Design as a source of renewal in the production of scientific knowledge in crop science

Quentin Toffolini, Marie-Hélène Jeuffroy, Jean-Marc Meynard, Julie Borg, Jérôme Enjalbert, Arnaud Gauffreteau, Isabelle Goldringer, Amélie Lefèvre, Chantal Loyce, Philippe Martin, et al.

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Quentin Toffolini[a, b, c]
Marie-Hélène Jeuffroy[b]
Jean-Marc Meynard[a]
Julie Borg[d]
Jérôme Enjalbert[d]
Arnaud Gauffreteau[b]
Isabelle Goldringer[d]
Amélie Lefèvre[e]
Chantal Loyce[b]
Philippe Martin[a]
Chloé Salembier[a,e]
Véronique Souchère[a]
Muriel Valantin-Morison[b]
Gaëlle Van Frank[d]
Lorène Prost[c]

a Université Paris-Saclay, AgroParisTech, INRAE, UMR SADAPT, 78850 Thiverval-Grignon, France
b Université Paris-Saclay, AgroParisTech, INRAE, UMR Agronomie, 78850 Thiverval-Grignon, France
c Université Paris-Est Marne la Vallée, INRAE, CNRS, ESIEE, UMR LISIS, 77454 Marne-La-Vallée, France
d Université Paris-Saclay, CNRS, AgroParisTech, INRAE, UMR GQE-Le Moulon, 91190 Gif-sur-Yvette, France
e Université Montpellier, INRAE, UE Alénya-Roussillon, 66200 Alénya, France

Abstract

Innovation is central to the strategic orientations of many agronomic research institutes. Little attention has been paid, however, to the links between knowledge production and design processes, defined as processes resulting in the creation of new objects in pursuit of specific goals. Our aim was to analyze the conditions and specificities of the production of scientific knowledge on agro-ecosystems through design processes. Drawing on design theory, we carried out a cross-analysis of nine research projects that included design processes and produced innovative objects (for example blending rules for variety mixtures in low-input crop management routes). These projects were managed by researchers from a range of disciplines (agronomists, geneticists, crop physiologists, and ecologists), and varied in their duration (from three to 15 years) and scale (from plot to landscape). We combined semi-structured interviews with these researchers and the analysis of various documents (scientific papers, PhD theses, technical publications, and research projects or reports). Our findings show that in all case studies, original and general scientific knowledge on agro-ecosystem functioning was produced at various stages throughout the design processes. The originality of this knowledge lies with the new representations that emerged, either of the agro-ecosystem processes at stake, or of farmers' practices. We show that these representations were formed gradually, through successive iterations of both refined formulations of the design target and new knowledge produced, required for its design. Finally, our results highlight the role of confrontation with real-life situations (particularly through agronomic diagnosis or experiments) in the evolution of these representations. Engaging in design processes can thus be seen as a research practice that leads to the production of original knowledge, allowing for a greater diversity of actors' ways of knowing to be taken into account.

Keywords:

innovation, design theory, diagnosis, farmers' practices, agroecology, research management

1 Introduction

In order to achieve the agronomic, economic, social and environmental performance expected of agricultural production, a radical transformation of agricultural systems is required. This calls for innovation, which has become central to the strategic orientations of agricultural research institutes (see for example INRA, 2016; Wageningen University of Research, 2016). Agricultural researchers are being asked to support the in-depth redesign of cultural practices and crop ideotypes (Hill, 2006; Hill and MacRae, 1995), to create agricultural systems that reduce the use of synthetic inputs, provide ecosystem services, ensure the sustainability of agro-ecosystem production and health-related functions, and thus contribute to innovation. Research supporting such redesign has been growing for several years (Bos et al., 2009; Dogliotti et al., 2014; Le Gal et al., 2011; Meynard et al., 2012; Prost et al., 2018; Romera et al., 2020). There has been little emphasis, however, on the design activities and methods used by agricultural researchers as such. The focus is rather on the knowledge gaps that hinder the development of technical alternatives (Duru, 2013; Tomich et al., 2011; Wezel et al., 2014), or the need for a greater diversity of knowledge sources (Doré et al., 2011), including expert or traditional knowledge (Altieri and Toledo, 2005; Francis et al., 2003). Such emphasis is consistent with the widespread idea that innovation ensues from the accumulation of relevant scientific knowledge. This understanding of the relationship between knowledge and innovation is exemplified by the linear scale of the Technology Readiness Levels originally developed by NASA (Mankins, 1995), for instance, defined in INRAE strategic guidance documents as the scale which "*assesses the level of maturity of a technology from research at the laboratory prior to its commercialization or application*". Innovation is thus seen as an *a posteriori* way of valorizing the scientific knowledge produced. In this article, we support a contrary perspective: innovation can also be seen as a way of generating scientific knowledge, specifically through the design stage of innovation. Here, design is defined as the process whereby a new object is shaped in pursuit of new goals, that is, the process whereby its identity is defined: what it will be, what it will do, or what it will make possible. A number of crop science publications have studied the knowledge that supports these agronomic design processes from the perspective of its nature, sources, general applicability and objects (Berthet et al., 2015; Duru et al., 2015; Toffolini et al., 2017). Yet little consideration has been given to the scientific knowledge that is generated during design, which is what we set out to study in this article. We thus analyze several design processes, in which agricultural researchers were involved, to answer the following question: *to what extent, and in what way, do design processes produce original scientific knowledge about agricultural systems?* To this end, we first explain our theoretical framework, followed by a presentation of our methodological approach to select and analyze nine case studies. We then present and discuss the results of our cross-analysis, emphasizing the connections between the design process and the scientific knowledge produced, and explaining the originality of that knowledge.

2 Theoretical framework

Largely studied within the Design Research community (see for instance Bayazit, 2004; Cross, 2007; Dorst, 2008; Papalambros, 2015; Vial, 2015), design is a process through which new objects are created to attain goals (Simon, 1969). It is thus a finalized process which pursues an "intention for the future" (Béguin et al., 2011). Design processes are specific insofar as the design problem to be solved is not clearly formulated at the start of the process. This problem's formulation will be gradually specified as design solutions are imagined and tested (e.g. Dorst and Cross, 2001). Designers therefore build their own representations of the design problem, which evolve as the problem is being solved and new objects are being designed. Based on these principles, design processes can be described in terms of their *initial design target* - which includes the initial intentions of the designers and the types of actions they target to implement - , a *cognitive reasoning* making evolve the formulations of the design target through the processes, and their final *outcomes*. Schön and Wiggins (1992) complete this analytical framework by conceptualizing design as a "*reflective conversation with the materials of a design situation*". According to these authors, the designer cannot imagine all the properties of an object before putting it into action: implementing a prototype, for instance, makes it possible to learn about some of its properties, and thus to manage the complexity of the object during its emergence. As a consequence, the design of an object is fed in and through the action in which the object takes place.

These different elements (initial design targets, outcomes, cognitive reasoning and actions featuring the object) will constitute our framework to describe our design case studies.

Research on design has also shown the existence of close links between design and knowledge. During the design process, designers use knowledge, particularly through analogies and abductions that are known tools for them to transfer knowledge from past projects to new ones by revisiting past solutions or problem formulations (see for example Bonnardel, 2000; Roozenburg, 1993). But design also involves the production of new knowledge (Eekels and Roozenburg, 1991; Glanville, 1999; Hatchuel and Weil, 2009; Owen, 1998). When designers imagine solutions to solve the problem they formulated, they often identify missing knowledge, leading to a dedicated knowledge production phase, which will in turn transform their representation of the design problem to solve. C-K (Concept-Knowledge) design theory thus represents design reasoning as the coevolution, through constant dialogue, of a space of 'concepts' in which an object that does not yet exist emerges through the gradual definition of its properties, and a space of 'knowledge', including what we know and what we learn (Hatchuel and Weil, 2009). In this article, we will propose to analyze the production of scientific knowledge regarding design processes by tracing the interactions between three moving spaces over time: the representations that designers have of the problem to be solved, the successive formulations of the design targets, and the outcomes of the design process.

