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ABSTRACT

1. Context

There is an urgent need to reduce the use of phytosanitary products in industrial vegetables due to environmental and health concerns. However, as in many industrial sectors, vegetables production is characterised by strong constraints related to the expectations of consumers, the profitability of distributors and the processing steps of industrial companies. These constraints impact farming systems through the elaboration of production contracts that hamper innovation and reduce farmers' latitude to evolve towards agroecology.

2. Objective

This study was initiated by a French distributor of frozen products, and aimed to create innovative agroeocological cropping systems by circumventing lock-ins of the sector thanks to a co-design methodology.

3. Methods

An existing methodology of innovative cropping systems design for fresh vegetable crops was adapted to the context of industrial production, considering the 3-year deadline granted to the project. Four farmers were involved, who were part of a working group consisting of a distributor, a processing company, a cooperative and a research team, all involved in the production of frozen vegetables. Four cropping systems were designed, consisting in combinations of agroecological farming practices, and tested on farm for two years.

4. Results and conclusions

Farmers reduced their Treatment Frequency Index by 15% on average, thanks to the combination of a wide range of agroecological farming practices. A multi-criteria analysis showed that there was no clear improvement in overall cropping system sustainability, due to economic weaknesses. Although these results were somewhat disappointing, especially with respect to the expectations of public policies, they represent a significant progress given the difficulty to reduce the use of chemical pesticides in industrial systems. Farmers underlined the importance of economic security but were nevertheless highly motivated to continue the transformation of their systems, and the working group collectively approved the methodology. Four methodological aspects are discussed, identified as key elements for consideration in this type of study: farm system scale, collective work, farm system flexibility, and farm system uniqueness. Based on these principles, the working group decided to extend the study to a larger scale, with the aim of recruiting more farmers from the sector.

5. Significance

This study shows that making cropping systems with industrial vegetables evolve toward agroecology is possible thanks to a co-design methodology. In the long term, such initiatives could support the transition of the whole agrifood system toward the production of healthier products, reducing negative environmental impacts of cropping systems.

KEYWORDS

Farming system ; cropping systems design ; industrial vegetables ; agroecology ; innovation ; collective approach

HIGHLIGHTS

- Industrial vegetables sector is characterised by intensive practices and strong constraints related to production, transformation and marketing.
- This study aimed to create innovative cropping systems by overcoming sectorial lock-ins thanks to an adapted co-design methodology.
- Four innovative systems based on combinations of agroecological practices were designed collectively and experimented by farmers.
- Despite fragile economic results, the working group was satisfied, approved the methodology and decided to extend the study to a larger scale.
- Such initiatives could support the transition of the whole agrifood system toward the production of healthier products in a more sustainable way.

INTRODUCTION

In France, 900,000 tons of vegetables are produced each year for the industrial market, and occupy about 70,000 ha (Bernardin, 2018). This sector is usually associated with big farms (about 130 ha) with a diverse range of activities, such as livestock farming and cereal cropping (Pierron, 2016). Vegetable crops are characterised by a large diversity of cultivated species, susceptible to many pests and diseases. To control pests and guarantee the quality and yield of vegetable productions, farmers use a significant amount of pesticides, potentially damaging agroecosystems and the services they can provide (Gregory et al., 2002; Pimentel and Lehman, 1993). Health issues related to pesticides are also increasingly regarded as a major societal problem, especially for consumers (Boccaletti and Nardella, 2000; Carvalho, 2017). Indeed, surveys in France found that chemical treatments on crops and their residues in food are one of the main concerns about food consumption (Hebel, 2008). In order to make progress on these issues, an increasing number of political decisions have gradually been made to ban the use of dangerous phytosanitary products. For industrial vegetables growers, these regulations are added to a large set of specifications (Henson and Humphrey, 2012) ensuring downstream processing, sanitary and visual quality of products, as well as yields, which are generally incompatible with a reduction in pesticide use (Lamine, 2011). In this context, a consultation between the different stakeholders in the industrial vegetable sector is clearly required to develop a consistent and sustainable strategy to reduce pesticide use and revalue products (Duru and Therond, 2015).

