agroecological practices. It will thus be possible to study the lock-in of systems by upstream entities or processes, especially for agri-chains with a high degree of integration. Finally, how should mixed systems with agricultural products resulting from both agroecological and conventional practices be designed, and how should these systems evolve more towards agroecology?

All of these questions call for methodological research, mainly on three points:

- Data acquisition, management and analysis are necessary at all scales: the micro scale (individual, product, company) and the macro scale (regions, countries, major world regions). Constructing benchmarks requires methodological work on the indicators needed to qualify agroecological practices and the products that result from them, but also construction and monitoring of databases on both product quality and household consumption.
- Modelling, with several large families of models for agri-food systems, is necessary to assess the integration of agroecological practices: LCA and multi-criteria analyses to evaluate their sustainability in different dimensions, global models to understand impacts

of local changes on large regions (for example, GlobAgri Agrimonde-Terra; Le Mouël *et al.*, 2018), complex-systems approaches, and the use of game theory.

• Case studies will be essential to understand fully the diversity of systems, their constraints, and the heterogeneity of resources, products, actors, markets, etc. Establishing and managing platforms and experiment centres can serve as a basis for demonstrating and promoting participatory activities with various actors. INRAE's experimental mechanisms can also illustrate cases and options or test creative ideas with various actors (citizens, consumers, users, etc.).

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2. The agroecological transition of farms

The agroecological transition is a systemic transformation of our agriculture and food systems (Duru *et al.*, 2015). It calls for changes in practices as well as the values that underpin them for a wide variety of actors. It therefore requires "new societal structures and interactions that imply changes in values and behaviour" (based on OECD, 2010). From an economic and social viewpoint, it consists of a transition in the making within our capitalist regime and not a revolution. Indeed, the underlying capitalist principles are not always called into question (Hinrichs, 2014), even though they are at the origin of the current unsustainable modes of production (Gorz, alias Bosquet, 1977).

Several models of transition undertake transition "on the fly". The agroecological transition is a transformation that is characterized by uncertainty about what it will lead to (Lubello *et al.*, 2017). This uncertainty is compounded by ambiguity in the relevance of the models that are emerging, in terms of the forms of agriculture, characteristics of work collectives, connections with downstream sectors (collection, processing, marketing, etc.) and consumers, as well as by how this relevance is assessed (Plumecocq *et al.*, 2018).

Few research studies have examined the transition of farms. Transition has been studied at a territorial scale, for example to protect a water resource (Bui *et al.*, 2016), or at that of a sector of activity, as for the development of a legume agri-chain (Magrini *et al.*, 2016). The farm, although central, has been neglected (Chantre *et al.*, 2014). The agroecological transition of farms requires radically transforming the way of thinking about production systems. Farmers must discard the traditional linear view of a production system that they supply with inputs to produce food. They must replace this vision by a representation in which this food results from an agroecosystem's proper functioning. The challenge is thus to replenish and manage this agroecosystem so as to leverage the local potential and to manage its complexity and uncertainties (incomplete knowledge, for example, on soil functioning, effects of climatic hazards, etc.; Magrini *et al.*, 2019).

Those who study or support the transition of farms are concerned with the issue of 'change', which the actors must understand and be properly equipped for. This change involves multiple dimensions: the actors' commitment and perseverance (motivation, learning, risk management, etc.); the need to deal with technical, organizational, cognitive and ideological barriers that result from the farm's social, technical and ecological environment; redefinition of what has value (types of performance, expected properties); new management methods (information, intervention thresholds); co-design with farmers to support changes in their modes of thinking; and ex ante, ex post, and on-the-fly assessments.

Implementing agroecology requires changing ways of thinking in order to base management of the agroecosystem on ecosystem processes. This line of reasoning differs greatly from those based on using and processing inputs into agricultural products because it relies on trial-and-error learning. Every solution is unique because the production system must be adapted to its production context by considering uncertainty (incomplete knowledge, effects of actions, etc.). As a result, the aim and trajectory of a farm's agroecological transition are determined locally and will have to be fine-tuned on the fly. This configuration also changes the advisory context to one in which the collective dimension takes precedence over the traditional one-to-one adviser-farmer interaction. The fundamental organization of agricultural advice thus must be revamped.

Researchers currently think about this change mainly from the prescriptive perspective of decision modelling and technology transfer. However, the agroecological transition of farms requires producing the knowledge necessary to analyse and support "in the making" (Elzen *et al.*, 2017) technical and organizational changes and methods of reasoning of the actors involved (farmers, advisers, trainers, etc.) during the redesign of systems.

Recent scientific advances

The importance of the socio-technical context and its unlocking

In research performed on the transition, the farm is considered to be embedded in a socio-technical system and an agricultural development system. Its agroecological transition therefore requires reconfiguring these dominant systems at the territorial level. The "dominant regime" here corresponds to conventional agriculture, which resists attempts to change it (Geels, 2004). The traditions and multiple interdependencies between the system's technical and social components have become stronger and more resilient over time, which limits actors' creativity and freedom of action. A systemic approach is therefore necessary to think of innovation at the multiple levels at which it is involved (Meynard *et al.*, 2017). For example, adopting a new crop in a rotation requires thinking about its functions but also about how to help farmers master it at the technical level and derive value from it. The multi-level approach describes a socio-technical world at three levels: niche, (dominant) regime and landscape (political, economic, etc.). Developed by Geels (2004) and applied to the agricultural sector in recent years (Magrini *et al.*, 2016), this approach provides an analytical framework for working to unlock the socio-technical context and promoting innovation.

The agroecological transition generates new elements to manage

The study of agroecological transition trajectories reveals new elements that must be managed (Coquil *et al.*, 2014). These elements correspond to the new categories which appear and around which the work will have to be organized: overall health (of plants, animals and ecosystems) and no longer only diseases; agrobiodiversity; complementarity among different production types (crops and livestock, market gardening and arboriculture, sheep, cattle, agroforestry, etc.); and non-productive elements of ecological interest and their role in the agroecosystem (hedges, woods, ponds, low walls, etc.). These changes also influence the desired properties of agricultural systems, such as resilience, efficiency, self-sufficiency, and working conditions conducive to human well-being.

Technological innovation: useful for the agroecological transition of farms

Technological innovation, while not the engine of the transition, is nonetheless a major element. In particular:

- plant or animal breeding makes it possible to increase the supply and efficiency of ecosystem services, for example by nitrogen fixation or soil cover, or by the use of local breeds that leverage genetic diversity to make a system more robust;
- robotics makes it possible to reduce the time the farmers spend on strenuous activities, helping them in their tasks, for example by the development of exoskeletons so they can lift crates easily in market gardening, or by automatic and mechanical weeding of crops;
- communication and information technologies provide new ways to manage knowledge. For example, they can help farmers formalize their empirical knowledge, discuss it and make it available to a wider community through applications such as GECO[24]. This latter tool includes a forum in which farmers discuss their problems and the solutions they are implementing. It also hosts a wiki in which experts validate the knowledge shared on the forum and present it in a form that makes it accessible to all.

Sharing of experiences: driving the agroecological transition of farms

The agroecological transition requires farmers to use and develop their ability to learn in order to adopt unfamiliar practices that break with the dominant regime. They must design and test alternative practices in the field to learn from them (Chantre *et al.*, 2014). New professional standards and references result from these transformations of practices (Meynard *et al.*, 2017). This often occurs within groups, sometimes with the support of advisers and/or facilitators (Chantre *et al.*, 2014; Coquil *et al.*, 2014). These discussion groups not only encourage creativity and learning, provide reassurance in the face of uncertainties, and help build new frames of reference for action, but also promote reflexivity and the adoption of new values (Plumecocq *et al.*, 2018). They help create a method of knowledge production based on exchanges between all those who produce knowledge deemed to be relevant, including, above all, the farmers themselves.

24 See https://geco.ecophytopic.fr/.

From collective action to individual capacity for action

Research performed on socio-technical unlocking and social learning has concentrated on the collective dimension of the agroecological transition. Some authors point to the need now to study actions by individuals that lead to a farm's transformation. Decision support through optimization processes – a dominant approach in the agricultural sciences – is unsuitable for supporting the radical and unique change undertaken by farmers engaged in an agroecological transition. The concepts of "holon"[25] or "agency"[26] or relational approaches (Darnhofer *et al.*, 2016) highlight the capacity for action, considered as an interaction between the rationality and values of an actor, as well as the opportunities and resistances offered by the environment. This capacity for action is accompanied by an adaptive capacity, defined as the ability to design and implement adaptations or changes and to manage new situations without compromising future options (Nelson *et al.*, 2007).

Adding to the body of existing research on the conversion to organic farming, recent studies have explored farmers' motivations for engaging in the agroecological transition. These motivations seem to be as much extrinsic (market opportunities) as intrinsic (desire to respect nature) (Plumecocq *et al.*, 2018). However, the perception of risk moderates their motivations (Bouttes *et al.*, 2018), and indeed, the transition appears risky because of its uncertainty and complexity (Duru *et al.*, 2015). Before committing to the transition, farmers assess trade-offs between external factors, such as product quality requirements, regulations and prices, and internal requirements, such as the risks associated with new production techniques (Bouttes *et al.*, 2018).

A conceptual framework to connect different agroecological transition approaches

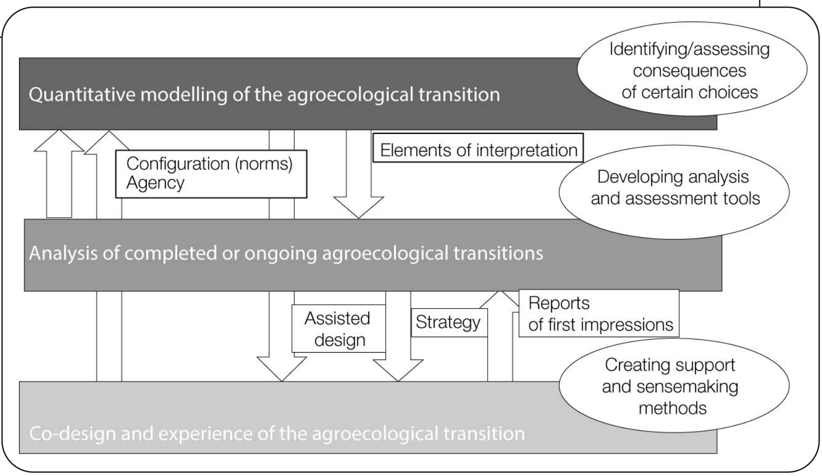
The agroecological transition of farms poses methodological challenges because managing it requires considering the dynamics of a complex system in a changing environment that is highly ambiguous and uncertain. The ambiguity arises from the fact that values can and do change during the transition: what was acceptable yesterday may no longer be so today or tomorrow. For its part, uncertainty is an intrinsic part of strategic activities that project themselves into the future. It is inherent in the functioning of complex systems and their emerging properties. It is also the result of gaps in knowledge. This partly irreducible uncertainty creates indeterminate situations in which farmers know that they can no longer continue their activities as usual, but do not know how to act differently. Finding solutions to these problematic situations requires researchers from different disciplines to collaborate in transdisciplinary approaches with all of the actors involved (Hazard *et al.*, 2018). To this end, different research stances coexist, such as:

25 Holon: the fact that something can be both a system and a sub-system of a larger system (Bland and Bell, 2007).
26 Agency: ability to act free from the dictates of the structure that predetermines us (Wilber, 2001).

• analysis of socio-technical transitions: observing and analysing transitions that have taken place or are in progress;
• modelling and serious games: representing farms and exploring their evolution; explaining rationalities and testing new practical arrangements;
• action research: participating in the transformation in order to understand it.

Martin *et al.* (2018) developed a conceptual framework to connect these three types of approaches to the agroecological transition and to produce a more complete and useful understanding of transitions in order to be able to design ways to support them through public policies or practitioners (Figure 4).

Figure 4. Complementarity between three research strategies for studying the agroecological transition of farms (Martin *et al.*, 2018).



Some examples

Evolution of the vulnerability of dairy farms during conversion to organic farming

This project ran from 2005-2018. Conventional dairy farmers faced an uncertain and changing context, as illustrated in France by the acute crisis in the price of milk after the end of milk quotas and the increasing frequency and intensity of climatic hazards. To avoid precarious economic situations and the resulting vulnerability, many dairy farmers chose to convert to organic farming, which is considered a promising alternative with high and stable milk prices for farmers and support from a growing market. To become part of this sector, however, dairy farmers had to change. They had to adopt new values, practices, social relationships on the farm and with the outside world, marketing methods, etc., all of which can be a source of uncertainty, especially in the initial years of conversion (1.5-2 years), without the benefit of immediately obtaining the milk prices of the organic sector. This situation raises questions about how the vulnerability of farms evolves during their conversion to organic farming, i.e. their capacity to face, adapt or overcome the effects of various hazards during and after conversion to organic farming.

In this context, Bouttes *et al.* (2018)'s work, performed in partnership with agricultural extension services in Brittany[27] and Aveyron[28], France, aimed to characterize this type of evolution and identifying conversion strategies that limit farm vulnerability. This work was based on dairy farm surveys performed from the last year of conventional milk production to the start of organic production (i.e. 3-5 years, depending on the farm). Data were collected on changes in farming structures (surface areas, herd sizes, etc.), practices (grazing management, supplementation, etc.), performance (dairy productivity, economic results, etc.) and the dairy farmers' satisfaction levels. Results indicated that dairy farmers perceived that farm vulnerability during conversion decreased on the economic, agronomic, zootechnical and social levels, regardless of the practices implemented. Thus, one dairy farmer testified, "I have the feeling of being more in tune with society's wishes, of being more accepting of the future, even if there are also risks." None of the farmers mentioned only negative or neutral perceptions, and only 6% of the responses revealed dissatisfaction with unanticipated agronomic or zootechnical issues or with the new working conditions. The vulnerability assessed by techno-economic indicators also decreased during conversion, with improved farm profitability (mean productivity in Brittany rose from 32,000 euros per worker per year before conversion to 42,000 euros after conversion). This decrease was made possible by more economical and self-sufficient strategies based on efficient use of prairies for grazing. Furthermore, differences in vulnerability among farms were due mainly to differences in the farmers' practices, either in the initial situations or the extents of the transitions made.

This work showed that there is significant scope for reducing the vulnerability of dairy farms that results during their conversion to organic farming, as long as the conversion is based on a clear transition towards a more economical and self-sufficient strategy based on efficient use of prairies for grazing. Based on these findings, a series of farmer testimonial videos was produced to raise awareness of potential impacts of conversion to organic dairy farming and of the strategies required to benefit from it.

Professional transition to economical and self-sufficient mixed crop-livestock farming systems

This project was initiated in 2009. Its aim is to identify resources (cognitive, material, teaching) that may be useful to farmers who wish to develop more economical and

27 With the Regional Federation of Organic Farmers (FRAB) and the Organic Farmers Group of Côtes-d'Armor (GAB22).
28 With the Chamber of Agriculture and the Association for the Promotion of Organic Agriculture in Aveyron (APABA).

self-sufficient forms of farming, thus putting to the test organic-farming regulations and practices described as agroecological. The project addresses these questions: How was the agroecological transition initiated among the farmers of the "Réseau d'Agriculture Durable" (RAD), a "network for Sustainable Agriculture".