3 Materials and methods

3.1 Choice of the case studies

The nine case studies were selected from design projects in the crop sciences (agronomy, population genetics, applied ecology). The case selection was based on two criteria guided by the theoretical framework: (i) all the projects were driven by an ambition to innovate exemplified by an explicit design target, and all ultimately resulted in the design of new objects (for example crop management routes, cropping systems, cultivar mixtures, decision support tools, and spatial organizations of agricultural landscapes – see Table 1); and (ii) all the projects produced scientific knowledge, as evidenced by *publications* in peer-review scientific journals or conference proceedings (Table 1). Publications provided a starting point for the case study analysis, for an in-depth description of the diversity of scientific knowledge produced. Moreover, in order to easily collect information about project management from one or more of the main actors involved, we only selected case studies with a deep involvement of researchers engaged in methodological reflection on design in agrifood systems as part of the IDEAS collective network (INRAE-AgroParisTech). This paper is a product of the IDEAS network, and its content was elaborated and debated within that network.

The case studies were not selected to be representative of current innovation projects. Rather, we aimed to cover a wider diversity of design processes, in several respects. The nine case studies thus vary in terms of (Table 1):

(i) the duration of the design process (ranging from three to 15 years), whether still in progress or completed: the oldest cases offer retrospective insight into all the knowledge produced relating to design, while the most recent ones and those still in progress provide a more detailed understanding of the most decisive aspects of the design process);

(ii) the actions which the object designed is supposed to transform (mostly farmers' practices, for example fertilization, varietal choice, and crop management); and

(iii) their spatial scale, ranging between a field, a farm, a landscape mosaic, a watershed or a breeding network. Some of the case studies involved researchers with a strong commitment to studying the valorization of agro-ecosystem regulations within the field of agroecology (Altieri and Toledo, 2005), for example looking at pollen beetle control with auxiliaries, vegetable intercropping, or participatory breeding. Others aimed to optimize input applications, which may be relevant for all types of agriculture, (such as "Double density strips", "NNI trajectories", and "Miscanthus", see section 3.3). All these case studies were carried out with non-research partners: farmers, agricultural advisers, engineers from advisory services, or applied research organizations.

3.2 Case study analysis methods

The case study approach was inductive and instrumental: "inductive" insofar as assumptions about the links between scientific knowledge production and design emerged from the exploration of the cases, and "instrumental" (Stake, 1994) in that the study was based on analyses moving back and forth between the exploration of each case and a cross-analysis of all cases. Hence, in each case, we retraced the design process from its outcomes back to the initial design target, and identified the scientific knowledge produced throughout the process. Semi-structured interviews with the researchers carrying out the research in each case study were held by the primary author of this article, who then combined or supplemented the information collected with an analysis of articles published in refereed journals, conference proceedings, research project reports, and PhD theses. All the researchers interviewed validated the accuracy of the analysis of their case study.

The following questions guided the interviews: what design target did you have at the start of the project, and how did it evolve? What knowledge was used during the design process? What scientific knowledge has been produced? In what way is this knowledge original, specifically with regard to the scientific disciplines in which it is embedded? At which stage of the design process was this knowledge produced? In relation to which question, and which experimental configurations? The interviews were transcribed and coded according to different categories:

1. the resources available and mobilized during the design process (stabilized knowledge, data, existing experimental arrangements);
2. the successive formulations of the design target that guided the production of new knowledge;
3. the concrete research practices mobilized, that is, the tools applied to produce data, analyze it, or test the knowledge produced (for example experimental or research frameworks, modelling, agronomic diagnosis, or prototype testing);
4. the agricultural situations targeted by the design processes, in other words the agronomic and ecological characteristics of farmers' contexts, the decisions at stake, and the constraints (technical, organizational) encountered in the implementation of solutions, as well as the representations that farmers have of the effect of their actions (Cerf et al., 2012).

Table 1: Description of the case studies and selection criteria.

3.3 Description of the case studies

We here briefly introduce each case study, focusing on the knowledge produced and the resulting innovations. These final outcomes of the design processes are summarized in Table 1, with each case referred to, using a short name provided in the titles below in brackets.

3.3.1 Case 1. A double density strip to maximize the Nitrogen Use Efficiency of wheat (Double density strip)

In the late 1990s, nitrogen fertilization of wheat required measuring soil inorganic N after winter, which is impossible in stony soils. The initial design target, defined by the advisory services of the main regions concerned, was a method to calculate N fertilization rate that did not require any measurement of soil mineral nitrogen. Researchers proposed a new equation to calculate the fertilizer rate to apply, based on nitrogen uptake in an unfertilized control case and the Nitrogen Use Efficiency (NUE) of the fertilizer applied (Meynard et al., 1997). In order to better understand the sources of variation of NUE, a large experimental network of farm plots was then set up by advisors and researchers: NUE appeared to be strongly correlated with the wheat's growth rate at the time of N application. A ^{15}N tracing of the fertilizer explained NUE variations through gaseous losses. This new knowledge opened the door for innovation surrounding the date of fertilizer application: to maximize fertilizer NUE, the recommendation was made to fertilize plants during a stage of high growth, thus delaying the application dates. An indicator (the yellowing of a more densely sown area, called a double density strip) was formulated to trigger fertilizer application.

3.3.2 Case 2. Wheat Nitrogen fertilization based on Nitrogen Nutrition Index trajectories (NNI trajectories)

The Balance Sheet method (Meynard et al., 1997; Rémy and Hébert, 1977), widely used in France for 40 years to manage N fertilization of wheat, does not prevent over-fertilization and pollution. The initial design target was a method for managing N fertilization, to replace the Balance Sheet method while also reducing N fertilization rates and maximizing NUE. A diagnosis of the Balance Sheet implementation, carried out by agricultural researchers in 2015, revealed that the estimation of crop requirement based on a target yield was a major source of error. Through design workshops involving scientists, experts and advisors, the new design target was formulated: an alternative fertilization method, based on the monitoring of the nitrogen nutrition status of the crop using the Nitrogen Nutrition Index (NNI). To explore this strategy, an NNI minimum trajectory was identified by re-analyzing available datasets, distinguishing between situations without yield loss despite N deficiency (above the trajectory), and those with yield loss (below the trajectory). A new fertilization method was thus developed, based on the real-time monitoring of NNI and a calculation of N inputs to avoid NNI values below the minimum trajectory.

3.3.3 Case 3. Nitrogen fertilization of rapeseed, accounting for N loss through frozen leaves (Frozen leaves)

The initial design target of the project, which began in 1996, was a crop management route for winter rapeseed, based on a sowing date realized one month earlier than in current management routes, in order to take advantage of the plant's ability to uptake large N amounts at the start of the cycle, thus limiting N loss through leaching, and highly competing with weeds. Trials, both in experimental stations and on farms, confirmed a large N uptake in autumn, but also showed that in some situations, a very large part of this nitrogen was lost during the winter due to leaves falling following frosts. This revealed a lack of knowledge about what happens to the N contained in frozen leaves. An experiment at an experimental station, combining incubations (to estimate the mineralization rate) and isotopic tracing of N in frozen leaves (partly absorbed after the frozen leaves' mineralization), produced new knowledge on the dynamics of nitrogen mineralization and reabsorption. It ultimately made it possible to account for the role played by frozen leaves, thanks to a method to calculate spring N fertilization of rapeseed, applicable with any sowing date and quantity of frozen leaves.

3.3.4 Case 4. Rules for creating wheat variety mixtures in various agricultural contexts (Variety mixtures)

The project, launched in 2014, focused on variety mixtures, the genetic diversity of which supports disease control and production stability. The initial design target was rules for creating variety mixtures. During the design workshops, attended by agricultural advisors, farmers, and researchers from various disciplines (agronomy, genetics, phytopathology), strategies were formulated for creating mixtures and defining the associated blending rules. A new hypothesis emerged on the diversity of heights and disease resistance among cultivars to combine in order to control the spread of airborne diseases in mixtures. This hypothesis was tested in a crop physiology PhD thesis that highlighted mechanisms for mitigating the spread of airborne diseases in cultivar mixtures with large height gradients. Moreover, a diagnosis of the implementation of variety mixtures on farms showed that farmers used mixtures either to stabilize production or to simplify their crop management. This led researchers to redefine their representation of farmers' practices, and to shift the formulation of blending rules to objectives other than productivity. A multi-criteria assessment tool for cultivar mixtures was then designed to provide support for choosing cultivars to be mixed. It combined blending rules for disease control, for stabilizing production, and for simplifying crop management.