The main goal of agroecology is to manage agro-ecosystems in a sustainable way balancing their environmental, economic and social aspects (Altieri, 1989). Agroecological farming practices can be defined as methods contributing to the sustainability of agro-ecosystems based on a diversity of ecological processes (Wezel et al., 2014). Farmers increasingly adopt these practices to adapt their farm systems to environmental problems, health concerns and political constraints (Méndez et al., 2012). As described in the ESR (Efficiency-Substitution-Redesign) framework (Chantre and Cardona, 2014; Hill and MacRae, 1995; Wezel et al., 2014), this appropriation can be achieved with different transition strategies. The complete redesign of farm systems is the most advanced approach, since it involves the design and the adoption of new combinations of innovative and coherent farming practices (Chantre and Cardona, 2014). It can require technically difficult and risky practices (*e.g.* modification of crop rotation, direct seeding into living cover crops, …) and is usually based on a long and non-linear process (Lamine, 2011). However, it can help creating robust and transformative systems answering the ambitious expectations of modern society (Pretty, 2018).

The design of innovative cropping systems developed strongly in France during the last decade, because it was identified as a promising approach to make agroecosystems more sustainable (Meynard et al., 2012; Prost et al., 2017). It is mainly characterised by a collective dimension, the aim being to design new systems based on established and empirical knowledge of various stakeholders (farmers, researchers, advisers, territorial players, etc.) (Lacombe et al., 2018; Lançon et al., 2008; Reau and Doré, 2008). Numerous initiatives have emerged worldwide, in developing countries but also in intensive production regions, for a diversity of crops, sectors, farming contexts, and purposes (Berrueta et al., 2021; Debaeke et al., 2009; Dogliotti et al., 2014; Falconnier et al., 2017; Lançon et al., 2007; Le Bellec et al., 2012; Lefèvre et al., 2014; Reckling et al., 2020). Modelling has been used to explore innovative management strategies at the farm level (Olesen et al., 2006; Sadras et al., 2003; Zingore et al., 2009). A lot of methodologies have been formulated, and some authors proposed syntheses and classifications of design studies (Le Gal et al., 2011; Martin et al., 2013). In France, guidelines were written (Aubertot et al., 2011; Barbier et al., 2011; Bruchon et al., 2015; Laget et al., 2015; Launais et al., 2014; Meynard et al., 2012) to help farmers and advisers implement complete and collective redesign of cropping systems, targeting the reduction of pesticide use. Numerous field studies were conducted under these guidelines, and have made significant contributions to solve the challenges of French modern agriculture. A good example is the DEPHY network, a French network funded by the Ministry of Agriculture and Food and dedicated to the trial and assessment of low inputs cropping systems (Eckert et al., 2018; Lechenet et al., 2017). However, despite the large diversity of design studies, few initiatives have concerned the vegetable sector, and fewer still the industrial vegetable sector, probably because of the strong constraints and regulations previously mentioned.

Reducing the use of pesticides in agriculture is an ambitious challenge, encouraged in France since 2008 by the Ecophyto plan (Lamichhane et al., 2019; Ministry of Ecological and Solidarity Transition, 2018). However, some major locks have progressively been identified, responsible for the disappointing results observed by involved stakeholders (Guichard et al., 2017). Among these locks, the lack of involvement of the whole agrifood system was pointed out as a big concern (Lamine, 2011). In a quite recent study, Meynard et al. (2017) argued for the design of coupled innovations, *i.e.* improvements jointly conducted by downstream and upstream stakeholders of agrifood systems. Farm system design is indeed usually driven by upstream actors (farmers, technical advisers), considering constraints and specifications from downstream actors (related to processing, distribution, preparation and consumption of food) that restrict innovation. In order to reach sustainability, all the components of the agrifood systems should however require a huge need for innovation, so working collectively seems an essential approach (Duru and Therond, 2015;

Gliessman, 2014; Lamprinopoulou et al., 2014; Meynard et al., 2017). The literature about socio-technical systems shows that in a locked-in system, as is the case for the industrial vegetable sector, radical innovations can emerge in “innovation niches”, *i.e.* in alternative socio-technical systems composed of outsider actors that can emerge from a collective design process (Geels, 2005; Kemp et al., 1998; Meynard et al., 2017).