This work required mobilizing agricultural sciences and ergonomics. It was based on analysing the professional transitions of 20 farmers working on nine economical and self-sufficient mixed crop-livestock farms belonging to RAD and 17 experimenters working with the Aster-Mirecourt[29] experimental unit, which also practises an economical and self-sufficient form of mixed crop-livestock farming. These farmers and experimenters had previously practised conventional crop-livestock farming based on inputs.

Among the sometimes interacting factors behind the farmers' willingness to undertake professional transition to an economical and self-sufficient form of mixed crop-livestock farming are their awareness of the disconnect between values and practices, practical or financial difficulties, the readiness to experiment and even the challenge of doing what had been considered inconceivable until then. The farmers' future wishes evolve "on the fly" during the transition. The knowledge and know-how they rely on when working with inputs are, in part, unusable in a low-input situation. Their work and the elements they must work with are no longer the same. The transition process is akin to a dialogue with the situation: the farmers thus compare their wishes to reality and try to solve the problems that emerge during the transition by seeking effective solutions. This process is equipped with and stimulated by the use of various resources, such as rotational grazing methods, assessment methods, and herbometers, which not only allow farmers to solve difficulties, but also to discover new possibilities.

This project obtained CASDAR (French Special Allocation Fund for Agricultural and Rural Development) funding twice[30]. One funding, TransAE, focuses on supporting the professional transition of farmers, facilitators, teachers and researchers towards agroecology. It starts from the postulate that farmers' professional transitions and ability to develop ways of doing and thinking in an agroecological perspective also require transforming the working methods of those who advise the farmers and orient their work during their careers. TransAE is an action-research project focused on supporting the transformation of farming of around 60 farmers and on the training of agricultural-college students: how, in the context of the agroecological transition, should facilitators, teachers and researchers change their ways of working in order to be able to support these transformations? TransAE is conducted using methods that promote the reflexivity of project participants, in an environment open to sharing and collective learning. This work on the creativity of farmers undertaking an agroecological transition is being applied in an experience-sharing mechanism involving the Aster-Mirecourt experimenters. The know-how, knowledge and attitude needed to be able to work in these systems are being mobilized and discussed.

29 INRAE's Agro-Systems Territories Resources unit located at Mirecourt.
30 PraiFacE 2011-2014; TransAE 2016-ongoing in 2019.

Connecting the collective to the individual to support the agroecological transition of dairy sheep farming

This project ran from 2015-2018. A farm's agroecological transition requires adapting general agroecological principles to its environmental, economic and social context. Over the past few years, research performed on supporting socio-technical transformations in agriculture has shown the importance of social learning to develop and/or contextualize the knowledge necessary for this transition (Cristofari *et al.*, 2018), as well as the importance of constructing with farmers the tools they will need to make their own changes (Cerf *et al.*, 2012). This project incorporated both of these aspects. It was located in the Roquefort area, where dairy sheep systems continue to intensify and expand (the famous Roquefort cheese, made from sheep's milk, comes from this area). Faced with this observation, the Association of Veterinarians and Livestock Farmers of Millavois (AVEM, created 40 years ago, after the 'fight for the Causse du Larzac'[31]) wished to initiate agroecological transition of farms in its territory. With the help of veterinarians, agronomists and a researcher, the sheep farmers on AVEM's board of directors developed the Salsa project (South Aveyron agroecological dairy systems). It was selected for CASDAR funding under the 'Collective mobilization for agroecology' programme. This project thus enabled sheep farmers, veterinarians and their partners (Grands Causses Regional Natural Park, INRAE, Centre for the Study of Agricultural Techniques, CETA 'From Grass to Milk', agricultural college of Saint-Affrique) to develop an agroecological assessment tool for farms with the aim of identifying good farming practices. The sheep farmers' hypothesis was that if their farms became self-sufficient in fodder and energy, costs would be reduced, as would the farms' negative environmental impacts. The partners were responsible for designing and implementing a method to monitor and support changes on the farms. INRAE researchers, including Camille Lacombe, as part of her doctoral research, participated in this project's stages.

Development of the assessment tool involved several iterations between design in the laboratory and testing on AVEM's farms. New criteria proposed by sheep farmers were incorporated to consider dimensions other than fodder and energy self-sufficiency when assessing animal production practices. The farmers asked for the assessment to be broadened to include economic and social dimensions. Even the value assigned to collective action was opened to discussion: visions of agroecology geared more towards local employment and direct sales were debated, which also encouraged the farmers' engagement in the agroecological transition. The sheep farmers also used the initial assessments to compare and discuss their individual strategies and practices. To help encourage use of the assessment tool as a medium for exchange between farmers, working groups of neighbouring farmers were created so that farmers could fine-tune and discuss their individual agroecological transition projects. During this time, the assessment tool was

31 The 'Fight for the Causse du Larzac' refers to non-violent civil disobedience protests by farmers against the expansion of an existing military base on the Larzac plateau. In 1981, after ten years of protests, the government abandoned its plans to expand the base.

used as a medium for exchange between farmers, a platform for explaining and discussing individual strategies, and a tool for monitoring and simulating practices.

This tool, initially designed to recommend good practices, was thus transformed during its implementation into a heuristic tool, i.e. into an aid for thinking about change. No longer intended to produce a standard for sheep farmers to adopt, it allows them to think about redesigning their own systems. It leads to an informed choice of a collective agroecological transition project. It helps farmers reflect on their own strategies for changing practices and more generally on their farming project. The tool has become a form of mediation between a collective project at a territorial scale and the individual projects of farmers on their farms.

Research questions

How should a farm's agroecological transition be analysed?

To assess the performance of agricultural systems, the agricultural sciences have until now concentrated on studying stable systems, in which the practices adopted are modified little, if at all, over the years. The issue of transition was thus reduced to the idea of the desired farm, and the path to reach it was considered to be the responsibility of agricultural development agencies and agents. However, for an agroecological transition, the correspondence between ends and means must be reassessed continuously, thus becoming a research topic in its own right, for which it is necessary to come up with interpretative frameworks.

In the tradition of "farming systems", defined as a set of farms with broadly similar characteristics (Darnhofer *et al.*, 2012), this research work can be organized around three tasks:

1. Identifying systems in transition, which constitutes a 'hunt' for innovations. It consists not only of developing methods to identify innovations, but also of understanding the potential to use them to design transition trajectories (outscaling) and the conditions necessary to do so. This issue is being addressed in particular by the resource centre of the Initiative for Design in Agrifood Systems (IDEAS)[32] in Île-de-France.

2. Analysing the simultaneous evolution of the context, practices, properties and performance of systems in transition in order to characterize necessary conditions and favourable factors, or, on the contrary, lock-in effects in the farm's and farmer's activities (technical changes, integration into networks, learning processes, changes in marketing methods and in the organization of work). Such analysis requires interdisciplinary work on ongoing transitions, and requires going into depth in two ways:

- developing concepts and methods that combine the framework of sustainability with frameworks for analysing the dynamics of systems (in particular, resilience, vulnerability, efficiency and viability) in order to be able to analyse the evolution of performance during

32 See https://www6.inrae.fr/ideas-agrifood.

the transition. The Resilience Alliance[33] network, founded around the concept of socio-ecological systems, is working in an interdisciplinary manner on the use of the concepts of resilience and vulnerability in agricultural systems.

• developing concepts and methods to analyse the transformations of work (organization of activities, increase in mental workload due to the need to manage complexity and uncertainty, transformation of professional worlds of reference). It consists of analysing how workload orients trajectories of agroecological transition. It is clear that farmers short of labour will seek the development of robust and simple agroecological systems that do not require too much work. This aspect is not sufficiently considered in the design of innovative systems, whose complexity will likely increase and will thus require a significant increase in physical and mental workload. This issue of the amount of work has been neglected in agricultural sciences.

3. Characterizing how management elements are called into question during a farm's agroecological transition and how they reconfigure themselves, such as the management of plant and animal health, agrobiodiversity and the integration of activities in diversified systems.

How should a farm's agroecological transition be modelled?

To model a farm's agroecological transition, it is first necessary to model the farm. To recognize changes, methods for modelling scenarios and for operational simulation must be developed. Furthermore, to decrease calculation times during interactions with actors in the field who are helping to develop scenarios, it may make more sense to use static rather than dynamic models (crop-production tables rather than growth models) and, in the pursuit of efficiency, couple meta-models rather than use models that are too complex and take too long to run. Finally, it may be useful to use additional information from experts from various backgrounds to test the farm's agroecological transition trajectory, for example with serious games. Here, these serious games are role-playing games for actors to simulate farm management practices. They allow for knowledge sharing and learning about farm management situations.

Modelling the farm requires simplifications not only to analyse and understand its functioning (baseline situation), assess scenarios and debate support measures (technical innovation, structural changes, public policies, etc.), but also to transfer knowledge. For farms, several modelling challenges must be overcome.

In general, functional modelling of the farm lies at the intersection of the modelling of socio-ecological systems and socio-technical systems. The farm can be represented as an actively managed complex system. Modelling it requires paying attention to cognitive structures (goals, plans, preferences) and the mechanisms by which these structures intervene in the farmers' decision-making processes and evolve over time (adaptation by feedback). This modelling must represent the complexity of physical structures (fields), social structures

33 See www.resalliance.org.

(for example, farming collectives such as GAEC), options for organizing farm work and the diversity of farms. Multiple farm-production units must be considered (for example, crop-livestock integration requires the model to consider more than only field crops, a single production unit, a full-time human labour unit, or a single income source). Of concern therefore is the ability of modelling to integrate the many new management elements that emerge from agroecological transition processes and to consider the properties expected from these systems, such as resilience.

Another challenge is to create modelling frameworks that consider uncertainty and learning over the long term. For example, how can the trial-and-error approaches that farmers adopt on their fields to test agroecological innovations be included? How can the conceptual framework of viability, which is concerned with the dynamics of a system in a constraint space, be included? What changes should be considered for optimization approaches in a multi-criteria framework? How can changes in the spatial and/or temporal scale be included? How can model properties that emerge when scales are combined be considered? How can the necessary trade-offs between a system's resilience, efficiency and viability be considered?

A network of actors is an important element of the agroecological transition of farms. Therefore, a research framework for management situations that include a collaborative dimension must be developed. Indeed, certain objectives, such as maintaining a landscape structure favourable for local biodiversity and associated biological regulation services, cannot be achieved by individual strategies; several farmers must collaborate and coordinate their actions. Collaboration can also involve exchanges between farmers of products from their farms (fodder, manure, etc.) or sharing of their resources (machinery, labour, etc.). This type of coordination problem, which combines individual initiatives in a collective approach, has been little addressed, even though it is of fundamental importance in agroecology, in particular for the agroecological transition.

How should scientific knowledge about providing support to farmers' agroecological transition be produced?

Providing support to farmers' agroecological transitions raises questions about the process of co-design and the learning that such a change imposes. Going beyond creativity methods, it consists of working on the nature of the knowledge required for co-designing, how to organize this knowledge, and the articulation between the design and the multiple forms of experience (from those lived by farmers to the analytical experiments they observe). This work requires participatory approaches based on problem solving that involve farmers and their advisers in order to mobilize their knowledge and choose orientations of the transition in a democratic manner. The method thus consists of analysing the process of change by participating in it. This participation results from iterations between involvements in active transformation of the systems and reflective processes with the actors to learn from the action taken. This leads to the production of scientific knowledge in human and social sciences as well as in biotechnical sciences.

This work can rely on the International Farming System Association[34], in conjunction with the work of CIRAD ('West African multicrop-livestock systems: involving farmers in the design of innovations') and of Boelie Elzen from Wageningen University. It consists of four major tasks:

1. Creating design methods in line with the usage context to produce locally adapted solutions. This involves narrowing the gap that has been created between designers and users, between creativity and testing, and between searching for solutions and determining their relevance. The research was organized in Île-de-France at the IDEAS resource centre.

2. Developing methods for supporting the agroecological transition, project management and governance (research, advice, training) by promoting participation, cross-learning, sharing of experiences and scientific investigation in action. It consists of exploring the relationship between the collective and the individual, after having focused on collective action until now.

3. Working on the connections among research, agricultural advisory systems and education by sharing investigation methods that promote learning: methods of investigation and learning in action bring research and teaching closer together, while the focus until now has been on promoting knowledge transfer.

4. Analysing and developing management indicators, tactical and strategic reasoning and their interactions in order to help farmers reduce the complexity of managing agroecosystems and thus be able to manage them better.

Developing the necessary transdisciplinarity

The research issues mentioned above clearly require interdisciplinary and even transdisciplinary research practices, i.e. with the actors themselves. Several projects are currently underway to:

- study connections among digital agriculture, modelling and social learning to support the agroecological transition of farms;
- connect studies performed in several disciplines (Figure 4). These studies were performed with research stances that are sometimes difficult to reconcile, as practices among disciplines can differ greatly in how they pose and address problems, furnish evidence and present results (Hazard *et al.*, 2019);
- pursue methodological development of transdisciplinary approaches that make researchers and non-researchers work together. Thematic training sessions such as 'Producing and mobilizing different forms of knowledge for and on the transformation of agricultural systems: interdisciplinary perspectives' (2015) and 'Participatory sciences' (2018), as well as the 'Sciences in society' mission supported by INRAE, have spearheaded this effort.

34 http://ifsa.boku.ac.at.

These initiatives must be extended to our partners in the field, because these approaches run counter to their longstanding perception of science – which they see as a top-down mechanism to provide the answers to their problems. Researchers and non-researchers alike are currently struggling to break away from this highly compartimentalized and disconnected practice of science to implement participatory approaches, as shown by experiments such as Co-create in Brussels or the projects of the Centres for Initiative to Promote Agriculture and Rural Areas (CIVAM). The idea is to consolidate methods of investigation and reflective practices that can be used by mixed communities of researchers and actors in the field, and also to succeed in combining the co-production of innovation with the academic requirements of scientific knowledge production.

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3. Leveraging regulation processes in multifunctional landscapes

The agricultural landscape is a mosaic of plots and interstitial spaces of varying sizes, shapes and arrangements in space, as also in time, changing with crop successions, agricultural activities and land use planning. These arrangements depend not only on the constraints of farms imposed by their modes of production and on the characteristics of the environment in terms of the distribution of soils and water tables, but also on non-agricultural activities, in particular at interfaces. These mosaics, closely tied to the territory's socio-economic dimensions, are part of a history and pose production and environmental challenges for society (Gascuel-Odoux and Magda, 2015).

How can value be derived from biodiversity and from ecological and hydrobiogeochemical processes? In other words, how can the biotic and abiotic processes and their interactions within landscapes be leveraged for a sustainable and multi-performing agricultural production, one that is more efficient, more resilient and less polluting (low levels of inputs, low leakages to the environment), and beneficial to all actors in an agricultural territory? This is the issue we address in this chapter.

The term 'multifunctional' encompasses a few key functions that have been studied much in recent years: regulation of pests, weeds and diseases; pollination; maintenance of soil and air biodiversity; regulation of the quality of water, soil and air and their availability; and maintenance of plant and animal production (soil fertility, animal nutrition). Functions that cannot be considered strictly agricultural (management of invasive species, conservation of traditional biodiversity) are not covered here.