3.3.5 Case 5. A risk indicator of the potential damage to rapeseed by beetles, allowing for the management of cropping system mosaics (Pollen beetles)

As in Case 3, the initial design target of this project launched in 2007 was a low-input rapeseed management route. An agronomic diagnosis performed by agricultural researchers revealed limiting factors, including pollen beetles that lay eggs in flower buds. In this diagnosis, the abundance of pollen beetles on a farm plot appeared to be linked more to the surrounding landscape than to the management of the rapeseed on the plot. The design target thus moved from the scale of the plot to that of the landscape, in which natural habitats, semi-natural elements and plot margins, as well as cropping systems, impact pollen beetles and their natural enemies. A landscape indicator was produced to anticipate the pollen beetle pressure that would not be regulated by natural enemies, also highlighting a critical need for knowledge about the dispersal distance of pollen beetles. The agronomists proposed to use this indicator for the landscape management of pollen beetle pressure.

3.3.6 Case 6. Cropping systems involving miscanthus and reducing net greenhouse gas emissions (Miscanthus)

The initial design target of the project, which began in 2009 and involved agricultural scientists, advisors and R&D organizations from the Burgundy region, was environmentally efficient cropping systems involving energy crops. It started with an on-farm diagnosis, which identified a greater variability of miscanthus yields than that observed at experimental stations. The year-to-year yield evolution of this long-cycle crop (15 to 20 years) was not known, as the miscanthus in the study area was grown since recently. The yield dynamics on a multi-year scale, as well as their sensitivity to local contexts, were then modeled on the basis of yields measured on farm plots over the first two years of production, within the study region, and on the basis of data from long-term trials in various locations across Europe. This new knowledge on yield variability and its dynamics over the growing period were then mobilized in a series of design workshops that brought together researchers, advisors, local experts and farmers. These workshops made it possible to design innovative cropping systems involving energy crops. They also identified the need for better knowledge on nitrogen loss under a miscanthus crop.

3.3.7 Case 7. Watershed-wide practice layouts to reduce erosive runoff (Erosive runoff)

In the project, launched in 1988, the initial design target was cropping systems and their organization to limit erosive runoff in silty watersheds in the Haute-Normandie region. A first field diagnosis showed the influence of tillage (tillage direction, dead furrows, dirt tracks, ditches) on the evolution of the soil structure under the effect of rainfall and runoff. The research team developed a spatially explicit model (STREAM) (Souchère et al., 2002) simulating the impacts, on each plot, of soil tillage on soil surface structures and, at watershed level, the effect of land use and soil tillage on the quantities of runoff and soil removed at the outlet of the watershed, after every rain. A first implementation of this model with farmers and advisors showed the need to integrate leeway for farmers into proposals to change practices, so as to accommodate their work organization constraints. Thus, at the end of the project, the research team proposed guidelines to the farmers to avoid situations conducive to erosive runoff as well as an erosion risk indicator, rather than rigid rules for the spatial arrangement and management of crops.

3.3.8 Case 8. Intercropping vegetables in organic systems and for short value chains (Vegetable intercropping)

In 2013, a system experiment was set up at a research station to design, test and assess an organic market gardening cropping system catering to short circuits, which made it possible to manage crop health through natural regulations (initial design target). The desire to promote natural pest regulation with intercropping raised the question of the choice of vegetable species, their spatial arrangement, and their management (trellising, irrigation, duration of cultivation). During the first years of the experiment, strong unforeseen interactions appeared between the techniques applied to different species within the tunnel, both in space (for example between trellising, species shading and barrier effects on pests) and in time (between the uprooting dates of the different species and pest flows, for instance). New knowledge was then produced around these interactions. The experiment, combined with participatory workshops and an analysis of farmers' practices, made it possible to gradually design an intercrop and management rules for pest and disease regulation that optimized the use of space by the different species.

3.3.9 Case 9. A collective setting for participatory wheat breeding (Participatory breeding)

In the early 2000s, geneticists familiar with singular situations where farmers cultivate old varieties or even crossbreed them wished to evaluate the contribution of these practices to the maintenance of genetic diversity, and to co-design a participatory wheat breeding scheme with farmers (initial design target). A diagnosis of practices raised the question of the consequences of multiple seed exchanges on genetic diversity. A database was produced with farmers in order to monitor the seed exchanges. The project studied the impact of these exchanges and of the mass selection, which made it possible to produce an indicator of intra-varietal diversity. The knowledge produced on the adaptation of population varieties to different farms supported the design and implementation of a method for participatory breeding that combined (i) a database on seed exchanges and performance in various environments, (ii) a network of on-farm trials with shared protocols, and (iii) a method to compare population varieties.

4 Results and discussion

4.1 The diversity of outcomes produced during the design processes

The design processes analyzed led to diverse outcomes (Table 1). In several cases, these outcomes combined both a set of innovative practices (for example fertilization strategies in the "Double density strip" and "NNI trajectories" cases; crop management routes, cropping systems and spatial arrangements of crops in the "Frozen leaves", "Miscanthus" and "Erosive runoff" cases respectively), and a tool focused on one specific decision-making aspect (for instance, indicators that trigger fertilization in the "Double density strip" and "NNI trajectories" cases). Some outcomes were decision-making rules focused on adapting modalities of action to singular agricultural and ecological contexts. These included a calculation method for spring fertilization of rapeseed, which accounted for autumn crop N uptake ("Frozen leaves" case), rules for blending varieties according to the pressure of dominant diseases ("Variety mixtures" case), rules for crop arrangement in space, and landscape management rules ("Pollen beetles" and "Vegetable intercropping" cases). Other outcomes were however more removed from farmers' practices, for instance new ways of describing agro-ecosystems (such as the indicator linking a quantity of water – runoff – to a quantity of sediment – erosion – in the "Erosive runoff" case; and the indicator of cultivated genetic diversity including intra-varietal diversity in the "Participatory breeding" case).

4.2 Knowledge on agro-ecosystems generated during design

Table 2 shows that none of the outcomes designed resulted exclusively from the application of pre-existing knowledge: all the design processes studied provided an opportunity to generate scientific knowledge regarding agro-ecosystems, and this knowledge was often necessary for further design. For instance, the quantity of mineralized N from frozen rapeseed leaves that is reabsorbed in the spring allowed to calculate N inputs in spring in the "Frozen leaves" case, or the dispersion distance of pollen beetles was determined to develop the landscape indicator for natural regulation efficiency in the "Pollen beetles" case.

Three types of knowledge on agro-ecosystems were generated during the design processes, which are identified in the third column of Table 2:

i) Biological or physical processes involved in the agro-ecosystem (in all case studies, for example N gaseous losses explaining ^{15}N Fertilizer Use Efficiency variations in the "Double density strip" case; the dispersion distances of pollen beetles in the "Pollen beetles" case; and the effect of height diversity across susceptible and resistant varieties on airborne diseases spread in the "Variety mixtures" case);

ii) Effects of technical actions on the agro-ecosystem, particularly with regard to biophysical processes that were not expected to be impacted (in six of the nine cases, for instance the impact of mass selection on genetic diversity and the adaptation of population varieties in the "Participatory breeding" case; the effects of miscanthus planting practices on the evolution of yields over time in the "Miscanthus" case; and the effects of the arrangement of vegetable species within a tunnel on pest insect populations in the "Vegetables intercropping" case);

iii) Systemic modeling of key physical or biological processes to steer action (in six of the nine cases; for example modeling the direction of water flow at any point on a plot as a function of tillage direction and field slope in the "Erosive runoff" case; modeling the relationship between NNI trajectory and wheat yield in the "NNI trajectories" case; and modeling the amount of N mineralized by rapeseed leaves that is reabsorbed by the rapeseed crop in the "Frozen leaves" case).