The aim of this study was to apply, adapt and evaluate the methodology of innovative cropping systems design for the industrial vegetable sector, from a guideline written for fresh vegetable crops (Launais et al., 2014). It is an original approach, since the work was collaboratively conducted by five major stakeholders in the sector, and especially a distributor and a processing company, characterised by different sets of constraints. Innovative cropping systems were co-designed and experimented in the west of France, with two main goals: reduce the environmental effects of farming practices and anticipate the progressive banning of phytosanitary products. The study was directly conducted in a context of vegetable production, with four pilot farmers.

METHODS

Study area

The study was carried out from 2015 to 2018 in Brittany, which is one of the major French regions where industrial vegetables are produced, with 33% of the total French cultivated area (Bernardin, 2018). In Europe, the sector is driven by a small number of large processing companies with similar agronomical, industrial and economic functioning. The results can consequently be transposed to some extent to the French and European sector at large. In Brittany, a large part of the region area is dedicated to farming, with a majority of crop-livestock farms with grassland, corn and wheat (Agreste, 2016). Vegetables, mainly green beans, peas, spinach and carrots, occupy nearly 3% of the cultivated area (Bernardin, 2018).

Background of the study

The study was initiated in 2015 by the company Picard, a distributor of frozen food products. Based on a life cycle assessment conducted on some of their vegetable-based products, this company realized that the production phase (in fields) was the most damaging for environment. They asked the processing company Ardo and the French National Research Institute for Agriculture, Alimentation and Environment (INRAE) to build a collective project to address this issue. An initial three-year working step was defined and contractualised between the three collaborators. The overall goal was to collectively design and experiment innovative cropping systems to reduce the environmental effects of farming practices and anticipate the progressive ban of phytosanitary products. Collaborators decided to work directly in the production context (instead of working in an experimental platform), first testing the method with a pilot group of four farmers. It was assumed that enough knowledge was available to design coherent systems, and that these systems needed to be tested directly by farmers to meet Picard expectations and project objectives in the allotted time of three years.

Collaborator's roles and constraints

Five major stakeholders in the industrial vegetables sector were involved in the study:

1. Picard is the French leader in the distribution of frozen food products, with a 19% market share. They have about 1,000 shops in France, where more than 70 types of vegetable products are sold every day. As all distributors, Picard needs to meet health standards and customers' expectations. This means offering vegetables alone or mixed in recipes, respecting the authorised threshold of physico-chemical and biological contaminants, and presenting a visual aspect and a taste adapted to consumer preferences. It can also means proposing products that reflect social trends, for instance about health considerations. Finally, Picard needs to offer these products on a regular basis, with a consistent quality. During the project, Picard was represented by two staff members belonging to either the Sustainable Development department or the Quality department.

2. Ardo is a major European processing group specialised in the deep-freezing of vegetables, fruits and aromatic plants. The company is established in nine countries including France, and one of the factories is located in Brittany. They collect harvested vegetables and they transform, freeze and pack them. Picard is one of their clients. Ardo and Picard are linked by contracts that specify Picard expectations about products quality and quantity, as previously described. In order to meet these specifications, Ardo needs to collect the right amount of vegetables at the right time, matching quality criteria and suitable for the different processing steps, *i.e.* sorting, cleaning, cooking, freezing and packaging. This means collecting vegetable batches without too many residues of foreign plants or animals, with a given size, a given texture, a given shape, etc. During the project, Ardo was represented by two staff members belonging to the sales and supply chain department (the director and his deputy) of the Britannic factory.

3. Four farmers were involved in the study, forming a pilot group. They are all members of the farmer cooperative Triskalia, and more precisely of the industrial vegetable subgroup. Farmers were solicited by Ardo, and took part to the project on a voluntary basis. A contract was signed between each farmer, Ardo and Picard, specifying farmers had to devote time to the project and that they were financially supported for the experiment. A budget was indeed defined at the beginning of the project to cover additional expenses and compensate

farmers' income in case of yield loss. The main characteristics of their farms are given in Table 1. Their vegetable crops are included in quite long cropping sequences (6-7 years) with other field crops (cereals, oilseed rape, buckwheat, etc). They however had different production and cropping systems, different initial levels of involvement in agroecology, and different priorities for their farms. This diversity is a key point of the study because it contributes to the representativeness of the pilot group. All industrial vegetable crops are grown under contracts, which impose the specifications, defined by the buyers (mainly Ardo in the pilot group), that the farmers must meet. This contractual system is used by all processing companies and allows configuring the raw material (vegetables here) according to the needs of the sectors. For farmers, it means respecting a precise crop management planning, including sowing (date and variety), fertilisation, pests management and harvesting (date and yield). As long as specifications are respected, farmers benefit from a guaranteed price for their vegetables.