A first step is to identify the determinants of an environment's spatial and temporal variability and the ecological processes that take place there, and to identify the landscape elements that are agroecological supports or mechanisms of actions. These landscape elements are not necessarily areas dedicated to agriculture; they can be natural areas. It is often necessary to consider both managerial scales (a field and its border, farm, territory, catchment) and ecological scales (ranging from the square centimetre to the agricultural landscape) and recognize that to understand landscape-scale processes, it may be necessary to consider processes that occur at finer scales. The question of the complementarity of different mechanisms, for example the spatial combination of different environments and different production systems, is essential at the territorial scale.

The processes' temporal dimensions are important for designing resilient multifunctional landscapes. Agricultural landscapes evolve rapidly in time, and this evolution is often inseparable from the spatial dimension, as underpinned by spatio-temporal strategies for cultivating crops and varieties and creating semi-natural habitats. A key longer-term challenge is to anticipate effects of global changes, including climate change, with its consequences for land use and urbanization. Specific needs for vigilance may arise, such as for the spread of invasive species and the emergence of diseases.

Synergies and antagonisms between ecosystem functions constitute a significant issue across multiple spatial and temporal scales. At the landscape scale, it is a matter of determining how the coexistence of different agricultural systems within the same territory generates a synergy of certain functions (recycling, complementarities, etc.). The issue of social trade-offs between ecosystem functions and services, their determinants and their consequences for the management of natural resources is also important and constitutes a growing area of research.

Societal challenges include assessing the extent to which the spatial and temporal organization of landscapes represents a mechanism for their multifunctionality and their resilience to global changes. It involves seeking answers to the following questions: What compositions, spatial arrangements and types of management do landscape elements have? What complementarities exist between production systems within a territory?

Societal challenges also include designing multifunctional and resilient landscapes better. It involves seeking answers to the following questions: What public policy instruments can promote multifunctional and resilient landscapes? Can concerted management – and involving which actors – help obtain these landscapes? What mode of governance should be implemented?

Research challenges consist of increasing knowledge about interactions among the biotic processes that underlie ecosystem functions of agricultural landscapes. They also consist of analysing and integrating interactions between abiotic and biotic processes, and of improving understanding of effects of the composition, configuration and management of agricultural landscapes on processes, functions and services in order to better understand their temporal dynamics, in particular to assess the resilience of agricultural landscapes. They also consist of improving understanding of economic and social determinants of the management of abiotic and biotic landscape resources and of analysing determinants of actors' relative preferences for different aspects of multifunctionality in order to understand their trade-offs.

Recent scientific advances

Scientific advances in recent years have improved the ability to capture the complexity of biophysical processes at different spatial scales and in heterogeneous environments.

Progress has been made in improving consideration of the spatial and temporal heterogeneity of agricultural practices when studying biophysical processes. Models of abiotic flows in landscapes have increased in complexity by explicitly representing production systems and farm constraints (for example, the Casimod'N set of models, built as part of two projects of the French National Research Agency (ANR)[35]: Acassya and, on the nitrogen cascade, Escapade). Representation of agricultural activities when studying ecological processes at the landscape scale has become more detailed, in particular the concept of 'hidden' heterogeneity (Vasseur *et al.*, 2013) and more explicit consideration of agricultural practices, which goes beyond the dichotomy between organic and conventional agriculture. Semi-experimental studies at the landscape scale have progressed and now permit analysis of interactions among landscape variables, ecological processes and agricultural production. There is also renewed interest in the ecology of movement, with advances in how landscape structure impacts the movements of organisms of interest, such as beneficial arthropods. Similarly, the functional role of organisms of interest and their responses to landscape configuration are now understood better, for example the biocontrol role of insectivorous birds in viticulture. Exposure of living organisms to contaminants is a dimension that is beginning to be incorporated into the study of the resilience of agricultural landscapes (Recotox Network[36]).

These changes have been accompanied by the creation of tools that have increased the ability to understand how landscapes function. For example, routine soil metagenomics methods now identify effects of land use on the spatial distribution of soil communities (Ranjard *et al.*, 2013). New molecular tools also make it possible to reconstruct trophic webs of agroecosystems and to study structural and functional responses of interaction networks along landscape gradients (Bohan *et al.*, 2013). Finally, virtual landscape simulation tools are now available that reduce reliance on experimentation at large spatial scales, which is often challenging to perform in real landscapes. Such tools can help identify new strategies for managing crop rotations by considering biophysical processes and actors' socio-economic constraints (Poggi *et al.*, 2018).

Recently, generic knowledge has been generated about the ecological functioning of landscapes. The publication of several meta-analyses of effects of landscape organization on pest regulation (for example, Veres *et al.*, 2013) highlights the major role of semi-natural habitats and of the spatial and temporal heterogeneity of crop mosaics in the landscape. Studies have identified the landscape determinants of pollinator communities, in particular the key role of the spatial and temporal distribution of floral resources.

More generally, abiotic processes are being increasingly integrated into the landscape by considering the agroecosystems and environments in which they occur, but they are often limited to a single chemical element. Similarly, while some approaches do consider several biotic processes in a single landscape, most studies focus on a single ecological process. Multifunctional landscape analyses are often based on using indicators or proxies, i.e. derived from relationships assumed to exist between, for example, habitat type and specific functions, rather than on directly quantifying processes and their interactions.

35 See https://www6.rennes.inrae.fr/umrsas_eng/Results/Tools/TNT2-CASIMOD-N-CSAM.
36 See https://www.recotox.eu/recotox_eng/.

There are some exceptions, however, such as studies based on mechanisms of Biodiversity Exploratories developed in Germany. In these studies, there are, for example, 14 types of measurements of diversity and processes in below-ground and above-ground grassland compartments (Allan *et al.*, 2015).

At the same time, more in-depth interdisciplinary research is connecting the social and biophysical sciences at the landscape scale. The socio-ecological systems framework (Ostrom, 2009) has been used widely to document social and ecological mechanisms, conditions, interrelationships and consequences. Action-research projects aimed to promote collective actions and agroecological innovations have been implemented at the territorial scale (Berthet *et al.*, 2016). Large-scale economic assessments of ecosystem services have become much more frequent, in Europe and elsewhere. We can cite here the contribution of Ian Bateman and his team, which is particularly relevant for assessing pollination services at the landscape scale (Bateman *et al.*, 2014). Advances in the spatialization of activities provide cost-effective analyses of different scenarios of spatial organization to provide ecosystem services. The issue of governance is also addressed, for example by analysing the increase in cooperation among actors to promote provision of ecosystem services. These studies provide the basic knowledge necessary to address the issue of social trade-offs between ecosystem services.

Some examples

The landscape and 'biological control' services

There has been a marked increase in research projects that document effects of the landscape on beneficial organisms, pests and diseases, and the intensity of biological control with routine use of sentinel prey. We can cite various projects supported by the ANR (Peerless, Landscaphid, Agrobiose), the Biodiversa Farmland[37] project and the EU FP7 PURE project. Meta-analyses and bibliographic reviews dealing specifically with connections between the landscape and biocontrol have shown that while semi-natural habitats can promote biocontrol in agricultural fields, managing agricultural spaces at the landscape scale can be decisive, for example the proportion of the landscape devoted to organic farming (Muneret *et al.*, 2019). Monitoring of networks of farmers' fields indicates that effects of the landscape on biological control often vary because they are generally influenced by how fields are managed, for example through local practices (intensity, etc.) of pesticide use (Ricci *et al.*, 2019). Monitoring of farming practices at Long-Term Ecological Research (LTER)[38] sites in France has made it possible to better understand the effects of the history of agricultural management of fields, their borders and landscapes on

37 See https://www.farmland-biodiversity.org/index.php?sujet=1&lang=en.

38 LTER sites (*zones ateliers* in French) are interdisciplinary sites for long-term environmental and ecological research on human-dominated landscapes. See https://inee.cnrs.fr/fr/zones-ateliers.

ecological dynamics. These studies have been accompanied by the establishment of long-term observation networks on landscape gradients and on the intensity of practices, with prominent examples being the national Sebiopag network[39] and the Bacchus[40] biodiversity and viticulture experimental site.

The landscape and 'pollination' services

There have been significant advances in recent years in the understanding of the ecology of the honey bee, the importance of the spatio-temporal distribution of floral resources for pollinators, the impact of pesticides, especially neonicotinoids, on honey bee colonies and the importance of pollination services for oilseed crops at the agricultural landscape scale. These advances were made possible by the Ecobee colony-monitoring tool (Odoux *et al.*, 2014). Monitoring of colonies and palynological observation of 50 hives placed in contrasting landscapes have revealed the importance of weed flora, particularly the poppy, for the survival of honey bees, as an essential resource between rapeseed and sunflower flowering periods. They have also shown the negative impact of neonicotinoids on bee colonies. More recently, experiments conducted along landscape gradients have shown that pollination by honey bees and wild pollinators can increase rapeseed and sunflower yields significantly. These results have been actively transferred to farmers and beekeepers, in particular through the partnership with Itsap-Institut de l'Abeille[41], and more widely to technical advisers and teachers through the 'Bees and the Environment' MOOC[42] launched in 2019.

Plant and animal epidemiology at the landscape scale

Managing agricultural landscapes to limit epidemiological risk became a major issue over the past ten years or so. In plant epidemiology, it is a matter of managing the intraspecific and interspecific diversity of crops at several spatial and temporal scales by relying on concepts in epidemiology, theoretical evolutionary ecology and landscape ecology (Papaïx *et al.*, 2018). In animal epidemiology, consideration of the landscape is much more recent and has focused mainly on vector-borne diseases. The European EDENEXT[43] project, which brought together 46 European partners, played a structuring role and created tools to monitor and manage disease vector populations. The Biodiversa SmallForest project focuses on ticks and Lyme disease at the landscape scale. The landscape and its influence on tick-borne diseases are at the centre of the Oscar[44] programme (a tool for cartographic

39 Ecosystem services provided by biodiversity in agricultural landscapes. See http://sebiopag.inrae.fr/.
40 See http://siteatelier-bacchus.com/en/.
41 Technical and Scientific Institute for Apiculture and Pollination.
42 Massive open online course.
43 Biology and control of vector-borne infections in Europe. See https://cordis.europa.eu/project/id/261504.
44 See https://www6.inrae.fr/oscar.

simulation of acarological risk at the agricultural landscape scale) used at the Armorique and Pygar LTER sites.

Strategies to manage territorial water resources

A Franco-Indian collaboration is an example of a project on strategies to manage territorial water resources. This project examines adaptation of irrigated agriculture in a context of water scarcity and climate change. Its study area is the Berambadi agricultural catchment in southern India, for which data on irrigation expansion and soil properties were obtained through remote sensing. At the same time, a typology of agricultural systems was developed, and vulnerability of the systems to climate change was assessed. The Record[45] modelling platform made it possible to couple the Stics crop model, calibrated for a diversity of crops, the Ambhas hydrological model, an economic model and a decision model to test aspects of tactical and strategic adaptive management. The simulations suggest that scenarios based on increasing the cost of irrigation would stabilize the supply of the water resource, but lead to financial risks for many farms or even force a return to subsistence rainfed agriculture. Scenarios that include better temporal distribution of irrigation and penalize crops that need large amounts of water during the hot and dry season appear to be the most promising. The ongoing ANR Atcha[46] project combines an integrated model with a participatory approach to support the adaptation of agriculture to climate change in a network of experimental catchments in southern India.

Actor strategies and plant health

Some projects have worked on strengthening synergies between the biophysical sciences and social sciences. Three projects, mentioned here as examples, have focused on organizational modes and conditions of collective landscape management of plant health.

The Fondu project investigated the use of fungicides in wheat and viticulture and showed that the most sustainable strategies must maximize the heterogeneity of the selection of resistant strains over extended spatial and temporal scales. The project shows that decisions should not be taken at the individual level, but rather at that of a territory.

The Eternal Rice project shows that a particularly high diversity of cultivated rice ensures the sustainability of terraced rice paddies in Yuanyang, China. This diversity is based on social norms that consider rice seeds to be a common good (Hannachi and Dedeurwaerdere, 2019) that can be maintained only by ensuring that actors create mixed-form markets, i.e. markets collectively aimed to economic gains as well non-monetary socio-ecological goals that enhance well-being. Destabilization processes are emerging and are visible through socio-economic tipping points.

45 Renovation and coordination of crop modelling for agroecosystem management.
46 See https://www6.inrae.fr/atcha/.

The economic and ecological modelling performed by the Peerless project shows that the landscape influences the effectiveness of pesticide use, especially in situations of non-intensive production. The project has identified the optimal composition of landscapes for a target yield or maximization of both production and beneficial organisms with reduced use of pesticides.

Research questions

Analysing effects of heterogeneity at nested spatial and temporal scales

Analysing effects of heterogeneity at different spatial and temporal scales remains a challenge in agroecology. This kind of analysis involves understanding interactions in space and time among abiotic, biotic, biogeochemical and ecological components. Research goals include a better understanding of population dynamics (e.g. disease vectors), interacting populations (pathosystems), and communities (e.g., natural enemies of pests) in heterogeneous and changing environments. The role of interfaces between cultivated and semi-natural environments (refuge, exchange of organisms between the two habitats, etc.) remains poorly documented, whether for disease management, biological control or pollination. Little is known, also, about effects of agricultural diversification on the intensity and stability of ecological processes of interest to agroecology at the landscape scale. Effects of the concentration, dilution, connectivity and regulation of the flow of organisms remain poorly understood. Developing multi-organism models at the landscape scale would help to better understand the provision of ecosystem services at different spatial and temporal scales.

These issues are being addressed in research on plant and animal epidemiology, landscape ecology applied to biocontrol and pollination (comparative ecology and experimental approaches) and the flows of chemical elements (pesticides, nutrients). This work requires a community of researchers who strive to understand biophysical and ecological processes at the landscape scale.

Developing integrated approaches to address the multifunctionality of landscapes

Abiotic processes are generally considered in a compartmentalized manner, by chemical element or landscape object. Ecological processes are rarely considered simultaneously. The flows among the soil, water and air are increasingly being connected, but doing so remains rare (e.g. for nitrogen). Likewise, research which addresses a set of flows in an integrated manner also remains rare. Finally, the issue of complementarity or synergy between different functions has yet to be addressed meaningfully. This limits our ability to analyse several crucial issues in agroecology, such as the coexistence of different production systems within the same territory and the synergies between them. Undertaking integrated studies to assess impacts of production systems on resources and organisms at the landscape scale therefore remains a major challenge. Integrated modelling approaches, aimed to couple soil, hydrological and atmospheric processes, as well as these processes and ecological processes, are showing some promise. Research into interactions between abiotic and biotic fluxes is at an early stage, but a unified modelling framework was presented recently by Vinatier *et al.* (2016). The use of landscape simulation requires research, particularly to represent feedback between the process of interest and landscape structure, consider the diversity of actors, and increase the realism of decision models. Incorporating this complexity into a model remains difficult, and other avenues can also be explored. In these integrated approaches, it seems essential to involve the economic and social sciences from the outset, and not afterwards.

Capturing the diversity of actors in the analysis of biophysical processes at the landscape scale

Actor participation is a key factor at the landscape scale, hence the importance of research on public policy instruments, more voluntary instruments such as non-economic incentives (“nudges”) and the process of building common frameworks and facilitating collective learning for landscape actors (community building). Identifying incentives that encourage coordination among territorial actors to promote agroecological management of the landscape remains a major challenge.