The production of knowledge, observed throughout the design process in all case studies, echoes the findings of the Design Sciences in various domains, as described in the Theoretical Framework section. Whereas, in our case studies, the design targets often addressed a narrow, even local innovation niche (for example stony soils in Case 1, low-input rapeseed in Cases 3 and 5, vegetables for short value chains in Case 8, and a participatory breeding scheme for a few groups of farmers in Case 9), at least part of the knowledge produced was reasonably general, as evidenced by its publication in international scientific journals (Table 1). In other words, even if the outcomes of design processes themselves were not always generalizable beyond the contexts in which they were produced, the way design processes led researchers to explore the reality at stake could produce general knowledge about agro-ecosystem entities and processes.

Far from just supporting design, the knowledge generated through design processes also contributed to further research. In the older "Frozen leaves" case, the longer timespan since the publication of the knowledge produced allows us to see that the knowledge produced during the design process was largely reused in academic research. The article by Dejoux et al. (2000) on nitrogen mineralization of frozen leaves has been cited 42 times (according to the Web Of Science databases) in articles also studying crop management routes, including, for instance, the use of companion crops and new fertilization strategies (N=10, in journals such as *Agronomy for Sustainable Development* and *Field Crops Research*), Nitrogen Use Efficiency and associated mechanisms (N=13), plant biology (N=13, concerning proteomics, flows and reserves, in journals such as *Journal of Experimental Botany* and *Plant Biology*), the mineralization of organic waste material N in soils (N=4), and winter GHG emissions (N=2, in journals such as *Plant and Soil* and *Plant Biology*). Similarly, the article by Rusch et al. (2013) describing the effect of landscape and cultural practices on pollen beetle populations ("Pollen beetles" case) has been cited 30 times in studies of the landscape impacts of pollen beetle populations (N=11, in *Agriculture Ecosystems Environment* and *Biological conservation*) or other pest species (N=11), as well as more general articles on the implementation of agroecological farming systems (N=5, in journals such as *Agronomy for Sustainable Development*) and entomology articles (for instance in *Biocontrol* and *PLOS One*) discussing concepts of spatial scale integration (N=3).

Moreover, some of the articles written by the agricultural researchers involved in our case studies underscored how the design processes shed light on areas of knowledge that needed to be explored. For example, Borg et al. (2017) pointed to the scarcity of work on varietal mixtures considering traits other than yield, such as grain quality, and indicated that ecological mechanisms of interaction between varieties could be explored in more detail by covering a range of varietal traits, partly discussed during the participatory workshops ("Variety mixtures" case). In the "Double density strip" case, Limaux et al. (1999) proposed research topics to explain the influence of wheat growth on Nitrogen Use Efficiency, and on the reduction of gaseous losses: "*The increase in crop height (...) may significantly modify physical conditions at the soil surface, for volatilisation particularly, by reducing wind speed just above the soil surface, reducing N infiltration due to increased drying of the topsoil, and increasing leaf absorption of volatilised NH3*".

Table 2: Knowledge generated during the design processes, and forms of originality of the representations on which they are based.

4.3 Originality of the knowledge generated during design

We analyzed the originality of the knowledge generated through design processes both by reviewing the articles in which this knowledge was published, and by exploring the expertise of the agricultural researchers interviewed. The nine case studies allowed us to identify two main forms of originality (Table 2), depending on whether the new knowledge *i*) relates to original agricultural objects, and thus offers new ways of representing processes within the agro-ecosystem, or *ii*) pertains to forms of farmer action that were not previously taken into consideration by agricultural researchers.

A renewal in the way agricultural researchers represent certain processes within agro-ecosystems. The knowledge produced often relates to new objects (that is, objects not intentionally studied as such previously), identified as determinants for the action targeted by the design ("Frozen leaves", "Variety mixtures", "Erosive runoff", "Vegetable intercropping" and "Participatory breeding" cases; Table 2). For instance, frozen rapeseed leaves were not traditionally studied in connection with plant development or the nitrogen cycle. In their review of literature, Dejoux et al. (2000) identify the objects more conventionally taken into account in the estimation of soil nitrogen supply for rapeseed as being the residues from the previous crop, and the burial of intermediate crops. In the "Vegetable intercropping" case, the intercrop targeting crop health led to use new criteria beyond those usually studied ("*The intercrop is usually described in terms of the choice of species and, in certain cases, by their spatial arrangement*" (Salembier et al., 2015)), in order to also consider different techniques which determine the effect of the mixture on pests and their natural enemies (for example trellising, planting and the uprooting dates of each species).

In several cases, the originality mainly pertained to the connections between objects conventionally considered independently of one another ("Double density strip", "Pollen beetles" and "Miscanthus" cases; Table 2). Here, while the objects may not have been inherently original, the design processes led to them being analyzed as part of a same system. For instance, in the "Pollen beetles" case, the landscape representation that was adopted to qualify the abundance factors of pollen beetles integrated both practices on the plot (not taken into account by landscape ecology, see Vasseur et al., 2013), and semi-natural elements of the landscape (not traditionally considered in agronomy).

A renewal in the farmer practices considered by agricultural researchers. The knowledge generated can pertain to new representations that agricultural researchers form of farmers' actions ("Erosive runoff" and "Participatory breeding" cases; Table 2). The direction of tillage in the "Erosive runoff" case is a typical example. In studies of runoff as a function of surface structures, the physical parameters traditionally taken into account in pedologists' and hydrologists' models (for example roughness, top-soil texture, etc.) do not account for the link between these parameters, on the one hand, and temporary tillage effects (dead furrows, dirt tracks and ditches, for instance) and direction on the other. By contrast, within the design process targeting watershed crop management consistency, the direction of tillage became a key variable, both in the STREAM model (Cerdan et al., 2002; Souchère et al., 2002) and in the analysis by Joannon et al. (2006) of changes in surface conditions during a cropping campaign. In the "Participatory breeding" case, the early identification of the amount of seed exchange (a new consideration for scientists as regards farmers' practices) during farmers' selection process led to changes in the scientists' representation of population varieties and to the modeling of cultivated genetic diversity dynamics. In other cases, although researchers did not identify possible new farmer practices, they had to pay specific attention to the dynamics of indicators supporting action ("Double density strip", "NNI trajectories", "Erosive runoff", and "Vegetables intercropping" cases; Table 2). In the "NNI trajectories" case, wheat tolerance to temporary nitrogen deficiencies was modeled based on a minimum NNI trajectory: provided that NNI remains above this trajectory from tillering to flowering, N deficiency has no detrimental impact on crop production. This dynamic formalism was preferable, for understanding fertilizer inputs in real time, to that which previously prevailed, proposed by Jeuffroy and Bouchard (1999), which was based on a static indicator (although involving the same types of datasets) combining the intensity and duration of deficiency periods *a posteriori*. Similarly, in the "Vegetable intercropping" case, the transfer of pests and natural enemies between crops observed within the intercrop led to increased interest in the characteristics of the intercropped species and of their management driving the dynamics of insect populations' evolution and movement, something that was not self-evident at the start of the project.

The design process thus contributes to renewing scientists' approach to the agro-ecosystem and to farmers' capacities for action. The dynamics of expansion of the knowledge space, linked to the design process (Hatchuel and Weil, 2002), here appears as a source for crop scientists to broaden their areas of interest, and to shift their attention towards new objects or dynamics within the systems under study. Tittonel (2014) makes the same point in a discussion on the paradigm change associated with the development of technical solutions grounded in natural regulations, arguing that "*classical agronomy and agroecology differ (…) in the way they deal with principles such as diversity, dynamics and scaling*".

4.4 Interactions over time between knowledge production and the evolution of the design target

The analysis of the dynamics of design processes in the case studies shows that knowledge production evolved hand in hand with the formulation of the design target, and with representations of agro-ecosystem processes.