4. Triskalia is one of the main farmer cooperatives in Brittany, with 16,000 members and 4,800 employees. It is organised in different subgroups depending on farm products. The industrial vegetable subgroup includes 600 farmers. Ardo is one of their clients. Triskalia was not part of the project creation and management but it was associated to the design of cropping systems and to the experimentation phase. For vegetables production, farmers usually rely on advices provided by technical advisers because it helps them following the specifications imposed by industrial companies. Persons involved were the industrial vegetable subgroup manager and the technical advisers of each farmer (one for vegetable crops and one for other crops).

5. The National Research Institute for Agriculture, Alimentation and Environment (INRAE) is a major French scientific establishment. Agroecology and farm transition toward sustainable systems are part of its numerous research topics. For this project, INRAE's role was to propose and manage an original approach to help farmers change their cropping systems. INRAE also provided a scientific evaluation to decision-making. During the study, INRAE was represented by two researchers specialised in cropping system design.

Table 1. Main characteristics of the farms involved in the project.

	Farm A	Farm B	Farm C	Farm D
Total cultivated area	111ha	110ha	93ha	94ha
Vegetable area	20ha	40ha	20ha	10ha
Activities	• Industrial vegetables • Cereals • Livestock farming (ducks, cows)	• Industrial vegetables • Cereals • Wheat, clover and ryegrass seeds • Farming work for	• Industrial vegetables • Cereals • Potato and ryegrass seeds • Farm tourism	• Industrial vegetables • Cereals • Livestock farming (chickens, cows)

		neighbors		
Cultivated vegetables	• Peas • Green beans	• Peas • Green beans • Winter spinach	• Peas • Green beans	• Spring spinach • Carrots • Broccoli • Cauliflowers
Other cultivated species	• Winter wheat • Winter barley • Grain corn • Oilseed rape • Faba bean • Buckwheat	• Winter wheat • Ryegrass • Clover	• Winter wheat • Winter barley • Triticale • Ryegrass • Potatoes	• Winter wheat • Corn silage
Commitment to agroecology	High	Medium	Medium	Low
Main agronomical problematics	• weeds and diseases control in vegetable crops • aphids and leaf weevils control in peas	• weeds control in spinach, wheat and ryegrass • diseases control in green beans	• volunteer potato • click beetles control in potatoes	• weeds control in carrots • selection of suitable cover crops
Main priorities of the farmer	• Conservation farming • New technologies	• Precision farming • Direct seeding into cover crops	• Reduction of working time • Concrete, local and social projects	• Technical progress • Cost efficiency

<u>Study approach</u>

The design and testing of the innovative cropping systems for the farmer pilot group was based on a framework proposed by Launais et al. (2014). This guide was written to help stakeholders from the fresh vegetables sector to design cropping systems using less pesticides. Four working steps are proposed: the diagnostic of the existing system, the design of an innovative system, the *ex-ante* analysis of the innovative system, and the identification of needed conditions to implement the innovative system. This methodology was adapted in order to work in the context of industrial vegetables production and to answer Picard request in the allotted time (i.e. including the experimentation and the analysis of implemented systems within three years).

Description of initial cropping systems

The study began with a complete and precise description of each farmer's initial cropping system. If a farmer had several cropping systems with vegetables, only the main one (*i.e.* the most represented in terms of area) was considered. Information was collected during interviews which purposes were to define and clearly understand the starting point for each farmer, encourage them to review the functioning of their system and identify its strengths and weaknesses. Each interview lasted half a day, took place on the farm and was organised in two parts:

- The overall functioning of the farm: establishment date, activities, cultivated species, abandoned species, cultivated area, number and size of fields, spatial distribution, main soil characteristics, weather conditions, agricultural equipment, manpower, main landscape characteristics, relationships with neighbouring and economic partners, contractual commitments, priorities, agronomical problematics, overall satisfaction;
- The precise technical operations carried out for each crop of the studied cropping systems: intercropping (cover crop, sowing and destruction dates), tillage (number of interventions, soil preparation tools), seeding (date, variety, sowing density, seed treatments), fertilisation (date and quantity of each organic and mineral product), pest management (target species, date and quantity of pesticides applications, other management strategies), irrigation (amount of water, equipment), harvesting (date, average yields).