We also note that the formal models used in the context of socio-ecological systems consider human behaviour through a rational-actor model, without considering human complexity. Incorporating this complexity into formal models has been a research goal in the management sciences for some time. To improve integration of the multiple aspects of human behaviour, researchers must analyse interacting actors and groups of actors in studies that span several disciplines, including those of the social sciences (economics, management sciences, sociology, anthropology). It also seems important to encourage learning by doing to overcome the inertia of actor groups and support the design of agroecological landscapes by explicitly considering actor needs and organization.

Supporting the design of agroecological landscapes

A landscape represents a collective scale, and establishing and managing ecological functions at this scale requires collective mobilization of actors. This mobilization can be encouraged by developing indicators and decision tools for landscape actors, especially if the latter are involved in this work through participatory research or action-research mechanisms. Such mechanisms raise the awareness and participation levels of local actors, while providing perspectives for innovative interdisciplinary research. Modelling and simulating biophysical and ecological processes, identifying decision rules using various approaches (metamodelling, for example), and modelling support tools (serious games, etc.) are all tools that can contribute to the design of agroecological landscapes within a framework of adaptive management. Several INRAE teams are working on coupling models designed to analyse landscape performance in terms of production, crop protection, greenhouse gas balance, pollination and biodiversity with the aim of identifying multi-performance landscapes (API-SMAL project). Advances depend heavily not only on data-acquisition and management mechanisms, but also on modelling and simulation tools.

Methodological mechanisms and developments

Data-acquisition mechanisms

Analysis and modelling of spatio-temporal processes, such as those at the scale of rural landscapes, are often rendered difficult due to a lack of consistent sets of observations that are spatially well distributed and over long periods. Therefore, to design or analyse agroecological landscape systems, three complementary priorities must be addressed.

- Creating multidisciplinary observation and/or experimentation sites (experimental landscape ecology). French LTER sites may be good candidates because they have been systematically documented over periods of one to three decades by well-established research-and-development consortia. In most cases, however, this infrastructure needs to be extended at the thematic level (biophysical, biotechnical, social sciences) as well as at an instrumental level in order to acquire data in a coordinated manner to study agroecological production systems. The emergence and maintenance over long periods of “networks” of contrasting landscapes is leading to the identification of production situations and landscape gradients in a harmonized manner. An example of this approach is the Sebiopag national network for the study of ecosystem services provided by biodiversity in agricultural landscapes, which covers landscapes in five French regions.
- Improving the means of observation, in particular through new sensors (proximity and remote sensing), to obtain high-density data at high speed for all the variables (biotic, abiotic and actor practices) necessary to analyse variability in ecological and agronomic phenomena at the landscape scale (see Chapter 6).
- Using participatory approaches more widely to supplement scientific observation with actors’ expert knowledge or with non-formal observations recorded by non-scientific and non-professional actors. It may be useful to set up large-scale economic experiments to study incentivizing mechanisms that encourage farmer participation in innovative agro-environmental measures (agglomeration bonuses, collective commitments, payments for results).

Data management and statistical analyses

Existing statistical methods need to be adapted to process heterogeneous data. Landscape-scale models are highly multidisciplinary (ecology, sociology, agronomy) and must therefore incorporate multiple data types (for example, count, occurrence, spectral measurement, genetic information) originating from big data – such as aerial images or high-throughput genetic sequencing – as well as from more occasional observations often obtained in ecology. In this context, classic statistical methods no longer apply. Many different tools are now commonly used in spatial ecology (PLS[47] regression for multicollinearities or big data, decision trees and random forests for heterogeneous variables and prediction, spatial statistics via INLA[48] that integrate data's temporal aspects, etc.). However, current data are increasingly spatio-temporal. They thus require characterizing dependencies in space and time that arise from dynamics of the processes studied. Models derived from spatial statistics are gradually being extended to the spatio-temporal domain. Although R[49] software can be used to find solutions, it requires work to be transferred to non-specialists. Finally, this transition towards the spatio-temporal domain can also be achieved via explicit modelling of dynamics of the studied processes. These "mechanistic-statistical" approaches are in full bloom due to advances in computational statistics (optimization of complex problems, Bayesian statistics, Approximate Bayesian Computation, pattern-oriented modelling).

Modelling, simulation and knowledge-extraction approaches

A major challenge is to find an acceptable compromise between a model that is too complex and thus unmanageable and a model that is too simplistic and thus poorly represents, or is unable to represent, interactions at the landscape scale. Modelling in a heterogeneous environment is currently oriented towards integrated or inclusive modelling (coupling of models) to study complex systems and interactions between processes, and also towards meta-modelling, i.e. designing models based on rules learned from simulations run on more complex models to adapt the modelling better to actors' requirements. Another strategy is to combine these two approaches, like the one chosen by the MAELIA[50] platform, which aggregates imperfect knowledge, or like that of targeted studies to deepen knowledge. In the latter, the connections between the elements of knowledge thus acquired ultimately remain difficult to establish. The experimental approach with landscape manipulation and long-term monitoring is of interest because it helps meet the needs of model calibration and validation, as do mechanisms for creating networks of contrasting landscapes. Simulating scenarios sometimes makes it possible to identify spatial and/or temporal configurations for a targeted function or set of functions. This simulation approach provides access to many variables aggregated at different spatial and temporal scales that can help users understand, analyse and take decisions. Exploring simulation data requires not only new developments in computer techniques, such as data mining and learning (Bouadi *et al*., 2017), but also advances in visualizing and querying spatio-temporal data.

47 Partial Least Squares.
48 Integrated Nested Laplace Approximations.
49 See https://en.wikipedia.org/wiki/R_(programming_language).
50 Multi-Agents for Environmental Norms Impact Assessment.

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4. Leveraging genetic diversity in plant and animal breeding

In an agroecological system, it is necessary to consider the possible contribution of biological diversity at all of its levels of organization and functionality, including through the domestication of new species. However, scientific studies often stop at the level of species diversity and interactions between species. Studying the contribution and role of intraspecific genetic diversity remains a major challenge in agroecology.

It consists of evaluating the contribution of genetic diversity to the performance of agroecological cropping and livestock systems, understanding this diversity's mechanisms of action and its interactions with the environmental context, identifying the major traits of interest involved in interactions between plants and between animals for the maintenance of diversity and for the agroecological performance of the cropping and/or livestock system. Ultimately, it is a question of defining the range of diversity that allows expression of mechanisms favourable for implementation of more resilient production systems.

This knowledge is required to take practical decisions, such as defining breeding criteria and the necessary ranges of genetic variability in these criteria for agroecological functioning of the production unit. It is a matter of creating breeding schemes that consider diversity objectives at the scale not only of the individual (plasticity), but also of the group of individuals in the plant cover or the herd. It is also a matter of defining how to implement the diversity as a function of the expected ecosystem service adapted to the environmental context, i.e. appropriate in space and time in a given environment. To this end, it will be necessary to remove certain obstacles, such as those that prevent assessing diversified crops and including them in a catalogue. Considering greater diversity can lead to difficulties in managing agricultural systems, increase the workload of crop or livestock farmers, reduce the ability to guarantee agricultural product quality, which becomes more heterogeneous, and thus call into question the use of automated processing methods and the standardization expected from final products. Genetic diversification must thus be assessed over the entire chain, from the production unit to the mode of production to the final agricultural and food product.

Recent scientific advances

Only recently have studies begun to explore the possible contribution of intraspecific genetic diversity to the development of agroecological systems. The first such studies focused on plants, while later ones also focused on animals. This approach is explored and discussed in review articles, for plants in 2015 (Litrico and Violle, 2015) and for animals in 2016 (Phocas *et al.*, 2016a, 2016b). For plants, a single homozygous variety often represents most crops of a species (e.g. wheat). For animals, a large amount of diversity already exists within the herd itself, even in highly selected breeds (dairy cows, for example). Despite this difference, plant and animal breeding have similarities in the concepts they use and their findings.

Plants and cultivated stands

For plants in cultivated stands, the main advances pertain to demonstrating the positive influence of genetic diversity on the stability of biomass production and drought resistance (Prieto *et al.*, 2015) and on the abundance of species in a cultivated mixture (Meilhac *et al.*, 2019).

Recent literature has little addressed incorporation of this genetic diversity into breeding schemes. Some ongoing or recently completed projects have relied on the old method developed for varietal mixtures or composite populations to address this issue. A recent example (Sampoux *et al.*, 2020) concerns selection of a species mixture, based on evaluating three breeding schemes, to judge its aptitude for interspecific combination:

- a scheme based on selecting each species based on its performance as a pure crop;
- a scheme based on selecting pairs of species based on their performance in mixed crops (selection for reciprocal mixture ability, SRMA);
- a scheme based on selecting a species that performs well in association with any other species (selection for general mixture ability, SGMA).

Comparing the gains expected from SRMA or SGMA to those from pure-crop selection has shown the advantages of using methods that consider combination ability when the selection pertains to traits subject to genetically determined effects of competition or cooperation between plants. It is therefore preferable to use methods designed to improve performance in mixtures in order to derive value from species associations.

The literature on community ecology includes valuable research on the mechanisms favourable to diversity and the traits to select for diversified crops. Litrico and Violle (2015) recommend relating some major traits to growth dynamics, phenology and aerial architecture, but there is still little experimental evidence of these relationships. Nevertheless, some studies are pursuing this idea (Prieto *et al.*, 2015; Meilhac *et al.*, *2020*).

The effect of genetic diversity on the functioning of plant communities constitutes an area of research in itself, but few studies have addressed this topic to date. Some recent work (Zuppinger-Dingley *et al.*, 2014; Prieto *et al.*, 2015; Schöb *et al.*, 2018) has shown effects of genetic diversity on the functioning of communities, in particular in grasslands (Meilhac *et al.*, 2019). These studies are part of an approach to analyse relationships among genetic diversity, the functioning of communities and the provision of ecosystem services in agroecosystems.

Projects currently underway aim to take advantage of species mixtures. An example is the ReMIX project (Redesigning European Cropping Systems Based on Species Mixtures), which focuses mainly on cereals and grain legumes to design agroecological cropping systems that are more diversified and resilient in the face of economic and climatic hazards and depend less on inputs (chemical fertilisers, pesticides, etc.). Based on a multidisciplinary and multi-actor approach, this project aims to produce new transferable knowledge in conventional and organic agriculture. It addresses practical issues in order to develop solutions adapted to production of the main cereal crops in different European pedoclimatic conditions. The project includes identification of end-user needs, co-design of field and farm experiments, and assessment of new varieties and practices.

Participatory breeding is another type of scientific advance. It was first tested on cereal crops. It changes the organization of breeding, considers possible advantages of genetic resources, and experiments with the choice of selection criteria. France is particularly committed in this direction.

Animals

For animal breeding, the objective of reconciling genetic progress while maintaining within-breed diversity has been pursued for a long time. Research was originally oriented towards either maximizing genetic progress at a given acceptable level of inbreeding, or not exceeding a certain degree of inbreeding at a given level of genetic progress. This work was based solely on using kinship relationships. Application of these methods was disrupted by genome sequencing and use of a high density of genetic markers, which made it possible to characterize and control diversity at a much finer level than before by analysing variation in diversity depending on the region of the genome. This development culminated in the implementation of genomic selection, whose founding publication dates from 2001 (Meuwissen *et al.*, 2001). The availability of inexpensive genotyping tools and improvements in calculation methods have led to their routine use for cattle breeding since 2009. Methods have been developed recently to estimate the genetic influence on social interactions in order to address animal welfare issues. Genomics can thus improve prediction of interactions between animals. The influence of an animal on the performance of other animals in the same group can thus be modelled and has been used to reduce cannibalistic behaviour in laying hens (Alemu *et al.*, 2016). These methods can be generalized for other traits of interest that may be useful in agroecological systems.

Animal genetics is currently based either on diversity in the breeding stock for adaptation to relatively local needs (e.g. ruminants) or on greater combination of lines for crossbreeding (e.g. pigs or poultry). While the level of within-herd diversity is not a goal in itself, Blanc *et al.* (2013) used modelling to show that diversified herds (their within-breed diversity) are more stable, which is in line with findings made in plant genetics with varietal mixtures and species mixtures.

Forest cover

For forests, genetic diversity is usually leveraged in one of two ways:

• genetic enrichment of stands, with the objectives of maintaining diversity (*in situ*) for future climate conditions and promoting the creation of diversity by mixing gene pools for intercrossing (allochthonous origins, improved varieties of the same species, or even related species with which the existing stand can hybridize);

• use of exotic species, an old technique often used in planting-replanting systems (e.g. Douglas fir). The introduced species can regenerate naturally (e.g. cedar). If its genetic diversity is sufficient, this type of stand has the advantage of limiting inbreeding in the initial generations.

These two strategies – genetic enrichment and introduced species for regeneration – that combine planting and natural regeneration have risks and benefits which must be assessed and uncertainties which must be managed.

Some examples

The Praise project

The Praise project (supported by ANR funding) focused on planted multi-species temporary grasslands, whose intraspecific and interspecific diversity has been exploited little to date. The project's objective was to establish genetic and ecological bases for improving species intended for mixed use, in particular to cope with climatic hazards. It consisted of identifying genetic and ecological conditions which favour large and stable production of multi-species grasslands over time, and to lay theoretical bases for an innovative breeding scheme for grassland forage species to be used in multi-species mixtures. Several disciplines (quantitative genetics, ecophysiology, functional community ecology, population genetics) were mobilized, and several approaches (combining experimentation and modelling) were applied to analyse and understand effects of the distribution of functional traits. Modelling allowed effects of intraspecific genetic variability on the production of grassland communities to be analysed. While species diversity improves the total amount of biomass produced in a water-limiting regime, genetic diversity improves the stability of production of planted grassland communities under the conditions tested. Furthermore, analysis of variability in aerial and root morphogenesis of a large panel of species chosen for their agronomic importance and contrasting morphological traits made it possible to confirm the robustness of the hypotheses which underpin morphogenesis in current production models that integrate the genetic diversity of species (Louarn and Faverjon, 2018).

After several years of research and specific breeding of multi-species forage mixtures, the Jouffray-Drillaud company, a Terrena subsidiary and partner of the Praise project, launched "M les Mélanges" (e.g. "Love Mixtures"). It is an innovative range of multi-species forage mixtures, in which each variety's behaviour has been tested in the mixture, in order to provide livestock farmers with technical data from the field and the feeder over extended periods. Development of these mixtures is the result of tests performed by Jouffray-Drillaud over four years, in collaboration with INRAE teams from Lusignan. Until then, the forage mixtures had combined only varieties specifically selected, tested and evaluated for their performance in association, for improved productivity, more balanced forage and high feed value. To develop these new kinds of mixtures, the propensity for competition between species, speed of implantation and resilience, defined as a plant's ability to recover after stress, were considered for the first time.

The Wheatamix project

The Wheatamix project (supported by ANR funding) concentrated on improving assessment of the possible role of varietal associations in a field to improve the multifunctionality and resilience of agricultural systems in the context of global changes. This project focused in particular on wheat production in the Paris Basin and relied on a multidisciplinary approach by researchers (geneticists, agronomists, ecophysiologists, ecologists, economists, management science researchers) and production-chain actors (chamber of agriculture, farmers). It contributed to better understanding of interactions between varieties, and between them and the environment, in order to obtain high-performance associations, whether in terms of yield and quality, ecosystem services or even outlets for production. In particular, it aimed to establish rules in a participatory manner for combining varieties and to assess their relevance in different production contexts (Barot *et al.*, 2017).