The "Pollen beetle" case (Figure 1) offers a good illustration. The initial design target was a low-input crop management route for rapeseed (first formulation of the design target, noted T1). This target was consistent with a representation of the agro-ecosystem limited to the plot (first representation, noted R1). An agronomic diagnosis, conducted to identify factors limiting plot production, highlighted the predominant role of insect pests and particularly pollen beetles (first knowledge produced, noted K1). The agronomic diagnosis showed that the populations of these insects were not dependent on crop management, but were particularly abundant in plots near forests. The diagnosis thus led to a change in the scale considered (the landscape) and to a renewal of the representation of the agro-ecosystem (R2). This then led to the formulation of a new design target: a landscape indicator to assess the probability that the pollen beetle population would not be regulated by the parasitoids (T2). A spatially explicit model was produced on the basis of the knowledge acquired, and identified the dispersion distance of pollen beetles and natural enemies as a major variable impacting the model's sensitivity. This resulted in a new formulation of the knowledge needed: what are the precise dispersal distances based on the phases of the cycle, the spatialized distributions and abundances, and the resources and habitats of pollen beetles (K3)? The design target, which reflects the action targeted by the design, evolved to take into account the new spatial scale, and included crop arrangement at landscape level (T3).

Figure 1: An example of the co-evolution of the design target, knowledge needs and representations of processes of interest in the agro-ecosystems at stake. Case 5: "Pollen beetles".

Similar evolutions were observed in all case studies (Figure 3). The initial formulations of design targets consisted of crop management routes, cropping systems, and crop or variety arrangements. From these generic formulations, the design targets were further specified over the course of the design process, mainly in connection with more elementary actions (for example spring nitrogen fertilization for a rapeseed management route based on early sowing in the "Frozen leaves" case; and crop arrangements and their trellises in the "Vegetable intercropping" case) (Figure 3). As Béguin (2011) points out, "*the desirable, the intention for the future, is not built once and for all at the beginning of the design process*". Our case studies therefore rather reflect the "non-transitive problematization" conceptualized by Matt et al. (2017), referring to the complex paths of innovation: "*Innovation journeys are very often like Columbus' discovery of America that started with the objective of India*".

Figure 2: Comparison of the co-evolutions of design targets, knowledge production, and representations of processes of interest in the agro-ecosystems at stake (the key in Figure 1 also applies here).

In all cases, this evolution of the design target resulted from knowledge generated during the design process. This knowledge was linked to the initial formulation of the design target, but also always led to a transformation of that target. Moreover, the production of knowledge went hand-in-hand with the evolution, over time, of researchers' representations of agro-ecosystems processes or of the actions that may impact them. In none of the case studies did the representation associated with the initial formulation of the design target remain over time (Figure 2). Through the exploration necessary to specify the characteristics and properties of the object being designed, knowledge was produced in fields that were not anticipated at the start of the design process. In other words, for all case studies, the design process cannot be likened to an accumulation and technological maturation of knowledge, driven by a definitive formulation of the design target. The relations between scientific knowledge production and design cannot therefore be described using a linear scale such as the Technology Readiness Levels "targeting identified goals" (Mankins, 1995).

Figure 2 shows that knowledge production can take place at any time during the design process, in connection with both (i) the specification of the object being designed, and (ii) the evolution of the representations of agro-ecosystems processes or actions. The literature mentioned in the 'Theoretical framework' section describes specific operators (such as *disjunction* – a knowledge supports the formulation of a concept – or *conjunction* – the explored concept becomes a new knowledge) for iterations between knowledge and the progressive specification of the object being designed (Hatchuel and Weil, 2009). Our results help to clarify some aspects of the dynamics of these iterations. They show that design is not only a matter of refining the properties of the object being designed: it may also lead to radical change in the design target, as a result of the knowledge generated over the course of the design process. Moreover, these disruptive reformulations of the design target also correspond to a change in the designers' representations of the processes of interest or of the practices targeted by the design.

4.5 Knowledge production stemming from the conditions of action in a real environment

Since the knowledge produced plays a significant role in specifying the design target, it is important to consider the drivers of this specification process. We have identified three types of drivers:

i) **The identification of rare, "singular" situations that revealed a weakness in available practices or objects, and led to the reformulation of a design target, better suited to these situations.** These situations were often brought to agricultural researchers' attention through informal interactions with farmers or advisors. In these singular situations, standard rules of action, reasonings, approaches and indicators could no longer be considered valid. Examples of such singular situations include stony soils in the "Double density strip" case, very early sowing of rapeseed in the "Frozen leaves" case, short supply chains in the "Vegetables intercropping" case, and ancient variety cultivation in the "Participatory breeding” case. Some occurred at the start of the design process (“Double density strip”, “Vegetables intercropping” and “Participatory breeding” cases), and then provided a definition of what was to be targeted, which set a constraint on the action but did not directly define the knowledge to be produced (for example stony soils which made it impossible to measure inorganic N at the end of winter and therefore to calculate a nitrogen fertilizer rate). Others arose in the middle of the design process timeline (for example situations where many frozen leaves were observed after an initial implementation of rapeseed management routes, applying very early sowing), and pointed more directly to new knowledge to be produced (for example the kinetics of nitrogen mineralization in frozen leaves for rapeseed sowed very early).

***ii)* Diagnoses of the diversity of situations, whether relating to practices, their impacts (“Double density strip”, “Pollen beetles” and “Miscanthus” cases) or their contexts (“NNI trajectories”, “Variety mixtures”, “Erosive runoff”, “Vegetables intercropping” and “Participatory breeding” cases).**

In the “Pollen beetle” and “Miscanthus” cases, diagnoses surrounding the impacts of practices (for example agronomic diagnosis, Doré et al., 1997) occurred at the start of the design process. In both cases, they directly led to the production of knowledge about the agro-ecosystem (determinants of the presence and non-regulation of pollen beetles; the plant density of miscanthus as a factor explaining yield). In the “Double density strip” case, the analysis of the diversity of NUEs observed revealed the correlation between NUE and wheat growth rate, and led to a new representation of the fate of nitrogen derived from fertilizer.

Diagnoses relating to the diversity of practice contexts (“NNI trajectories”, “Variety mixtures”, “Erosive runoff”, “Vegetables intercropping” and “Participatory breeding” cases) can take several forms. In the “NNI trajectory” case, a “diagnosis of uses” (Cerf et al., 2012) was carried out from the outset of the design process, and revealed the problems surrounding the implementation of the Balance Sheet method, thus helping to determine some desired characteristics of action (that is, managing fertilizer inputs without setting a yield target) in a new formulation of the design target. In other cases, the diagnosis occurred later on in the design process, for example during design workshops involving future users of the object being designed, who highlighted new dimensions to take into account with regards to the practices at stakes (for instance, in the “Variety mixtures” case, during the workshops, farmers and advisors based blending strategies on variety traits different from those initially identified by the researchers; and in the “Vegetables intercropping” case, the market gardeners participating in organized visits to the experimental station stressed the importance of the type of trellising used for successful pest control). The functional aspects of practices (in other words, why a technique is used and how its impact is assessed) were then addressed, and the contribution of non-academic actors (advisors, groups of farmers) was often crucial to the reformulation of the design targets.

iii) Early experiments with initial prototypes of the object being designed (“Frozen leaves”, “Erosive runoff” and “Vegetables intercropping” cases). In the “Frozen leaves” case, the implementation, within a network of farms, of crop management routes with very early sowing, resulting in a high N uptake in autumn, highlighted the difficulty of envisaging spring fertilization, due to the fall of N-rich leaves in winter. In the “Vegetables intercropping” case, the experiment showed that the uprooting dates of short-cycle species could cause health problems to long-cycle species, due to the transfer of parasites from the former to the latter. These experiments therefore served to test a prototype of the object being designed, and shed light on dimensions not taken into account in an earlier representation of the agro-ecosystems processes. Therefore these were not tests to validate "what works and what does not work" (Thomke, 2003), but tests that offered an early and exploratory confrontation with the situations of actions that might be taken into account in the continuing design process. We can see here the "*reflective conversation with the materials of a design situation*" conceptualized by Schön and Wiggins (1992), mentioned in the 'Theoretical Framework' section of this article: putting into action the object under design enriches and even re-orientates the design process, as well as the associated knowledge generation.