Collective conception of innovative cropping systems

Innovative cropping systems were designed during workshops organised in 2016. Before workshops, the project leaders (Picard, Ardo, INRAE) selected a set of aims which constituted a guiding thread for designing the innovative cropping systems:

- Reduce the use of pesticides as much as possible;
- Adjust fertiliser inputs to crop needs;
- Introduce a large diversity of alternative agroecological farming practices, based on scientific studies and previous empirical trials by farmers.

For each innovative system, these technical aims were supplemented with the expectations of the farmer concerned. Economical and social parameters were not directly included in the workshops' aims, but were always kept in mind during discussions (for instance when a choice had to be made between two practices), in order to design sustainable cropping systems. Economical and social characteristics of the systems were assessed in the evaluation step.

Each workshop was one day long and was located on the farm of the farmer concerned. The aim was to completely redesign the initial cropping system, *i.e.* the crop sequence and technical operations carried out on each crop, following the expectations and ideas of all participants. There were 12 to 14 participants in each workshop: members of the central working group (Ardo, Picard, INRAE and the four farmers) and specific guests (one animator, one or two farmer technical advisers, and one or two agronomy experts specialised in vegetables). This configuration allowed Ardo, Picard and the focus farmer to express their expectations and the whole group to come up with a maximum of new ideas. The four farmers were present during all the workshops, so each of them was involved in the design of his own cropping system and in the design of other farmers cropping systems.

Each workshop was organised in five parts:

1. The farmer presented a detailed summary of his current cropping system;
2. The aims for the new innovative cropping system were specified. These aims were determined collectively since the new system must meet everybody's expectations;
3. New ideas for the innovative system were proposed (new crop sequences, new farming practices). During this step, all participants (except the farmer) wrote their ideas on post-it notes then shared with the group;
4. The best ideas were chosen to create a consistent and operational innovative system, based on the combination of compatible farming practices. Once again, these decisions were made collectively, with the exception of the farmer concerned who just observed the group;
5. A collective synthesis and feedback was given from the farmer concerned on his new cropping system.

After each workshop, a decision sketch was prepared, which is a comprehensive representation of the aims and the management strategies relative to a cropping system (Schaub et al., 2016). It helps to visualise the overall consistency of a system (combination of farming practices) and provides a good tool for discussion and management.

In 2017, an additional half-day workshop was organised with each farmer. The aim was to collectively take stock of the first year and get an update on each innovative cropping system, based on farmers' observations.

In 2018, farmers were met individually to take stock of the second year.

Testing the innovative cropping systems

The four farmers tested their own innovative systems in 2016, 2017 and 2018. The aim was to set up the innovative systems entirely from the start, *i.e.* to make as many of the designed changes as soon as possible and on as many fields as possible in each farm. Technical advisers from the cooperative and a researcher from INRAE guided the farmers to i) help them anticipate the specific needs (*e.g.*, mechanical weeding equipment), ii) remind them regularly of the necessary changes to be made, iii) observe the consequences of these modifications.

Assessing the sustainability of the innovative cropping systems

Three complementary tools were used to evaluate the sustainability of the cropping systems. Each tool was used to compare i) initial cropping systems, ii) theoretical cropping systems designed during the workshops, and iii) cropping systems actually implemented in 2016, 2017 and 2018.