The Eternal Rice project

The Eternal Rice project (funded by INRAE's SmaCH[51] metaprogramme) studied sustainable management of varietal resistance in rice in terraced paddies of Yuanyang, China, which are listed as a UNESCO World Heritage site (southern Yunnan). It combined approaches from genetics, genomics, social network analysis and modelling. As this region's farmers do not use fungicides, the rice is surprisingly well protected from epidemics. Even though *Magnaporthe oryzae* is present there, this fungus has little influence on these rice terraces. Two types of rice varieties are co-cultivated: ordinary rice (*indica*) and sticky rice used during festivals (*japonica*). Research has shown that *japonica* strains have a high basal immunity and few resistance genes, while *indica* strains have low basal immunity and many resistance genes. These two rice varieties with such different immune systems have led to the existence of two specialized populations of fungi, each able to infect only one specific rice variety. These two types of ultra-specialized pathogens therefore cannot proliferate in a heterogeneous landscape.

51 Sustainable Management of Crop Health.

This study ties together two of the articles cited most in plant biology over the past 15 years. One focuses on a plant immunity model ("zigzag" model), which predicts that an appropriate mixture of basal immunity and resistance genes could increase the durability of resistance. The second describes an example in rice cultivation of successful use of plant diversity to impart durable resistance to blast. These results show that implementation of diversified immune systems makes it possible to design agroecosystems with durable plant protection and opens up possibilities for other field crops, particularly wheat.

Examples in animal production systems

For animals, we can mention three types of examples.

1. Mobilizing genetic diversity to develop more resilient production systems that can be described as agroecological. In the sheep breeding experiment performed at the La Fage experimental station (Saint-Jean-et-Saint-Paul, Causse du Larzac, France) since the 1970s, multidisciplinary research bringing together genetics, zootechnics, physiology, ethology and ecology has culminated in a fully outdoor suckling sheep production system with high performance in an environment with strong pedoclimatic constraints. Comparing the zootechnical performance of several breeds and genotypes (Romanov, Lacaune, F1) made it possible to develop a herd of Romane ewes on the pastures. This composite breed (a mixture of the complementary Romanov and Berrichon du Cher breeds) exhibits good behavioural and physiological characteristics for adapting to the restrictive environmental conditions. The environment was also studied through long-term monitoring of plant communities (biomass, diversity) and characteristics of species. Introduction of human-managed fertilization was accompanied by a drastic change in the vegetation towards annual species, with an increase in the biomass produced and improvement in the quality of the leaves compared to the unmanaged pasture. Other projects of this type have been set up in hot climates in experimental and partnership contexts, such as in Guadeloupe, where the Creole cattle populations, from mixed breeds, have adapted remarkably to a difficult environment, or even in a context of development aid, with an NGO's dairy cow breeding programme in India, funded by the Bill and Melinda Gates Foundation. In this latter programme, a participatory method is used, and crossbreeding is designed to maintain the dairy cows' capacity to adapt to a hot climate.

2. Combining production under a quality label and maintenance of genetic diversity, as for local sheep breeds (Nozières-Petit and Lauvie, 2018). Bresse chicken was a pioneer in this regard, but its foremost objective has always been product quality; benefits derived from biotic interactions in the farming system remain secondary.

3. Identifying genetic markers linked to traits favourable to the development of agroecological systems. These markers have been incorporated into ongoing breeding programmes but have not yet been used to establish agroecological systems. It is a matter of feed efficiency (feed substitution, reduction in inputs and pollution; projects for ruminants, poultry, or fish) and disease resistance (addition of disease resistance criteria

in breeding programmes, reduction in inputs). In Guadeloupe, original experiments have been combined with genomic approaches to study heat adaptation in pigs and nematode resistance in goats.

Research questions

Two major areas of frontline research have been identified.

Understanding and estimating the genetic component of the variation due to interactions within complex stands

The objective is to develop breeding methods that drive or take advantage of the genetic variability in interactions between species. At this scientific frontier of interactions between plants or between animals, the trait-based approach contributes a functional aspect and opens up the potential to identify plant and animal selection criteria.

Studying relationships between genetic diversity and ecosystem services provided by cropping and/or livestock systems

The issues of concern are the ability of genetic mechanisms to improve ecosystem services; the effective range of diversity and its application in the context of heterogeneous environments in which genetic-environment interactions are key; and identification of plant and animal traits that must or must not be diversified to optimize expected ecosystem services while maintaining production levels.

Associated methodological obstacles

It is a matter of studying the genetics of G × M × E × C × P interactions:

G: genetic variability between individuals (plants, animals, trees) and between populations; M: variability in the microbial environment: intestinal microbiota, leaf, root and soil microbiota[52]; E: variability in the physical environment (climate, water resources, hydrological system, soil distribution, etc.) in connection with agroecosystem functioning; C: how the farm, production system and cropping system are managed, in particular how farmers' choices are modelled; P: variability in raw products from agroecological farms, which questions the paradigm in which processing can achieve everything by eliminating the initial diversity.

52 Plant breeding is becoming interested in augmented phenotypes, animal breeding has begun to identify the microbiota as a new component for predicting performance and the concept of a holobiont (individual + microbiome) is developing.

It is a matter of integrating different levels of diversity into approaches to designing cropping and livestock systems. These systems must be assessed using multi-criteria approaches to connect impacts to the breeding objectives. This implies developing breeding strategies for populations in mixtures of breeds or lines or for use in crossbreeding to better meet the needs of low-input systems. These strategies must be co-constructed with the actors: how should the actors be organized, and for which selection method? How should an adapted genetic resource be defined? These topics call for participatory research.

It is a matter of revisiting processing: using diversity to balance the final product, instead of eliminating the variability by processing that alters the basic material. In other words, can the initial variability not be an asset? Relationships between the initial genetic traits and the quality of the final product need to be better established. As the product is "defined" in the final step before it reaches the consumer, establishing these relationships is a determinant of the acceptability of systems that leverage genetic diversity.

Experimentation and research systems

The methodological approaches in animal or plant genetics align with the leveraging of genetic diversity for agroecology. In contrast, this is less so for "systems" approaches. Although some recent projects recommend returning to crossbreeding for ruminants, genetic diversity is usually not considered a priority parameter in systems experiments, while agroecology is characterized by its systems approach, and genetic diversity is a mechanism to be considered and optimized. The same situation is encountered in economic studies which do not include the dimension of genetic variability in the models developed, usually because the data are lacking. Collaboration between the economic sciences and animal or plant genetics will provide access to data, or at least to knowledge necessary to simulate them in a model.

Special data-acquisition mechanisms are required to address these research questions. Interaction modelling requires not only having suitable methods available and coupling genetic and ecophysiological models, but also collecting a large amount of data by integrating different types of data. Current experimental systems do not provide enough combinations to understand the mechanisms by which genotypes adapt to an agroecological system. Selection in a changing system (environments and species of interest) must involve the downstream better and include crop and livestock farmers in a participatory manner to increase the diversity of the situations available for study. Farm networks and other arrangements co-constructed with actors are necessary to study adaptation. These two levels of data acquisition – data collection in well-known experimental environments (fine phenotyping) and on-farm data collection – must be combined. Modelling interactions within stands is useful, for example with individual-based models that represent individual-to-individual interactions, as well as local selection pressures from neighbouring individuals and from their effects on abiotic parameters. In principal, these models' scale of application should be the field or herd, but this level of integration is still not encountered often, especially in animal genetics, which tends to use models at the population scale for selection.

Under experimental conditions, functional approaches make it possible, in a complementary way, to determine major traits of individuals' responses to environmental conditions (soil, climate, nutrients) and to develop new selection criteria. For example, one way to improve benefits of animal breeding protocols would be to always genotype all animals in systems experiments, using a common genotyping tool, in order to pool data and identify genetic markers associated with greater herd hardiness in different environmental conditions.

Systems experiments contribute to the search for innovation. To date, however, few designs of cropping systems have included the genetic dimension. This design process is also particularly, but not exclusively, complicated by the difficulty in articulating levels of organization from the genome to the community and in relating the systems approach to research focused on a single discipline.

In conclusion, breeding methods in plant and animal genetics benefit from tools that allow for fine monitoring of genetic diversity, which must be leveraged for the benefit of the agroecological transition. The major change brought about by agroecology is to look no longer for an ideal individual, but to seek instead an ideal group for a given production context. This change requires redesigning breeding objectives and breeding schemes, going beyond identification of new selection criteria. This must be done in conjunction with the evolution of cropping or livestock systems to better derive value from genetic diversity. This leaves the question of which genotype to choose at each scale, from the farm to the entire agri-chain, which still needs to be better integrated.

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5. Modelling interactions between living organisms in their environments and socio-economic contexts

Modelling in agroecology remains a challenge for two major reasons. First, agroecology is just emerging in France and is also evolving elsewhere; therefore, the knowledge and body of data that could form its base are still developing and incomplete. Second, it inherently involves modelling complex systems in uncertain environments. These systems are dynamic and host many varied interactions between living organisms. Nevertheless, this modelling is expected to guide and support the transition of agricultural systems. Although modelling in agroecology still struggles to make accurate predictions, it can help explain dynamics of agroecosystems, orient courses of action, identify important points and dead ends, establish warning systems to help manage agroecosystems, and estimate the orders of magnitude of risks and gains induced by the agroecological transition.

Agroecology has the objective of leveraging rich and varied biological processes to boost agricultural production and sustainability. The modelling work undertaken to support this objective is intended to represent and predict these biological processes and their interactions in agroecosystems, possibly coupled with environmental dynamics or social or economic dynamics. These models help represent, partially or totally, the ever-growing body of knowledge about agricultural systems and practices, rural landscapes, biodiversity, and agroecosystems' ecosystem functions and services.

In addition to these models that explicitly represent biodiversity (process-driven models), there exist data-based statistical approaches (data-driven models) that establish relationships between the components of biodiversity and their functions.

Other models, not initially designed for agroecology, can also be resources, for example when the methods implemented are generic enough to be useful for agroecology, or when interactions between organisms are not yet clearly represented, but could be, or are beginning to be, in the form of empirical functions. This is the case of the activity of soil microorganisms and their role in nutrient availability and biogeochemical cycles. They are beginning to be considered explicitly, based on large functional groups.

Recent scientific advances

The field of modelling in agroecology is in full bloom. For example, 107 models were identified at INRAE in 2018 (Monod *et al.*, 2018). These models have contributed to around 400 publications, most of them published recently. Some of them belong to families of models, while others are single models. The scientific community concerned is beginning to organize itself into a few collaborative networks. A survey of the designers of these hundreds of models made it possible to analyse what the models are capable of, as well as their limitations, in the field of agroecology.

Several domains and types of ecological processes represented

Models in agroecology encompass several domains:

- interactions between genetics and the environment;
- relationships among plants, pests and pesticide use;
- crop associations and access to resources (water, nutrients);
- animal health and management of antibiotics and of vector populations (ticks, etc.) in relation to wildlife;
- the farm, its animal production unit and management of its plant resources and herds, considering intra- and inter-herd relationships;
- conservation policies (conservation strategy, relationships between species).

These models are used to study several categories of interactions or ecological functions such as parasitism, predation, competition, facilitation, and decomposition of organic matter. Some models represent the spatio-temporal distribution of populations or "biotic particles" (e.g. microbes, pollen...). Models can be used at different scales: intra-host, population, territory, etc. Some significant examples are:

1. EmuLSion is a generic epidemiology simulation framework (Picault *et al.*, 2017). It uses "state machines" to represent infection processes and animal life cycles and can thus describe sequential systems whose evolution is complex.

2. Biodiversity is explicitly modelled during key phases of biogeochemical cycles, with the representation of microbial functional groups and their role in models of decomposition of soil organic matter (GDM, Cantis, Eezy models; Iqbal *et al.*, 2014; Moorhead *et al.*, 2012, 2014).

3. Esomed (Environment for simulation and optimization of partial differential equation models) is an environment for modelling and simulating population dynamics in realistic landscapes (Roques and Bonnefon, 2016). This environment makes it possible to couple dynamics in two-dimensional fields and one-dimensional landscape elements (hedges, roads, etc.). The environment includes a stochastic generator of fields and land uses.

From agricultural systems to agroecosystem services via biodiversity

Modelling in agroecology is beginning to come into its own. Models are starting to represent the "cascade" that relates agricultural systems and rural landscapes to biodiversity and agroecosystem functions and services. Indeed, biodiversity is now widely represented in models. Almost all of these models are meant to help scientists understand various aspects of agroecological systems. Some models fall within theoretical ecology, while others go so far as to model biodiversity functions and even the resulting ecosystem services. Models designed for targeted research tend to predominate. Relationships with environments or actors are often modelled by an independent module which is connected to the biological module. However, these connections, in particular those that represent dynamics of actors, remain few in number. Integrating dynamic processes that work at different scales remains a challenge for modelling in agroecology, including at the methodological level.

A need to base modelling on field data

More field data are necessary to inform and calibrate models designed for targeted research. While most models are intended to generate and test agroecosystem management scenarios, the number of approaches that go on to forecast, in the sense of predicting short-term changes for reasons of tactical adaptation, remains small. The models more often include a temporal component rather than a spatial one.

The beginnings of probabilistic approaches

A few probabilistic approaches are beginning to see the light of day. Most models in agroecology are based on mathematical equations and incorporate a probabilistic component, which allows uncertainties to be represented or the model to be simplified, by avoiding, for example, the modelling of mechanisms with weak effects. The main advantage of these probabilistic approaches is to make predictions in the form of confidence envelopes, rather than single trajectories.

Some examples

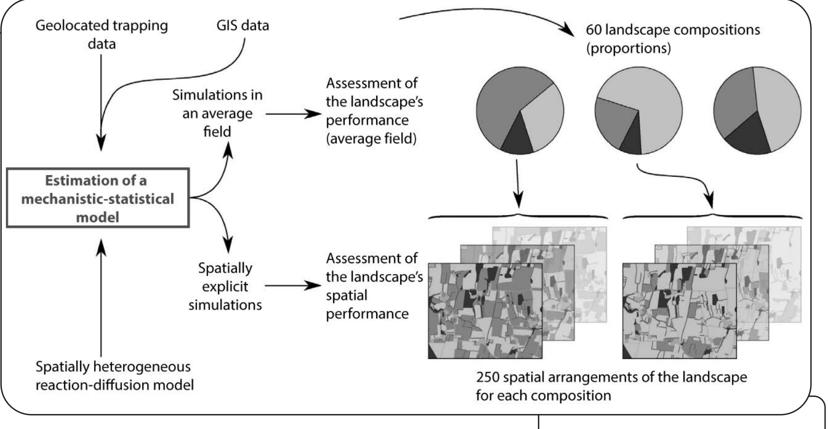
Interdisciplinary scientific facilitation networks on modelling in agroecology

The ModStatSAP[53] network, created in 2011, aims to bring together modellers and statisticians who work on dynamics of host-pathogen or host-pest systems. To this end, for the past seven years, the network has, in particular, maintained a website, a mailing list and a Twitter feed, and organized annual meetings and workshops. These seminars and workshops illustrate how the models contribute to knowledge about epidemic processes and demo-genetic processes (i.e. those pertaining to demographic and evolutionary

53 Modelling and statistics of animal and plant health.

aspects) at the population or landscape scale, and to the management of agroecological systems through, for example, optimizing the use of resistance, land use or monitoring. The study of Parisey *et al.* (2016) (Figure 5) focused on the influence of the spatial arrangement of agricultural landscapes on the presence of beneficial organisms, and corresponds to a typical representation of these encounters.