These three types of drivers resulted from proactive approaches by the researchers involved in the case studies. In most of the design approaches studied, the researchers applied research methods that allowed the unexpected to emerge in the real-life situations of action. This unexpected often led to changes in the representations of the processes of interest in the agro-ecosystem, as well as changes in the identification of new knowledge needs. The diagnoses described above (for example agronomic diagnosis, the diagnosis of uses, and experimentation in a large diversity of situations) played a decisive role in the emergence of the unexpected, especially when they were intentionally managed to highlight and analyze the diversity of situations and its perceptions by the farmers and advisors. As Louridas (1999) points out, "*Design is a continual interplay between events and their handling by the designer; design is successful when it handles contingent events well*". These unexpected events, as well as dialogue between various actors around prototypes (Cerf et al., 2012; McCown, 2001), therefore contributed to the production of scientific knowledge. Thus, as Prost et al. (2018) have already evidenced, our results show that confronting prototypes to the real-life situations of action is not an end for the design process (in other words, this does not just serve to assess the outcome) but a step in the problematization process. For agricultural researchers, facing the situations of action through a variety of practices can be a driving force in the evolution of their representations of agro-ecosystems and of their knowledge needs, and therefore their representation of the design process in which they are involved.

Our analysis of the production of scientific knowledge through design echoes debates on the orientation and organization of agricultural research. In particular, the holistic and complex agroecology approach is often argued to involve interdisciplinary research, combining, notably, ecology and agronomy (see for example Hatt et al., 2016). We show that rather than being a necessity required from the outset, interdisciplinarity can be built throughout the design process, in coherence with the evolution in the representations of the ecosystemic processes of interest, and can thus sometimes be unpredictable. In fact, during the design processes studied, the changes in the representations of ecosystemic processes mostly caused the boundaries of the systems studied to be redrawn, and led to the production of knowledge on objects given little attention in the researchers' original disciplines: for instance, the major role of the plants in nitrogen flux in the soil in the "Double density strip" case; and landscape characteristics including plot practices in the "Pollen beetles" and "Erosive runoff" cases. Regarding the organization of research, this on-going construction of interdisciplinarity calls for scientific project formats that allow for a degree of agility to explore the links between design issues and new fields of knowledge, without these links having been anticipated at the start of the project.

Numerous authors have also called for greater attention to be paid to local real-life situations and contexts, from three main perspectives: (i) questioning the alignment between the knowledge produced, the techniques implemented and specific contexts (Duru et al., 2015); (ii) emphasizing the value of hybridizing scientific and local knowledge (Caron et al., 2014; Doré et al., 2011); and (iii) promoting the involvement of a diversity of actors in problem formulation and experimentation (Cerf, 2011; Warner, 2008). Our findings add a new dimension: this relationship to local real-life situations appears to be a driver of evolution in crop scientists' representations of the ecosystemic processes they explore, and therefore, indirectly, of the production of general knowledge. Thus, in research projects, knowledge production guided by confrontation with real-life situations challenges the dominant approach to agricultural research (Hatt et al., 2016), where funding is associated with a schedule of predetermined timeframes and deliverables. The timeframe of research projects combining design and the generation of scientific knowledge seems difficult to predict: as most cases show, knowledge can be produced far into the design process. Moreover, the production of the unexpected, which appears to be frequent in our cases, disrupts the upstream identification of deliverables (for example new fields of knowledge can be opened and explored) and timeframes (a reorganization of experimental frameworks may take much longer than envisaged at the start of the design) (Meynard et al., 2012; Prost et al., 2018).

5 Conclusion

We have shown that original scientific knowledge may arise from a design process. Across all our crop science case studies, three types of knowledge were produced during the design process: knowledge on biological and ecological processes within agro-ecosystems, on effects of management actions on agro-ecosystems, and models to represent these processes. However, our cross-analysis of the case studies yielded further insights into the specificities of the production of scientific knowledge through design processes. In most cases, the knowledge produced was not predictable at the start of the design process: it followed a change in the design target, resulting from the researchers' confrontation with a wide range of real-life situations, or from the application of prototypes of the object under design in these situations. We therefore do not support the linear approach of the relationship between scientific knowledge and innovation exemplified by the Technology Readiness Levels scale.

A further contribution this study makes to agricultural systems research is the description of how design-related methods lead to renewal of representations underlying the study of processes within agro-ecosystems. There is no doubt that sound and relevant knowledge can be produced without engaging in design processes. Nevertheless, we have shown that confronting an object under design with real-life situations of action contributes to opening up opportunities for exploration of unexpected knowledge issues, and stimulates the renewal of researchers' representations surrounding the processes under study. These findings suggest that even researchers dealing with subjects seemingly removed from the action (for example crop physiology) would stand to gain from engaging with actors in their diverse situations of practice, so as not to miss unexpected but relevant problematization reorientations.

These insights provide a sound basis for further reflection on the organization of research. Our results show that innovation is not only the valorization of existing knowledge, but may be a source of original and peer-reviewed scientific knowledge. This raises questions about the organization of research institutions that should promote both innovative design and original knowledge generation. Such an organization should accept unpredictable timeframes, the unpredictable characteristics of knowledge production, and the management of innovative design activities as drivers of knowledge production. This form of organization of research institutions is yet to be invented.