1. The number of agroecological farming practices provided a first evaluation of cropping system sustainability. Like Wezel et al. (2014), we considered agroecological farming practices in the broad sense of the word, *i.e.* all farming practices "*aiming to produce*

significant amounts of food, which valorise in the best way ecological processes and ecosystem services in integrating them as fundamental elements in the development of the practices, and not simply relying on ordinary techniques, such as chemical fertiliser and synthetic pesticide application or technological solutions, such as genetically modified organisms". We considered that one farming practice is one action carried out by a farmer on a crop. Consequently, if a farmer made mechanical weeding on two different crops of its cropping systems, it was counted as two different practices. After each trial, farmers were asked about tested and non-tested farming practices. Reasons of non-inclusion of some farming practices identified during the design phase were collected and classified. Farming practices enumeration does not match with the systemic way of thinking associated with a co-design approach, but it provides quantitative data, useful to evaluate cropping systems and exchange with farmers.

2. The Treatment Frequency Index (TFI) is an indicator used to evaluate the intensity of phytosanitary products use by farmers. It is calculated as follows:

$$TFI = \sum \frac{dose\ applied}{recommended\ dose} \times \frac{treated\ area}{field\ area}$$

TFI is widely used by farmers and agronomists since it is easy to calculate and operational at different levels: it can be calculated at different scales (field, crop, cropping system, farming sector) and for diverse pesticide categories (herbicides, insecticides, fungicides). In this study, mean annual TFI were calculated for each cropping system, distinguishing between classic pesticides and products registered as "NODU vert Biocontrôle" (called "biocontrol products" in the article). This French certification describes products of natural origin used for the control of pests (French ministry of agriculture agribusiness and forestry, 2015a). This distinction was made because using a biocontrol product was considered as an agroecological farming practice.

3. Multi-criteria analyses encompass numerous approaches used to combine environmental, socio-political and economical information in tools helping stakeholders to understand multifactorial situations and make decisions (Huang et al., 2011). In this study, we used DEXiPM-FV, a hierarchical qualitative and multi-criteria model, developed to analyse the sustainability of field vegetable cropping systems (Estorgues et al., 2017; Pelzer et al., 2012). This model allows *ex-ante* analyses on virtual cropping systems not yet tested by farmers, with qualitative data. Since the *ex-post* version of the model to analyse actual cropping systems with quantitative data has not yet been developed, we used the existing tool to compare all cropping systems in the study using qualitative data only. For each cropping system, 87 indicators were included in the model, chosen with the help of the farmers pilot

group. Analyses were conducted on IZI-EVAL 2.0.1, an interface created to use DEXi models.

RESULTS

Implementation of agroecological farming practices

During the study, the four farmers mobilised 21 types of agroecological farming practices, which were classified into seven categories (Table 2). This large diversity of farming practices included modifications of crop sequences, the main technical operations carried out on crops (intercropping, tillage, seeding, fertilisation, pest management), and more indirect actions related to biodiversity observation and enhancement. The four farmers implemented the innovative cropping systems on their whole farms, except for fields occupied with permanent grasslands or unsuitable for some practices (for instance fields with a lot of rocks unsuitable for vegetable production or for mechanical weeding). Although the duration of the study was insufficient to observe the whole crop sequences, this working scale allowed to observe all crops.

Table 2. Agroecological farming practices tested by the four farmers in the pilot group, before and during the study. Practices were classified under general and more detailed categories. For each practice, a concrete example is given.

General categories	**Detailed categories**	***Examples***
Modification of crop sequence	Shifting the sowing date	*Spring wheat instead of winter wheat to reduce the need for fungicides*
	Inserting a new crop	*Insertion of a buckwheat crop in the sequence to diversify the system with a low inputs crop*
	Sowing cover crops	*Sowing of an oats-phacelia-radish-sunflower mix during winter to improve soil structure, reduce soil leaching and add nitrogen in the system*
Action on the soil	Mechanical weeding	*Pea hoeing instead of herbicide use*
	Using false seed beds	*False seed bed before green bean sowing to reduce the need for herbicides*
	Direct seeding into cover crops, precise seeding	*Direct seeding of winter wheat into the previous cover crop to keep a ground cover and reduce the need for herbicides*
	Reducing conventional tillage	*No conventional tillage before cereal crops to preserve soil structure*
Choice of varieties and species	Growing a resistant or tolerant variety	*Selection of a potato variety resistant to late blight to reduce the need for fungicides*
	Mixing varieties in the same field	*Mix of wheat varieties to control the development of diseases and reduce the need for fungicides*
	Combining species in the same field	*Combination of broccoli and Chinese cabbage to control the cabbage root fly and reduce the need for*