Figure 5. Simulation of the influence of the spatial arrangement of agricultural landscapes on the presence of beneficial organisms (based on Parisey *et al.*, 2016).



GIS: geographic information system.

Other networks have also been created. The Payote network is interested in modelling agricultural landscapes and studying their impact on propagation phenomena and population dynamics. The EpiArch network focuses on the role of plant architecture in epidemic processes.

Generic models and platforms

FlorSys (for weed flora and cropping system; Colbach *et al.*, 2017) is a model that simulates multiannual dynamics of multi-species weed flora and interactions with cultivated plants in a field islet and semi-natural habitats, while considering cropping systems and pedoclimatic conditions, in order to then simulate impacts of weed flora on agricultural production, biodiversity and the environment. It incorporates several types of interactions (plant-plant, plant-parasite, plant-fungus, plant-predator) and ecosystem services.

The Capsis platform is a generic software platform that provides access to tree growth and mortality models for various architectures, with differing degrees of heterogeneity, pure or in mixtures of species, in temperate, subtropical and tropical zones, and for various types of management (Dufour-Kowalski *et al.*, 2012). This platform, meant primarily for forest management, is also used for tree-based agrosystems (orchards, etc.). It uses a set of mathematical equations which relate dendrometric characteristics of trees (height, diameter, volume, etc.) to the stand that they are part of, their number, and their age, to represent the trees' dynamics as a function of the competition between them.

Research issues

Deficit of scientific knowledge

A major scientific obstacle facing the agroecological modelling research community is the lack of knowledge about interaction mechanisms and their integration into systemic approaches to complex objects such as farms or landscapes. While the elementary models, or "building blocks", that describe each compartment of the system under study separately can be calibrated using data or expert knowledge, it is the connections between these building blocks that are difficult to establish, for example connections of competition, synergy, and predation between biological compartments.

The number of interactions included in most models remains low. For example, current models represent binary interactions between plants and pests or between plants more often than multiple interactions. There are a few exceptions, such as FlorSys, cited above, or Virtual Grassland which simulates dynamics of grassland stands. Another observation is that few studies have focused on interactions between below-ground and above-ground biodiversity.

Methodological difficulties

Outputs of models are often extremely sensitive to the choice of interaction functions between elementary compartments. This sensitivity makes it risky to rely on agroecosystem modelling approaches that simply integrate different building blocks without identifying these interaction functions.

Approaches based on interactions between building blocks must continue to be developed by using more appropriate data, better organizing communities of modellers and experimenters, and making validated building blocks available as soon as possible. At the same time, however, other approaches to complexity must be considered, in particular stochastic approaches, which avoid modelling mechanisms with weak effects, for example by replacing them with a "noise" value to simulate the sum of these effects with a random function. It is also a matter of adding constraints to models, which can limit the amount of data needed, as in mechanistic-statistical approaches (Dusseux *et al.*, 2015; Soubeyrand, 2016; Figure 5). These methods combine a mechanistic model (based on processes and incorporating certain constraints), a probabilistic model that connects processes and data, and a statistical estimation method. Finally, new avenues must be explored, for example those from models calibrated with data from complex interactions, such as remote sensing data.

Scarcity of data on systems in transition

The scarcity of data on systems in transition or on agroecological systems is a fundamental concern. Few experiments have been performed, and few data have been acquired, even though there is an enormous need for them in order to be able to model the large number of interactions in these systems. Modelling ideally requires a large body of varied and medium-term data, across many pedoclimatic and agronomic conditions. One priority is therefore to use observation or experimentation systems better and to develop them so they become more relevant to agroecology. Long-Term Ecological Research[54] sites are especially useful at the landscape and territorial scales. It is also necessary to rely on information from society. Experiments in agroecology set up by the CIVAMs[55], chambers of agriculture and organic farming networks can provide expert knowledge and data on a wide variety of systems. Extensive data on organic farming systems around the world also exist, as shown by meta-analyses of the relative performance of organic farming systems and other systems. However, accessibility of these data is often an issue. Participatory science initiatives can also help enrich observation contexts.

Random and uncertain nature of some processes

Better understanding of and integration into models of the random, uncertain, and sometimes chaotic nature of certain processes are major challenges, especially for processes which interact with abiotic processes, particularly those related to the climate. Methods for analysing risks in agroecological systems or systems in transition to agroecology must be developed. The concept of risk is important to incorporate into predictive modelling approaches; it goes hand in hand with the concept of adaptive management (management which adapts as conditions, constraints and risks are assessed). The concept of risk is often inspired by economics and mathematics literature, for example by the mathematical representation of viability theory. The scientific community must become involved in discussions on the concepts and representation of risk in agroecological systems. The concept of resilience, which reflects a system's capacity to return to a state of equilibrium after climatic shocks or diseases, should also be used more often. It is a matter of determining the ability of agroecological systems to acquire a certain robustness and resilience in the face of climate variability rather than to adapt to an optimum of the best climatic years.

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54 LTER sites (*zones ateliers* in French) are interdisciplinary sites for long-term environmental and ecological research on human-dominated landscapes. See https://inee.cnrs.fr/fr/zones-ateliers.

55 French Centres for Initiative to Promote Agriculture and Rural Areas.

Spatio-temporal dimensions

The temporal dimension is more important in agroecology than in conventional systems due to the importance of interactions between sequential processes, in relation to biotic and abiotic conditions (rotation, carry-over effect, climatic variability, etc.). Consequently, it is necessary to revisit long-term data by considering changes in the acquisition context, which can bias the analysis, and by relying on pattern-oriented modelling approaches, which can identify the time steps characteristic of the processes and the important data that must be acquired. It is just as necessary to strengthen models developed with short-term objectives. Some of these models were developed to generate or compare scenarios, but they are compared relatively rarely to reality or to the short term. Scenario generation, i.e. constructing a relevant story to guide action and then translating it into a "what if?" question so it can be tested by simulation, forms part of this field of research. Research into modelling is continuing for short- and long-term aspects of biocontrol (fundamental approaches, such as demo-genetic modelling of small populations or studying insect dependence on symbiotic organisms); of landscape ecology (biotic regulation, geomatic analysis, epidemiology, regulation of flows of chemical and biological elements); of symbiosis, which still has few benefits for agriculture; and of epidemiology for disease-control strategies.

Combining biotic and abiotic processes

Models that combine biotic and abiotic processes at the landscape scale are starting to be developed in several countries. Another aim is to improve consideration of biotic components in nutrient cycle models (GDM, Eezy, Cantis models), for example in the decomposition of soil organic matter. Increasingly advanced knowledge about microbial communities and their functions represents an opportunity. New areas of research can open up if microbial ecologists work with scientists who represent functions using empirical relationships. Models that represent trophic networks and their dynamics are also lacking. The same is true for models based on biodiversity that simultaneously represent different ecosystem processes and services and their interactions. Many models represent biodiversity explicitly via traits or sometimes ecological guilds[56], with associated functions, without however going as far as the provision of ecosystem services. There are still relatively few multiservice ecosystem models. Significant progress remains to be made to represent the cascade that connects farming practices to biodiversity, and then to ecosystem functions and services. Managing biological invasions, especially in relation to climate change and changes in agricultural and forestry systems, also remains a challenge.

56 An ecological guild defines a set of species that share the same ecological niche.

Multi-criteria assessment of agroecosystem performance and services

Finally, a strong societal demand is to include the agroecological dimension in tools that assess agroecosystem performance and services. Multi-criteria assessment of agricultural systems is based on platforms and tools (MEANS[57] platform and Agribalyse[58] database) that use life cycle assessment approaches and are beginning to consider biotic interactions. The Dexi framework (Bohanec *et al.*, 2008) and tools, such as Masc (Sadok *et al.*, 2009), Dexi-PM (Pelzer *et al.*, 2012) and DexiFruits[59], developed to assess the sustainability of agricultural systems, including agroecological ones, consider biotic interactions, for example in evaluating effects of organic amendments on soil fertility. It is necessary to strengthen this aspect to obtain multi-criteria assessment methods that consider many biotic dimensions by using indicators or even coupling dynamic models.

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57 Multicriteria Assessment of Sustainability. See https://www6.inrae.fr/means_eng/.
58 See https://www.ademe.fr/expertises/produire-autrement/production-agricole/passer-a-laction/dossier/levaluation-environnementale-agriculture/loutil-agribalyser.
59 See http://wiki.inra.fr/wiki/deximasc/DEXiFruits/.

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6. Contribution of agricultural equipment and digital technology to agroecology: considering living organisms better

Several research-orientation studies have addressed the role that agricultural equipment can play in adapting agriculture to new challenges. For example, two studies – "Agriculture and innovation 2025" (Bournigal *et al.*, 2015) and "Agricultural equipment and triple performance: obstacles and mechanisms for the agroecological transition" (Machenaud *et al.*, 2014) – recommend using digital technology and agricultural robotics to improve agriculture's economic, environmental and social performance. The rationale is simple: if, through better knowledge about plant and animal needs, one can control interventions and regulate inputs as finely as possible, the system will become more virtuous. It will be more economical, avoiding unnecessary waste and pollution. It will be more environmentally friendly because it will consume less fossil fuel and generate fewer environmental losses, and more socially fair because it will reduce arduous labour. It will be better suited to each situation's specific characteristics and better able to meet specifications, become part of short supply chains, and meet consumer expectations. These documents look upon technology as a means for progress.

Paradoxically, the ability of agricultural equipment and digital technology to enable and push an agroecological model of agriculture remains a gamble, because these technological developments can also intensify industrialization of agriculture further, in a continuity of 60 years of productivity-driven development. It is therefore necessary to reflect specifically on how agricultural equipment and digital technology can contribute to agroecological approaches. For agroecology to benefit from these technologies, it must provide tools to follow the enhancement of biological activity and derive value from the heterogeneity of environments encountered at different scales. While conventional agriculture seeks to suppress heterogeneities in the pursuit of standardized cropping practices, agroecology aims to take advantage of local conditions to derive more value from them, spread out risks, and leverage complementarities between animals or between crops.

If used properly, technology can be a major source of progress (Bellon-Maurel and Huyghe, 2017), and even one endowed with multiple virtues. However, not all agricultural systems of the world have access to it, not all farmers are equipped with it, and not all possible advances have yet been made. As an illustration of benefits of technology, use of digitally controlled spraying equipment leads to savings in pesticides without reducing effectiveness (Box 6.1). However, while this example falls entirely within the scope of precision agriculture[60], it does not use any specifically agroecological processes.

Box 6.1. Technological control of spraying.

Technological control of mechanized spraying makes it possible to regulate the dose applied as a function of the sprayer's forward speed, to define sections below the area to be treated, with the sprayer automatically matching the height of the nozzle arm(s) to that of the vegetation to avoid areas of double application or gaps. Water and pesticides can be mixed automatically, with standardized caps being screwed and unscrewed on the sprayer without any human involvement. Tachographs record the intervention and pre-populate the computerized follow-up files. Collectors or other mechanisms can better restrict the spraying so that it does not disperse, and anti-drift nozzles decrease losses outside targeted areas. By combining information on the state of vegetation and the detection of pests, the intervention is targeted better on areas known to be at risk of pests and also considers weather conditions. In this way, the application becomes optimal, and thus the doses applied are as low as possible. With some of these technological advances, pesticide use can be reduced by 10-30% without any decrease in effectiveness. It is hard to find any downsides to this trend, especially as most sprayers in use have become obsolete, and more than two-thirds of them are still set to default factory settings, i.e. have not been adapted to local conditions. In addition, it seems difficult to believe that the necessary information and knowledge have not been provided, as all farmers in France have trained for and obtained their "Certiphyto" (e.g. pesticide-application certification) in the past five years.

Thus, discussing agricultural equipment for agroecology makes sense only if the former enriches or facilitates implementation of the latter's principles. We suggest that technology's major role should be to facilitate integration of ambitions from different disciplines. Indeed, agronomy, ecology, management sciences and geography have only just embarked on this technological journey, which has to date been driven mainly by the engineering sciences, algorithmics, robotics, guided geolocation, wireless access to physical sensors, and information aggregation in a system that controls solenoid valves.

Agricultural equipment, and more broadly all that belongs to the category of tools for action (decision support tools, dashboards, forecasts, cartography, etc.), helps with agricultural

60 Precision agriculture is concerned mainly with optimizing essentially external inputs. Agroecology is concerned instead with internalizing them within the system and integrating them into the agroecosystem, thus making it more self-sufficient. It is concerned with their availability, which requires managing flows and rebuilding stocks. It is also concerned with their efficiency, which implies knowledge about their possible functions to ensure their best use.

knowledge-based management and its adoption by as many users as possible. It is therefore clear that the terms “agroecology” and “agricultural equipment” come together only when one can identify methods to encourage adoption of agroecological practices and the management and support tools necessary to do so, by closely monitoring an agroecosystem’s dynamic functioning. This theme therefore refers broadly to information acquisition and processing that enable agriculture to become more sustainable by applying agroecological engineering.

Recent scientific advances

Advances in agricultural equipment and digital technology have not been limited to agriculture in temperate countries or to conventional agriculture. They concern all types of agricultural systems. A technology can be considered to support agroecology when it helps provide information on or direct the processes that underpin the principles of agroecology, such as: making visible and integrating the reality and mechanisms that trigger stimulation of internal defences by plants or animals, as partly advocated by biodynamic cultivation; quantifying natural regulation mechanisms, some of which are highlighted by organic farming; assessing occupation of ecological niches and their preservation, in part recommended by conservation agriculture and agroforestry; taking advantage of complementarities between organisms to reduce competition and create synergies, as advocated by organic farming, biodynamic cultivation, conservation agriculture, etc.; rebuilding stocks and maintaining environmental parameters within a range that respects the environment’s local characteristics and potential, through closing cycles by deriving the most value from biomass, but also by recycling resources and using them parsimoniously and efficiently. Much of this knowledge can be considered only if dedicated agricultural equipment uses it to adjust its action. For example, one can take advantage of complementarities among several plant species in the same field only when mechanical harvesters can harvest a composite stand.

Cognitive challenges of agricultural equipment for agroecology thus concern characterization of an agroecosystem’s functioning; consideration of biological regulation mechanisms; estimation of the potential for processes such as predation; release of fertilizing elements by degradation of soil organic matter; carbon storage capacity; water retention potential (Dobriyal *et al.*, 2012); and mobilization of organisms’ immunity and resilience mechanisms. These processes involve controlling the information-management chain, starting from the collection of information to its final translation into a form that can be used to adjust equipment action, using tools that provide information on the underlying biological processes. More broadly, they involve connections with the upstream and downstream sectors of agriculture concerning the choice of species and varieties, regulated management of heterogeneities, and traceability from production methods to the consumer.