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	Case studies (short names)	Case study selection and characterization criteria **Scientific publications** (selection criterion)	**Initial design target** (selection criterion)	**Final outcome of the design process** (selection criterion)	**Duration**	**Scale**
1	Double density strip	Limaux et al. 1999, *Plant and Soil*, 214 :49-59. Limaux et al. 2001, *Persp. Agri*.,	*Action targeted by the design*: to fertilize wheat (rate and timing of nitrogen applications). *Design target*: a calculation method of N fertilization rate that does not require any measurement of the inorganic nitrogen in soil after winter	A decision support tool to determine the date of the first nitrogen application based on the yellowing of a double density strip (DDS). A N fertilization strategy that maximizes Nitrogen Use Efficiency and uses the DDS indicator to decide on the first N application.	10 years (1990 – 2000)	Plot
2	NNI trajectories	Ravier et al. 2016, *NJAS*, 79 :31-40. Ravier et al. 2017, *EJA*, 89 :16-24. Ravier et al, 2018, *Nutrient cycling,in Agroecosystems*, 110 : 117-134.	*Action targeted by the design*: to fertilize wheat (rate and timing of nitrogen applications). *Design target*: a method for managing N fertilization that replaces the Balance Sheet method while reducing application rates and maximizing NUE.	Nitrogen fertilization rules based on real-time monitoring of the crop throughout the cycle, maximizing the use of nitrogen fertilizer and accepting deficiencies that are not detrimental to yield.	5 years (2012 – 2017)	Plot
3	Frozen leaves	Dejoux et al. 2000, *Plant & Soil*, 218 :257-272. Dejoux et al. 2003, *Agronomie*, 23 :725-736.	*Action targeted by the design:* to manage rapeseed cropping practices (including fertilization) and the consistency between them. *Design target*: A low-input rapeseed management route that improves environmental performance while maintaining economic performance.	A low-input rapeseed management route based on very early sowing, which limits the use of pesticides and N leaching. A method to calculate spring N fertilization on rapeseed (usable for any sowing date), accounting for frozen leaves.	4 years (1996 – 1999)	Plot
4	Wheat variety mixtures	Borg et al. 2017, *Field Crop Research*, 221: 298-313. Vidal et al. 2017, *Plos One*, 12 : e0187788	*Action targeted by the design:* to select wheat varieties to be grown together, in order to reduce crop sensitivity to biotic and abiotic stresses (N and water). *Design target*: Rules for building variety mixtures that have an advantage over a pure variety on farms.	Blending rules for stabilizing production and simplifying crop management, adapted to the characteristics of the agricultural situation. Locally designed variety mixtures. A multi-criteria assessment tool for variety mixtures.	4 years + (2014 – in progress)	Plot
5	Pollen beetles	Valantin-Morison & Meynard 2008, *Agron.Sust.Dev*, 28:527-539. Rusch et al 2011, *Agr. For. Ent*., 14:37-47. Rusch et al. 2013, *AEE*, 166:118-125. Vinatier et al. 2012, *Landscape Ecology*, 27 :1421-1433.	*Action targeted by the design:* to manage rapeseed cropping practices and consistency between them, at plot and landscape level. *Design target*: improved low-input rapeseed management routes.	A landscape indicator to determine the probability of exceeding a pollen beetle's abundance threshold. Landscape management rules to favor natural enemies and biological control of pollen beetles.	16 years + (2002 – in progress)	Landscape
6	Miscanthus	Lesur et al. 2014, *Global Change Biology Bioenergy*, 6 :439-449 Lesur et al. 2013, *FCR*, 149 :252-260 Lesur-Dumoulin et al. 2015, *GCBB*, 8 :122-135.	*Action targeted by the design:* to choose the crop sequences and management that increase the cropping system's multi-performance. *Design target*: environmentally efficient cropping systems including energy crops in a local context.	Cropping systems that include miscanthus and reduce GHG emissions by 75% compared to the territory's dominant cropping system (Rapeseed – Wheat – Barley rotation).	7 years (2009 – 2016)	Farm and plot
7	Erosive runoff	Souchère et al. 1998, *J. of Hydrology*, 206 : 256-267. Cerdan et al. 2002, *Catena*, 46 :189-205. Joannon et al. 2005, *AEE*, 111 :13-20. Joannon et al. 2006, *LDD*, 17 :467-478.	*Action targeted by the design:* to choose crop rotation, tillage and management practices that limit erosive runoff. *Design target*: cropping systems and their spatial organization to limit erosive runoff in silty watersheds.	Guidelines to avoid crop spatial arrangement and management practices that generate erosive runoff at watershed level. An indicator linking a quantity of water – runoff – to a quantity of sediment – erosion.	18 years (1988 – 2006)	Watershed
8	Vegetable intercropping	Salembier et al. 2015, INNOHORT Lefèbvre et al. 2015, FSD symposium	*Action targeted by the design:* to choose the species to associate, their management, and their arrangement in space. *Design target*: a market gardening organic cropping system catering to short value chains, which makes it possible to manage crop health using natural regulations.	An organic vegetable cropping system that promotes natural regulations, catering to short circuits. Management and blending rules for a intercropping, according to agronomic and commercial criteria.	6 years (2012 – in progress)	Plot
9	Participatory wheat breeding	Goldringer 2001, *Gen. Select. Evol.* Bonneuil et al. 2006, *Cour.env. INRA*, 30 : 29-51. Bonneuil et al 2012, *Ecol. Ind*, 23 :280-289 Thomas et al. 2011, *Gen. Res. Crop Evo*., 58:321-338.	*Action targeted by the design:* to preserve and manage cultivated wheat genetic diversity through mass selection and seed exchanges. *Design target:* A participatory breeding scheme (dynamic management of genetic diversity) for wheat.	An original participatory selection approach (experimental multi-local system and statistical analysis method). Population varieties adapted to growing environments. An indicator of cultivated genetic diversity.	15 years + (2003 – in progress)	Breeding landscape

Table 1: Description of the case studies and selection criteria: scientific publications, action targeted by the design and design target, final outcome of the design process, duration and main scale of the project.

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	Cases	Three types of knowledge generated: *i) Agro-ecosystem processes* *ii) Effect of actions* *iii) Systemic modeling to steer the action*	Dominant representations in the scientific field at the time of knowledge production	Originality of the representations on which knowledge is based	
				New objects of interest and new processes within the agro-ecosystem	New forms of farmer practices and indicators for action
1	Double Density Strip	Relationship between NUE and the crop growth rate (*i*). NUE variations explained by gaseous losses (*i*). Modeling of the evolution of NUE (*iii*).	Flow and process modeling of the N cycle in soil, mainly influenced by soil conditions.	The plant as a major factor in the variation of N gaseous losses.	The evolution of NUE during the crop cycle as a reference to set the date of the first fertilizer application.
2	NNI trajectories	Minimum NNI trajectory that maintains wheat yield and quality (and increases NUE) (*i*). A fertilizer rate calculation method based on the viability theory (*iii*).	Modeling N cycle in soil to improve the estimation and prediction of Balance Sheet terms. Modeling the effect of temporary deficiencies on yield based on a static indicator, combining the intensity and duration of the deficiencies.		A trajectory of nitrogen nutrition status to decide on nitrogen input (tolerating deficiencies but avoiding yield losses).
3	Frozen leaves	Quantity of N absorbed by rapeseed in autumn under non-limiting conditions (*i*). Fate of the N from frozen leaves: the N from frozen leaves is mineralized quickly enough for the crop to absorb 50% of the nitrogen (*iii*).	Modeling the mineralization of the residues of the previous crop.	The frozen leaves as providers of mineral N to the crop in spring.	
4	Wheat variety mixtures	Quantification of mean overyielding. Effect of height diversity across susceptible and resistant varieties on the spread of airborne diseases (*i*). Influence of cultural factors and varietal characteristics on overyielding (*ii*). Change in the evaluation criteria for mixtures, integrating multiple objectives including the simplification of management (*ii*).	Epidemiology-ecophysiology: spread of diseases in variety mixtures. Evaluation of the over-yielding effect of mixtures, without taking into account the production context and the farmers' objectives.	The multi-varietal stand in diverse farming conditions, with a wide range of heights, and analyzed across diverse farmers' evaluation criteria.	
5	Pollen beetles	The limiting factors of rapeseed in low-inputs systems: weeds, nitrogen, and pests including pollen beetles. Distance of response of pollen beetles and auxiliaries to landscape. Distances of dispersion (*i*). The environment of the plot influences the presence and abundance of pollen beetles more than cultivation practices do (*ii*).	Study of species abundance and richness according to habitat qualities in landscape ecology (mosaics of cropping systems not taken into account). Study of the effects of pest damage at plot level.	The natural and semi-natural elements of the landscape and the cropping system mosaic as part of the same landscape.	
6	Miscanthus	Variability of Nitrate losses under a young miscanthus crop (*i*). Stem density during the crop establishment explains the variability in miscanthus yields observed within a network of agricultural plots (*ii*). Modeling of the temporal evolution of miscanthus yields (*iii*).	Performance of miscanthus evaluated on the basis of experimental data and models unrelated to the cropping systems in which it is grown.	The on-farm miscanthus crop in relation to the diversity of farmers' cropping systems.	
7	Erosive runoff	Effect of the arrangement of surface crop patterns, related to the direction of tillage, dead furrows, dirt tracks, ditches, and the quantity and direction of runoff flow (*ii*). A model of the impact of the spatial arrangement of crops and management practices on runoff and erosion (*iii*).	Deterministic modeling of biophysical processes that influence surface conditions, not taking into account temporary soil structures resulting from tillage.	The temporary soil condition induced by the soil tillage direction, dead furrows, dirt tracks, ditches.	The runoff dynamics according to the evolution of soil surface conditions and meteorological events.
8	Vegetable intercropping	Effects of the composition, arrangement and management of intercrops on different pests (*ii*); interactions between technical options (for instance the spatial arrangement determines possible irrigation methods) (*ii*).	Intercrop usually described in terms of the species involved and their spatial arrangement. Pests and diseases within the intercrop mainly linked to the sensitivity of each species.	The intercrop characterization also includes other techniques (trellising, uprooting, etc.) influencing plant health.	The dynamics of insect populations' evolution and movement, informed by the traits of the intercropped species and their management.
9	Participatory wheat breeding	Evolution (conservation) of cultivated genetic diversity through breeding and seed exchanges (*ii*).	Varietal breeding in networks of controlled trials in experimental stations, and non-limiting conditions.	From peasant seeds exchanged and selected to several populations selected within a network of farms.	

Table 2: Knowledge generated during the design processes, and forms of originality of the representations on which they are based.