		insecticides
	Using a susceptible variety as indicator	*Sowing of a potato variety sensitive to late blight in a small area to detect the disease and adapt the amount and frequency of fungicides*
Adjustment of fertilisation	Estimating nitrate availability during plant growth and after harvest for precise N-fertilisation	*Use of an instant measuring device to adjust cauliflower fertilisation*
	Using a decision tool for fertilisation	*Mapping of nitrogen uptake by wheat crops with drones to adjust fertilisation*
	Using a manufactured natural product to promote plants nutrition	*Use of the bacterial product Rhizocell® to stimulate green beans root growth and reduce the need for fungicides*
Modification of the phytosanitary protocol	Optimising chemical weeding at the crop sequence scale	*Intensification of cereal chemical weeding to clean the crop sequence and reduce the overall need for herbicides*
	Using a biocontrol product instead of a classic pesticide	*Use of the molluscicide Sluxx® on spinach crops*
Observation of crops	Pest monitoring and adjustment of treatment thresholds	*Monitoring of carrot fly populations with sticky traps to reduce the need for insecticides*
	Using a decision-support tool for pest management	*Use of the decision tool ScanBean® to optimise Sclerotinia chemical management for green beans*
Observation and promotion of biodiversity	Participating in an observation network for farming biodiversity	*Sampling of field earthworms with the French national observatory of farming biodiversity*
	Installing nesting boxes and perches to encourage the presence of birds	*Installation of raptor nesting boxes to enhance voles predation in vegetable crops*
	Sowing flower strips	*Sowing flower strips along pea crops to enhance the biological control of aphids and reduce the need for insecticides*

Each farmer implemented a set of practices in a consistent way, i.e. following a logical combination as defined during workshops and represented in decision sketches. In figure 1, the initial and the innovative (2016 theoretical cropping system) decision sketches of farmer C are presented as an example. For this farmer, the objectives of the innovative cropping system were reached thanks to the modification of the crop sequence (order and nature of cultivated species were changed in order to improve weeds management and reduce the need for herbicides in the overall system), the suppression or the reduction of chemical treatments, and the implementation of mechanical weeding, resistant varieties, biocontrol products and other alternative practices.