The intersection of digital machinery and agroecology, a space to explore

Only a few hundred publications exist at the intersection of agroecology – and its extension to ecological engineering in agriculture – and agricultural machinery, as represented by tractorization, robotics, imaging, sensors and all mechanical engineering in agriculture. This literature represents less than 0.01% of the corpus of the mechanical sciences. As may be expected, some of these studies focus on weather forecasting and irrigation management. Others concern remote sensing and proxi-detection for characterizing the environment's physical states and the diversity of situations in order to characterize heterogeneities at different scales and monitor effects of compaction on biological activity and soil functioning.

From a methodological viewpoint, emphasis is placed on applying machine-learning techniques to large data sets acquired for pre-existing issues, some of which pertain to matters of agroecological interest. Thus, inserting a mechanization or engineering component at the crossroads of the founding disciplines of agronomy and ecology leads to the involvement of scientific communities which appear to have few common interests. As it is, several scientific studies in agroecology can be described as monodisciplinary. Seen through the tools and management approaches of engineering, agroecology is still adopting disciplinary building blocks rather than developing major interdisciplinary objects itself.

This relative scientific no-man's land contrasts with the many conventions that have advocated rapid implementation of agroecology. Sivakumar *et al.* (2000) analysed them and cite "the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD) and the United Nations Convention to Combat Desertification (UNCCD). [...] The World Food Summit Plan of Action (WFSPA), which was developed in 1996, includes several commitments to make agricultural production sustainable."[61] The flow of conventions has not stopped since, and the FAO is particularly invested in this theme[62] – but without addressing the role that agricultural equipment and digital technologies can play in implementing measures that promote sustainability.

Estimating the potential to use biological regulation mechanisms

Biological regulation mechanisms form one pillar of agroecology. However, it is difficult to qualify the state of these mechanisms or the potential to use them. Currently, to decide whether to intervene, farmers can use traps (connected or not to an information system) to provide early information on a major pest's demographics (for example, using yellow basin traps to quantify beetle attacks or pheromones to capture certain Lepidoptera). However, a large body of scientific literature on predator-prey relationships, their predictability and their cyclical functioning still struggles to translate theoretical knowledge into practices that

61 See https://unfccc.int/; https://www.cbd.int/; https://www.unccd.int/; http://www.fao.org/3/w9990e/w9990e07.htm.
62 See www.fao.org/agroecology/en/.

encourage populations of predatory beneficial organisms to settle. Certain agroecological infrastructure such as hedges can play a role in maintaining beneficial organisms by providing them with "room and board". Some biocontrol actions could consist of quantifying predation potential in real time and connecting it to a potential release of resources that would help maintain predators at high densities. There is currently no set of equipment that can assess the needs of beneficial organisms and then create conditions necessary to release food resources to stabilize their population in a field during periods of scarcity so that they do not leave the field and its surroundings.

Managing heterogeneities, modulating risks

Instead of orienting species and systems towards specialization and unequivocal selection, agroecology promotes variability and diversity as a way to improve the performance of systems in an environment that is less altered by inputs likely to unbalance ecosystems.

There are currently two visions of how heterogeneities should be addressed. In the first, differentiated action is deemed necessary to better absorb heterogeneities, smooth them out and provide the most homogeneous production possible in line with market standards. In the second vision, heterogeneities signify the existence of underlying variation that calls for a differentiated response. Considering heterogeneities calls for adopting an approach that requires the best possible adaptation to each dimension of the gradient observed. In this second vision, considering interactions among genetics × environment × agricultural practices aim, unlike in the first vision, to maintain or even amplify the differentiation observed. This vision is thought to guarantee better risk distribution, less competition between individuals, complementarities, and the capacity for a biological response adapted to environmental conditions. It is almost certain that in the short term, implementation of agroecological practices will mark the end of the paradigm of a homogeneous herd in which all individuals are managed identically and of a single crop of a single variety per field per year. At present, agricultural equipment is just starting to be designed to help manage this local diversity.

Some examples

Visualizing plant and animal "stress"

Agroecology emphasizes the network of interactions among organisms which revolve around cultivated plants or domesticated animals. These interactions positively or negatively modify the health of crops or herds to degrees that can be measured and thus mobilized for agroecological management. While physiologists are continuously improving their knowledge about plants' and animals' differing metabolic pathways for responding to various stresses, there is still no reliable method that can be used routinely and, if possible, in a non-destructive manner to characterize the stress of plants or animals at a given time.

This information is necessary, however, for agricultural equipment to perform precision corrective actions in a localized manner in time and space. Use of such equipment would go beyond the current state of precision farming, as these precision actions would be based on biological information. Already, progress in analysing signals related to nitrogen deficit in plants makes it possible to envision managing fertilization based on the expression of needs by the plants themselves instead of using a predefined fertilization scheme at the start of the season. Continuous sensing of crops' nitrogen needs – such as through the widely disseminated technique of drone mapping of field heterogeneities – already allows for a variety of avenues for optimization. Directly measuring deficiencies in plants would be useful for supplementing an analysis of needs in order to direct fertilization so that plants receive only as much fertiliser as they can absorb and benefit from (Ravier, 2017). Dynamic fertilization control, by replacing a predictive approach, can be considered emblematic of the agroecological dimension because it is based on real-time dynamic information on physiological needs and therefore on expression by living organisms themselves.

In addition, knowledge about the physiological state of crops could substantiate the mechanisms behind certain "unconventional" practices, such as those applied in biodynamics which claim to stimulate natural plant defences, even though the validity of implementing these practices and the conditions that lead to their success have not been formally established.

While there is no doubt that advances are taking place, including in the development of standards, this laboratory progress has yet to be transformed into automated or semi-automated devices or made available to many actors. How can a plant's reversible state of deficiency be measured for dynamic fertilization management? This question constitutes a case study of what should be made available to farmers.

Towards large-scale use of phenotyping tools

Phenotyping is being driven, on the plant side, by the French Phenome project supported by the "Investing for the Future" programme and, on the animal side, by several projects (CASDAR-funded Morpho3D project for morphological phenotyping by 3D imaging, SmartCow and Aquaexcel2020 EU projects). This work is being undertaken by field research units and experimental units to make progress in three major areas of innovation:

- quantification and qualification of the characteristics of robustness, resilience and plasticity that agroecology can mobilize; this is particularly important in animal production to better characterize resilience. This has been studied little to date due to the lack of high-throughput phenotyping. It could explicitly cover all or part of the animal's lifespan, its health and immune system, the state of reserves and their variations with 3D imaging, and its ability to reproduce;
- consideration of heterogeneities within fields and herds, which can be not only characterized, but directed in a differentiated manner;
- one possible consequence of this characterization can be improved resilience in the face of hazards and better connection between farm performance and sustainability;

• rapidly developing genomic prediction of the value of individuals, in cattle production for example. It offers the potential to predict and thus integrate new traits. It consists of amplifying characterization of the desired traits and measuring them in an automated or semi-automated manner over time, which allows them to be integrated and articulated with genomic information collected or modelled elsewhere. By managing individuals in a herd differently, we can not only spread out the risks better, but also reduce competition between individuals by playing on their complementarity. In addition, there should be no negative implications for collection and marketing as long as traceability is enhanced.

Advances in agroecological engineering for indoor cultivation

A number of agroecological engineering techniques are being used for indoor cultivation: managing pests by solarization, traps, releasing beneficial organisms, trap plants, using relay plants, closing vents if clouds of spores appear that risk airborne contamination, using some solar radiation, etc. These engineering practices often require dedicated equipment and cover a gradient of practices that mobilize biodiversity to a greater or lesser extent and are favourable to the environment and health. The FioriMed[63] joint technological unit and a support platform have been created, supplemented by a few smartphone apps (in particular the Di@gnoPlant series of apps, developed in Bordeaux[64], to better identify, know and control plant diseases). One can also note the educational opportunities provided by several UVED[65] modules, in particular EcoHort, "The design of ecologically innovative horticultural systems". In all of these cases, the expertise and know-how provided are, in general, very much oriented by and towards biological functioning. This attitude leads theoretically to more virtuous and sustainable approaches, which use agricultural equipment when necessary. However, the connection to equipment and support tools remains more indirect than direct.

Research questions

Tools and approaches to derive value from biodiversity in its local context

Previous approaches to modernizing agriculture in temperate climates have focused largely on simplifying agricultural management through greater homogenization of plant and animal production units, thus facilitating widespread dissemination of these advances. Approaches to managing agroecological systems, however, are increasingly

63 See https://www.umt-fiorimed.fr/
64 See http://ephytia.inra.fr/fr/C/23654/Veg-Di-g-Applications-web-et-smartphones.
65 *Université virtuelle Environnement et Développement durable* (Virtual University of the Environment and Sustainable Development). See Virtual University of Agroecology (UVAE) at https://www6.inrae.fr/uvae/Ressources-UVAE/Types-de-modules/Ingenierie-agroecologique.

oriented towards deriving value from intraspecific and/or interspecific diversity as a preferred means of increasing the resilience and efficiency of production systems. These production systems can be very productive as long as some biomass is left in place to support biological activity and maintain trophic chains. This agroecological approach also seeks to mobilize the local environment's specific characteristics and properties, relying on them to increase the implemented system's sustainability. This calls for continuous and widespread phenotyping of crops, livestock and major components of the natural biodiversity used to satisfy requirements and to ensure their functions. Many studies currently underway are seeking to better identify these properties and take advantage of this dual source of diversity, both external (the local environment) and internal (what is introduced and managed) (Box 6.2). This requires careful articulation with models to simulate effects of biotic interactions on the phenotypic value in order to help best manage systems (see Chapter 5).

Pilot studies are underway to leverage biodiversity in heterogeneous vegetation covers: agroforestry; plant associations, including those in grasslands and mixed forests; varietal mixtures, etc. Characterizing the resulting properties, such as robustness against various hazards, productivity, and ease of management (such as simple destruction of a cover crop by rolling), often lies at the heart of existing or planned studies. These studies rely on the use of sensors, measurement campaigns and mapping – which perhaps cannot be defined as (agricultural) equipment in the strictest sense – but it is likely that future agricultural equipment will make on-board or embedded use of such diagnostic elements to adjust settings and perform differentiated actions (e.g. selective crop weeding).

Box 6.2. Managing plant diversity at fine scales: importance of densimetric and optical sorting technologies.

Equipping farms or agricultural-equipment cooperatives with sorters that use different densimetric or optical technologies will allow them to use applications that take advantage of agroecological processes. Two key moments in the cropping cycle are of interest: a prophylactic operation before sowing for farm-saved seeds, and post-harvest sorting to achieve the homogeneity standards required by markets and processing technologies. With this type of equipment, it becomes possible to cultivate associations of species and varieties adapted to local conditions on a majority of fields. This type of mixed cropping derives value from biodiversity, limits the risk of epidemics and adapts better to the cropping season's meteorological characteristics. While what will be harvested cannot be controlled when sowing a multi-species mixture, the probability of a successful harvest increases greatly. Several processing sectors, such as for animal feed or beer, have been able to change industrial processes to suit the nature of the raw material being processed. Ultimately, with such sorting capacity, it will become possible to manage the diversity advocated by agroecology while satisfying market expectations and needs for standardization.

Quantifying and deriving value from the ecosystem services of agroecosystems

Quantifying ecosystem services opens up possibilities for "payments for ecosystem services". More generally, improving characterization of the environment in the form of identifying simple measurable quantities that underlie its functioning can contribute to the sustainability of agroecosystems. This quantification will become all the more necessary as incentives shift to depending on the results obtained instead of the adoption of specific practices. Behind the strategy of recognizing the ecosystem services provided by agroecosystems lie the issues of certification of the actions implemented, multi-criteria assessments and internalization of externalities, which are directly related to the choices of targeted agronomic practices. For agroecology to develop, the effectiveness of public policy tools (incentivizing or regulatory) must be measured and, ultimately, the specifications to meet must be framed correctly. Only then can appropriate financial or other recognition take place.

While this domain draws heavily on the objectives of research projects on ecosystem services, it does so from a perspective of measurement and knowledge-based management, and potentially insurance coverage of risks. Here, too, studies focused on measurement and knowledge-based management are rare. It should therefore be a scientific priority to intensify this research, and to make it more visible and more easily usable.

Using the 'perception-action' loop to relate pest assessment to a dynamic action

Different scientific fields must be mobilized to move from assessment to action. Four such fields are traditionally cited: making a measurement, interpreting it, deciding, and performing an action. Each stage can require mobilizing a range of skills, approaches and tools. The scientific communities working on these stages have their own standards, and the ability of their tools to communicate with each other is a major issue. Whether an interpreted observation can lead to an action to perform depends on the metrics used, as the outputs of one stage must be the inputs of the next. As agroecology strives to free agriculture as much as possible from human alteration of the environment and the input of exogenous inputs, the focus must be on the dynamics of ecological processes rather than on absolute states: Is carbon being stocked or destocked? Can the potential of regulation mechanisms be mobilized quickly? Etc. Agroecological processes are inherently dynamic: they pertain to flows of matter and energy, and changes of state. It is therefore necessary to choose suitable quantities to measure, not to report the crossing of thresholds per se, but to provide the value (positive or negative) of a trend, in other words, quantities constructed as trajectories, or at least as differences between situations. As agroecology is built on complex systems that rely heavily on the functionality of interactions between organisms, its metrics target relative measurements, i.e. "deltas". It is clear that much remains to be done from a scientific viewpoint to drive this dynamic approach to agriculture. It is therefore a matter of studying how new technologies – ranging from high-resolution remote sensing to *in situ* sensors – may help characterize the environment and its heterogeneities and of monitoring the trajectories of major biological processes which influence yields, looping of cycles, regulation of water resources in terms of quantity and quality, and dynamics of entry and exit flows.

To satisfy all of these expectations, the "delta" between two points or two dates is more interesting than absolute values, unless the latter lead, via threshold effects, to tipping points of the system's functioning. These issues refer in particular to the need to assess biological activity (Wells *et al.*, 2013) and, more broadly, ecosystem services, which may lead to rules for distributing financial assistance based on the service provided. It is still relatively difficult to predict what type of equipment is necessary to analyse and understand the biological processes that make ecosystem services possible.

The large amount of information to be managed complicates the work of decision-makers if effective tools are not developed to incorporate this information into management systems. The expectations from potential interactions among genetics × environment × practices constitute a true innovative research area in themselves but remain little studied. The inability to make sense of these interactions can call into doubt the production of rich and comprehensive information unless it helps decision-makers. For example, how can information for predicting the genomic performance of animals in adapted individualized breeding schemes be integrated to take advantage of this diversity, and then be done in different environments? How can these flows of dynamic information on different phenotypes and genotypes be combined to decide which operations are the most relevant at fine scales (individuals or small areas)? The question of the value added or provided by interpreting these data, once translated into decision rules, lies at the heart of research issues. Both measurement and knowledge-based management issues can be explored more in depth, but research is needed to shed light on and distinguish between "phenotyping tools" and "knowledge-based management tools".

The issue of access to data, and of rights and obligations for their use, reuse and dissemination, may require recourse to legal expertise to anticipate the difficulties likely to hinder technological developments.

Socio-professional partnerships for different application challenges

The methods that must be mastered can be grouped into five major sectors, which also structure five fields of socio-professional partnerships, whose members remain largely independent.