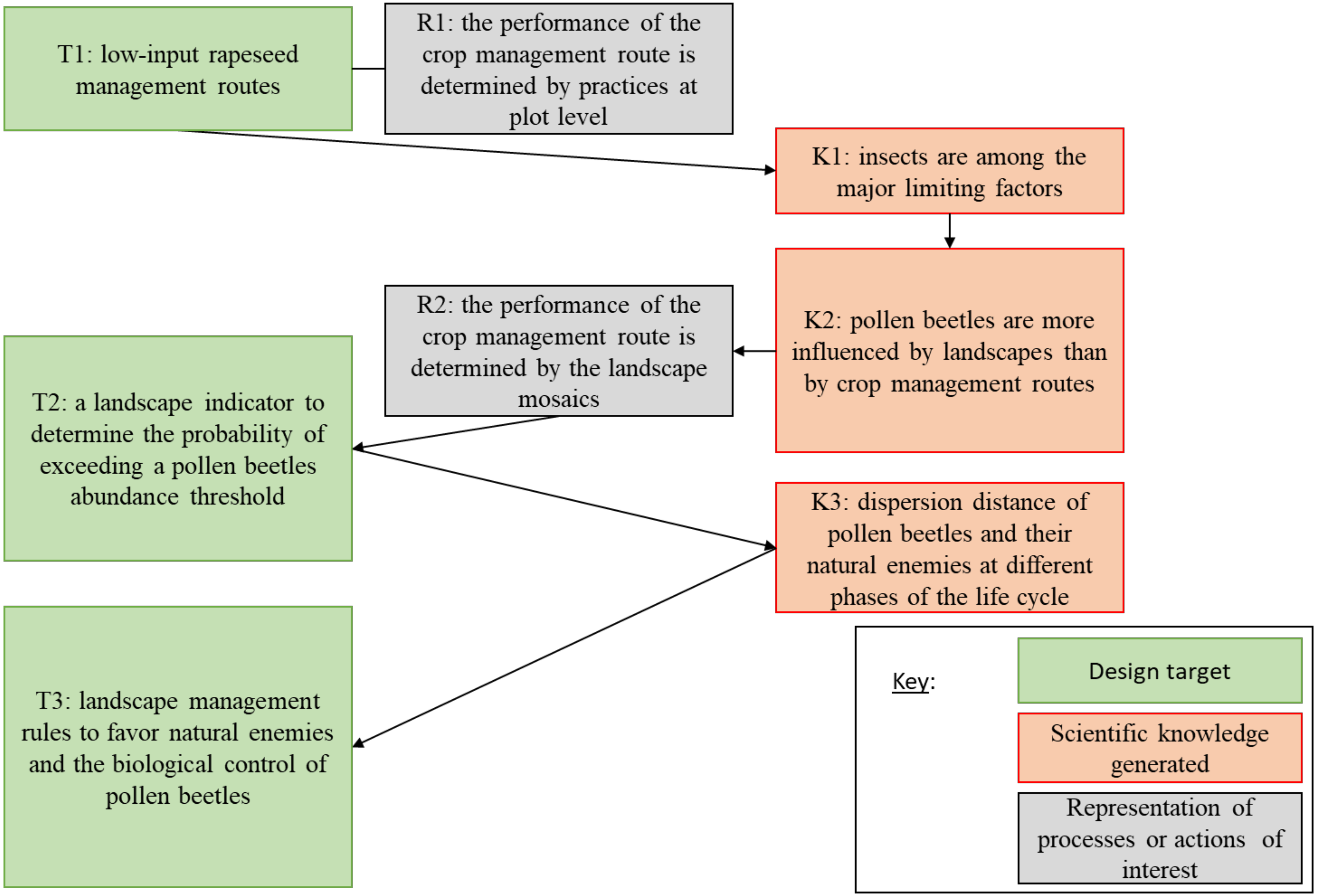

Figure 1: An example of the co-evolution of design target formulations, knowledge needs and representations of processes of interest in the agro-ecosystems at stake. Case 5: "Pollen beetles".

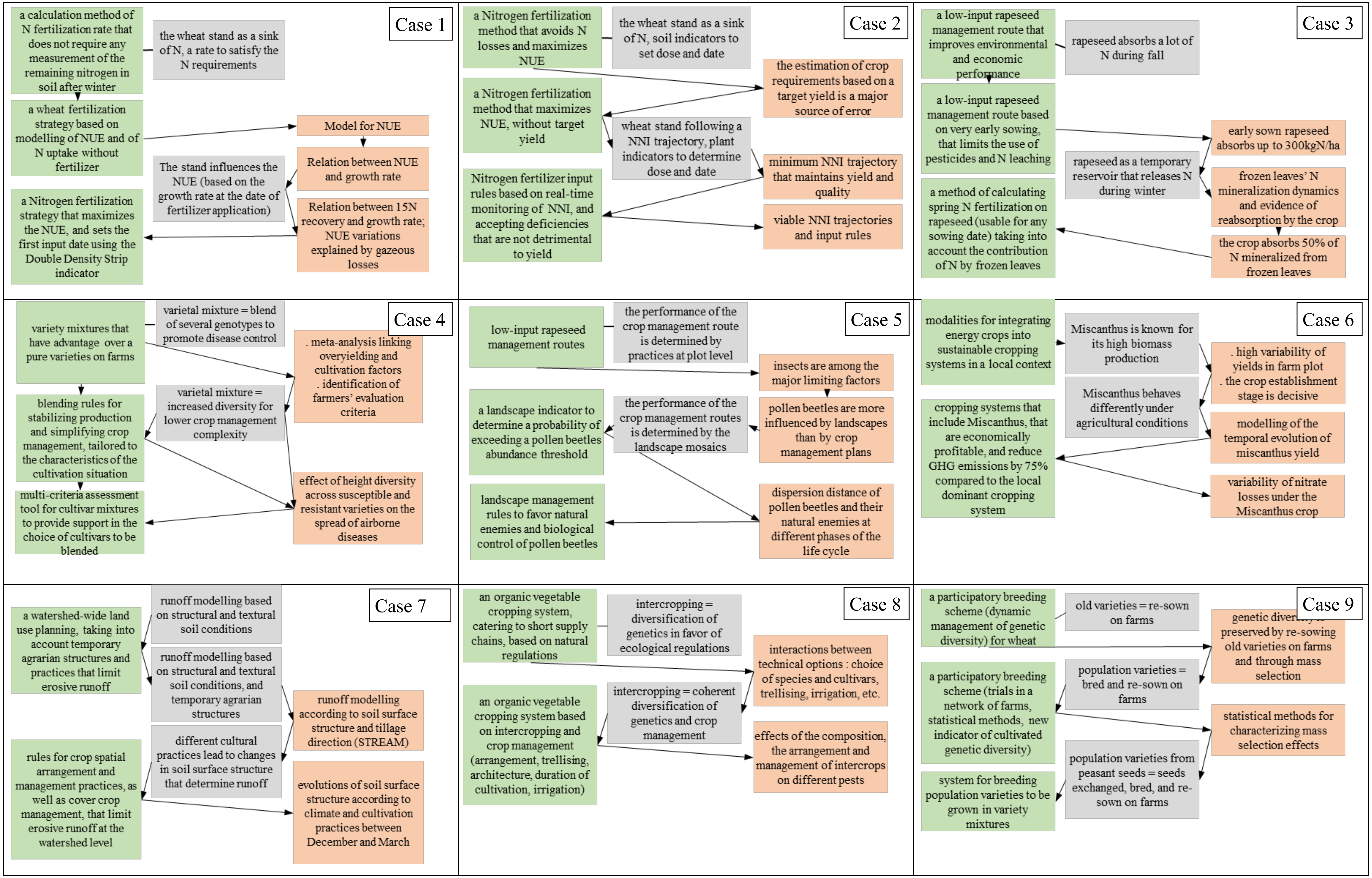

Figure 2: Comparison of the co-evolutions between design targets, knowledge production, and representations of processes of interest in the agro-ecosystems at stake (of the key in Figure 1 also applies here).