1. Characterization of the environment, plants or domesticated animals to better direct, analyse and understand the associated processes and actions. The objectives of improving soil fertility and mitigating climate change lie in this field.

2. Information-sharing among territorial actors to adopt the agroecological rationales that are expressed at the supra-farm scale for characterization of epidemiological risk,

matching of supply with demand, and connections with upstream and downstream agricultural sectors.

3. Agricultural equipment for the specific needs of agroecology and its practices (such as seed sorters, selective harvesting, and other equipment to manage hedges or isolated trees).

4. Characterization of responses of organisms for phenotyping and selection purposes. Digital technology will reshape experimentation and observation networks profoundly.

5. Elements of traceability of practices to differentiate through collection, processing and the market. The ambition of developing and disseminating multi-criteria assessment tools for agricultural and food systems all the way to the consumer depends greatly on it.

The "Agriculture and innovation 2025" report (Bournigal *et al.*, 2015) recommended avenues to pursue in these fields. Much of this work could be performed in experimental units, which still have a low degree of digitization and a lack of situations that provide experience in managing dynamic processes, except for digesters and growth chambers. In particular, all performance measurements need to be included to create an attractive business model – something that cannot automatically be taken for granted. The research community can and must help meet this expectation through its possible partnerships.

In addition, the distinction between "measuring to know" and "measuring to direct" embodies major challenges in making effective advances. While we can easily identify and describe soil biological activity using measurements in a dedicated experiment, we do not yet know how to use this knowledge to adjust practices in the field or assess risks of hitting dead ends. Nor do we know how to use it to manipulate corrective factors to increase or decrease the observed dynamics, such as spreading green manure; using the priming effect to initiate mineralization of organic matter in phase with plants' ability to absorb the nutrients released; taking action via physical factors and possibly chemical ones; or modifying microbial communities, microfauna or macrofauna by adding organisms with strong impacts (aeration, increasing drainage, reducing acidification, etc.). A symposium on agronomic innovation recently took stock of these issues.[66] What needs to be used to manage soil microbiota no doubt applies in a similar way to ruminants' intestinal flora. Co-design approaches can be used to find suitable mechanisms that can be used to adjust responses of living organisms. The ability to orient generally complex agroecological systems while keeping their management systems simple will depend on this.

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Conclusions

These six chapters highlight convergences among the challenges that confront agroecology and research into this relatively new and vast field. We observe that the stage of adoption of agroecological principles and their consequences for how research is designed is still not complete. It is also now clear that the dimension of assembling knowledge about agroecology appears to be very interdisciplinary in nature. Indeed, transversal issues have been identified concerning data, models, and tools to (re)design and drive agricultural activities in order to consider direct and delayed effects of the agroecological transition. In any case, skills must be decompartmentalized and aligned to move forward on the six themes developed in this book. To this end, existing skills must be mobilized by bringing them together around agroecological issues, "assemblers" of skills must be found and/or trained, and transversal areas that require strengthening must be identified. Expertise on interactions between genetics and the environment, and between the environment and food systems, must be developed, socio-ecosystems must be conceptualized and analysed, bioeconomic modelling must be performed, etc. In all of these areas, the ambition is to promote a systemic vision. While recruiting and training in agroecology is important, it is essential to further promote involvement of thematic researchers in interdisciplinary approaches at the interfaces between agriculture, the environment and food systems, and between the biotechnical sciences and social sciences.

Diversity and diversification: observe, translate, direct

Agroecological systems, diversity and diversification are associated with each other at different levels: genotypes, reared/cultivated species, intra-field and inter-field scales, lengthening and diversifying rotations, crop management methods, processing systems, food systems, etc. One consequence of this diversity and diversification is the increase in heterogeneity at all levels, down to the qualitative aspects of the agricultural products themselves. A broad research frontier has been identified on this basis: to consider more levels of interaction in breeding and production, and, as a result, accept more diversity in agricultural and food products. The challenge is to take advantage of this diversity, from the initial diversity of raw materials to that of the final food and non-food products, and ensure the satisfaction of end users. This is an opportunity to reflect on the traceability of characteristics of agricultural products and their relation to the practice of combining complementary batches at the time of processing. This heterogeneity of products requires reworking the scope of norms and standards. To date, they have been developed to ensure a level of quality to end users, often through homogenizing products. How can standards now support the agroecological transition in a new way? Labels can translate a societal motivation for improving the environment, managing resources sustainably, or the intrinsic quality of products resulting from agroecological practices. As one can see, standards and labels will henceforth have to encompass different types of principles.

The need to characterize and manage all dimensions of heterogeneity arises from these observations. Some progress has already been made through digital phenotyping of individuals (imaging, sensors), which complements the already digital genotyping (sequencing, databases), characterization of the environment (satellite data, embedded or *in situ* sensors) and development of tools (software, decision support tools, etc.) to support diversified farm management. New types of agricultural equipment can help. Sensors and crop or animal monitoring tools are still used little to help direct agricultural systems, whether agroecological or not. This progress concerns more than the simple acquisition of information. What is important is the ability to maintain processes in dynamic equilibrium, especially by measuring flows.

From massive acquisition of biological data to new types of experiments

A massive amount of new data is required to consider multi-dimensional interactions. It is necessary to improve understanding of agroecosystem dynamics, to scale up experiments and observations, and especially to combine the two. The contributions of digital agriculture, proxi-detection and remote sensing methods, followed by spatio-temporal data analysis (spatial ecology, spatio-temporal statistics, big data approaches, etc.), are essential. The data must rely more on biological sensors and monitoring for the purposes of knowledge and management of systems in order to capture the complexity of agroecological systems, which are by their nature rich in biotic and abiotic interactions. Strengthening multi-criteria assessment is useful to be able to internalize, at the farm level, externalities – such as biodiversity – that are not currently considered.

Experiments can contribute to this by collecting information through instrumentation and digital data acquisition. For example, it would be beneficial to generalize the genotyping of individuals (animals, plants, trees) with a set of common markers defined by species to integrate genetic diversity into protocols designed to test new farming systems, and thus quantify current diversity and compare it among protocols. Most current experiments for the agroecological transition of farms do not yet include the genetic dimension. As a result, the choice of genotypes is generally unavailable or made by default. Experiments could also focus more on characterizing biological interactions by developing, for example, functional approaches that can determine major response traits of individuals to environmental conditions (soils, climates, water conditions, farming practices, etc.).

Experiments will not be enough, however, because they cannot provide enough combinations to test all the levels of interaction identified! Even though innovative and integrative initiatives are being studied, such as those that create experimental agroecological landscapes, variations – even disconnects – will always exist between the practices implemented in experiments and those of a farm's real conditions. New strategies must therefore be designed that combine experiments performed by the research community with other data sources, for example those from networks such as the Dephy farm network, which may make these strategies evolve (types of practices tested, types of data collected, etc.). More research will have to be performed in a participatory manner to take advantage of the knowledge developed within actor networks, created through "actor-driven" or "citizen-driven" societal initiatives. Farm networks and other arrangements co-constructed between the research community and farmers are especially useful for studying the adaptation and transition of agricultural activities. For the genetic selection mentioned above, the breeding industry and farmers must come together to work on a changing system (environment and species of interest).

"Open innovation processes", or living labs, in which citizens, residents and users are considered to be key actors of research and innovation processes, can supplement and support research efforts on agroecological systems-level experiments, or be implemented within "Territories of innovation" projects. Such open and large experiments are increasingly relied upon and developed to: analyse dynamics of knowledge exchanges among experimenters, farmers, and actors of agri-food chains and territories based on a diversity of unique and local experiences; use multi-criteria analysis to highlight strengths and weaknesses of the systems tested, depending on the criteria analysed (agronomic, zootechnical, environmental, economic, social), at different time steps (start and end of the transition, fully stabilized system) and in different contexts (price of inputs and products, economic and climatic hazards, etc.); co-construct indicators and scenarios with partners; produce knowledge beyond the production dimension on what agroecology is, from the viewpoint of managing uncertainty, anticipation, the relationship with the environment and with plant or animal health, etc.

These experiments – regardless of whether they are strictly experimental or pertain to open innovation, or are even a hybrid of the two – often lead to data that are incomplete or obtained from only a few samples. This calls for adapting data analysis methods. Efforts must continue to better acquire and use data that are currently scattered or incompatible. This issue, already recognized in traditional experimental research systems, is even more critical for systems that involve external actors, as data collection for them is a trade-off between the time needed to collect the data and their perception of the data's usefulness for managing their activities.

Large-scale experiments and/or observations in the human and social sciences, pertaining to perceptions, obstacles, mechanisms, and public policies must be made more widespread, and integrated even more from the very start of co-designing actions. For example, research on the multiple functions fulfilled by the landscape remains compartmentalized, with economics and sociology being often absent or integrated downstream of research.

Understanding risk and uncertainty: modelling and sharing of experiences

The agroecological transition involves challenging well-established practices that depend on supplying inputs, but without defining a target, better or dominant system, in advance. This transition thus carries high risk, not only for each farmer but even more so for agri-food chains, which will have to manage a greater diversity of actors, products and risks. There are also consequences for consumers, who can choose to encourage or ignore the diversification of systems through their purchasing behaviour.

Three approaches seem to be essential:
- modelling, to improve the ability to predict dynamics of agricultural systems at different time scales; this modelling must be combined with approaches to address uncertainty in order to better manage new agroecosystems; it should help identify dead ends, risks, and capacities of robustness and resilience;
- collective learning, by sharing experiences and knowledge of various origins, as part of a participatory science approach, to enrich the levels of innovation and their testing under different conditions;
- analysis of the perception and objectification of risk, and support for the risk taker from a socio-economic viewpoint.

Scaling up and changing agri-food organization for agroecology

Agroecology requires considering short-term objectives (a plant's immediate nitrogen requirements, regulation of weeds that are competing with crops, etc.) and medium-term ones (maintenance of soil fertility, inoculum of pests, seed banks, etc.). Because of the principle of reducing the use of inputs, solutions to drastically reduce pest populations that have become too abundant are no longer available in agroecology. Deficits, accumulations, and all other dynamics must be anticipated better by considering both the short and medium terms. In agroecology, the provision of ecosystem services besides the production of biomass alone is also pursued. Agricultural activities are therefore no longer managed according to a "predetermined" plan; they must be managed adaptively. The objectives and decision rules can change as new information becomes available, both in the short term and in the long term, as the state of the "system" varies and by making trade-offs between ecosystem services.

Agroecologically managed systems will depend more on neighbourhood effects and landscape elements than will systems that rely less on ecological processes. An agroecological system's managers must therefore consider spatial scales larger than the field or farm. Farms engaged in agroecology will have resources (grass, compost, etc.) in certain areas of the territory which can be used in other places. Exchanges will be more important. For pathogens, nutrients or pests, it will notably involve thinking at the scale of meta-populations or landscapes. Finally, the actors of collectives (cooperatives) and processing industries are important in the agroecological transition, in particular their coordination within a territory.

These issues of changes of scale are complex because the solutions are specific to a given time and space, and therefore depend greatly on local conditions, which calls for a management framework that is adaptive. Generality in implementing agroecological transitions will not be found in technical solutions, but rather in the frameworks and tools to promote actors' adaptive capacity.

It is also a matter of improving skills in the domain of the circular economy by considering the circularity of material flows, innovative business models to promote the circular economy, and adaptation to local conditions that accompany these circularities and that preserve the environment. Industrial ecology approaches can contribute to this, as can the most recent developments in life cycle assessment on regionalizing calculations of environmental impacts of agricultural and food products. A discussion on agro-logistics, in particular the environmental impacts of transporting products resulting from agroecology, is also necessary.

"Territories of innovation" projects in France are being developed, and their momentum can be used to encourage inter- and transdisciplinary efforts in a context favourable to interactions with actors. For example, four such projects in France address the challenges of agroecology: Dijon's "Sustainable food system of 2030", Nouvelle-Aquitaine's "Economic actors and citizens build responsible and innovative wine-growing territories of tomorrow", the Rennes water authority's "Terres de Sources" quality label, and south Alsace's "Fields of the possible, cities of the future" project. These territorial initiatives should be capitalized upon and used to determine what is general and what is specific. It should be possible to move from these initiatives, which are tied to local conditions and objectives, to other scales.

Outlook

Key research topics have not yet been addressed here, in particular some pertaining to the conditions necessary for scaling up and generalizing agroecological systems.

- As agroecological transitions start to occur in France, Europe, and elsewhere in the world, what will the consequences be for yields, global production, and food availability in terms of quantity and quality, especially in the context of climate change? Agroecological systems will always be more resilient to climate variability. While some of them will be more productive as long as they have sufficient water resources, the viability of many others at larger regional scales of the world remains in question.
- The amount of agricultural labour required will change, reduced by technology in some situations, but no doubt more time consuming in many others. What will the economic and social consequences of this change be, including for the well-being of rural populations?

• Will agroecological transitions result in higher food costs? Will all consumers have the financial resources to buy agroecological products? How can it be made easy for them to do so? Public systems of institutional catering will no doubt support local developments, but wider generalization of the use of these products at national, European and global levels will require research to analyse trajectories, from the local to the global, of agricultural systems, agricultural production, diets, and economic and social consequences.
• Will the agroecological transition of farms, the evolution of agri-food chains and the quantitative and qualitative changes in agricultural production lead to a shift in the locations of production or to reorganizations of national industrial agri-food structures?
• Agroecology uses ecology as a functional driver and guarantor of the resilience and sustainability of the transformation of agricultural and food production systems. What will the interactions be with other expected transitions and their consequences (energy transition, carbon neutrality, contribution to climate change mitigation, preservation of water resources, etc.)? Will there be synergies or, on the contrary, oppositions in certain territories or pedoclimatic situations?
• Many agroecological trajectories are designed locally, at the territorial level, by bringing together local actors, but global reflection is also necessary to think about and anticipate consequences at a planetary scale. What degraded land can be reclaimed? What spaces can become multifunctional or multi-productive (plant and/or animal production, timber, etc.)? Can the agroecological transition engender a new vision of productive spaces, and of agricultural and agri-food production?

In any case, there is no doubt that the research community will be able to address any new issues that agroecology might raise and will be able to embrace a new way of thinking about its activities. Capitalizing on local experiences is necessary to find answers to these broader questions.

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Agroecology was chosen by INRAE as one of its interdisciplinary scientific foresight studies designed to identify research fronts in response to major societal challenges. Eighty researchers drew up an assessment and proposed research avenues for agroecology.

This book summarizes their main conclusions. Agroecology, as a scientific discipline that puts ecology back at the centre of agricultural system design, is now well established. Diversification of living organisms in agroecosystems is a broad objective that is intended to make these systems more robust and resilient. Research in genetics and landscape ecology must be mobilized so that agroecology can use mechanisms from the field to landscape scales. Progress is being made in modelling agroecological systems to better understand the many biotic and abiotic interactions, to predict them, and to begin to manage some of them. Diversification of living organisms in agricultural production (species, varieties, crop rotations, etc.) leads to more varied products. The consequences will be significant on the commodity chains, and more precisely on agri-food systems, from production methods to product consumption. These changes are long-term. The agroecological transition, which is adaptive, co-constructed with all actors, is in itself a research subject, and will rely on experimental devices, farms, and 'Territories of innovation'.

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