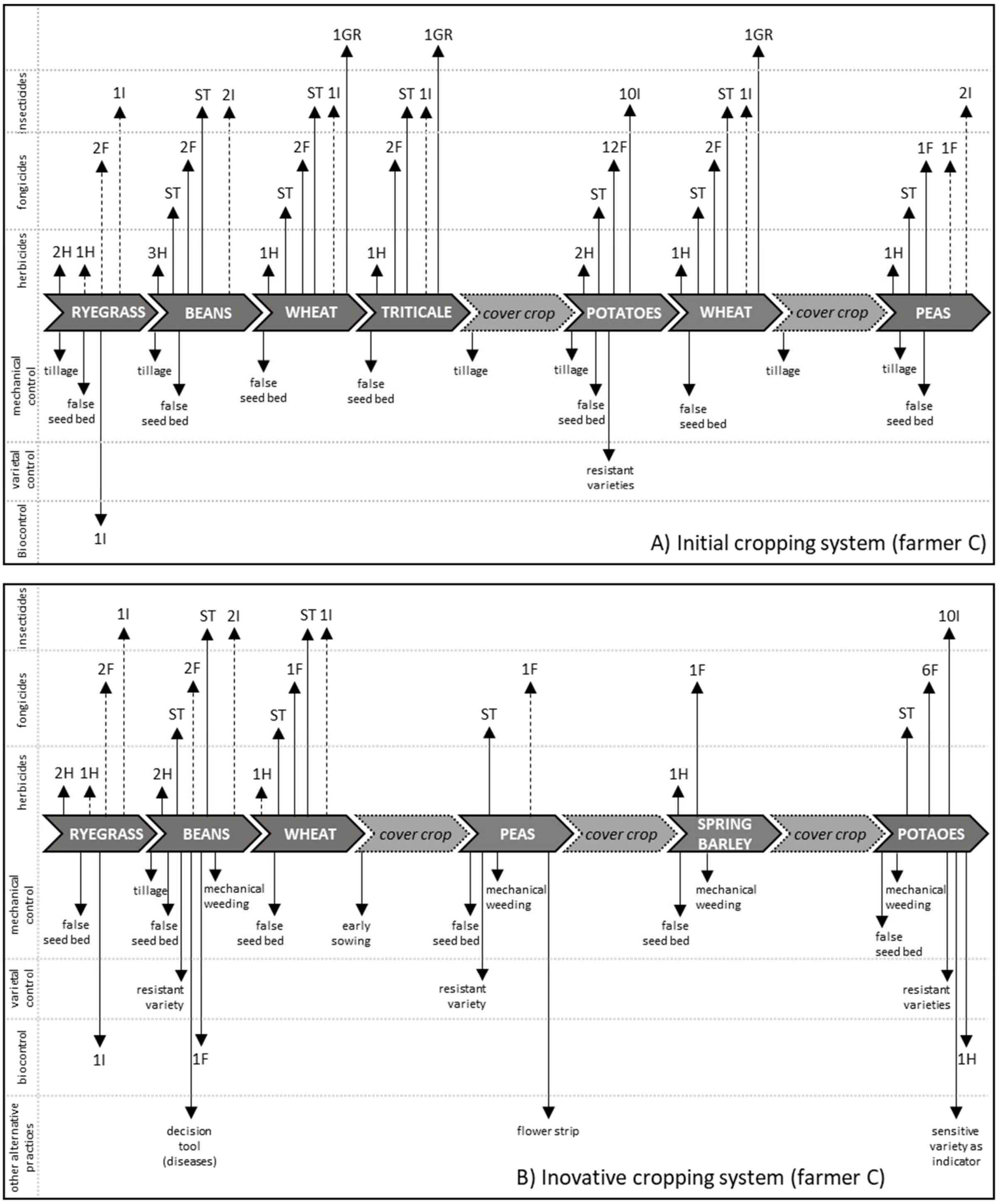

Figure 1. Decision sketches designed for farmer C after his workshop. Sketch A is the initial cropping system and sketch B is the innovative cropping system (2016 theoretical cropping system). In each figure, the crop sequence is written in the middle. The upper part is for chemical treatments: growth regulators (GR), insecticides (I), fungicides (F), herbicides (H) and seed treatments (ST). Numbers indicate the number of treatments. The lower part is for alternative farming practices, categorised in mechanical control, varietal control, biocontrol and other practices. Full arrows indicate systemic practices and dotted arrows indicate non-

systematic practices. Fertilisation is not indicated on the sketches because no change was done for farmer C.

Fourteen of the 21 agroecological farming practices had previously been put to the test by farmers in their initial cropping sytem (Figure 2). Most of them, such as false seed bed, picking a resistant or tolerant variety or sowing of cover crops, are low-risk, and are part of the most trialed practices during the study. Due to the high level of technical skills of several of the farmers, more risky practices were also observed in the initial cropping systems (*e.g.* direct seeding into cover crop and mechanical weeding on vegetable crops).

Most of the trialed farming practices involved actions on the soil, such as the creation of false seed beds and mechanical weeding. The cooperative encouraged farmers to use a natural molluscicide on many crops, which explains the significant use of biocontrol products. Promoting plant nutrition was also one of the main concerns of the group and especially the farmers, who used natural products to stimulate root growth, enhance nutrient absorption, or improve soil structure by promoting bacteria and fungi. Using a decision-support tool for pest management was also a recurrent farming practice, and a variety of models was proposed to the farmers. Several practices related to the observation and promotion of biodiversity were implemented by almost all farmers on different crops. These included sowing flower strips and installing nesting boxes and perches for birds.

Some of the less experimented farming practices required a higher technical level, such as direct seeding into cover crops, the combination of different species or uptake of a new crop. Optimising fertilisation was not a priority subject during workshops, so few practices were targeted to this purpose. Cooperatives decide on sowing dates of industrial vegetable crops at a regional scale to ensure the timely supply to the factories, so few changes were proposed regarding crop timing.

Fifty percent of the agroecological farming practices were directed to the vegetable crops, 33% to other crops, and 17% to the whole cropping system. Some practices were preferentially tested on vegetable crops, such as the use of natural products to promote plant nutrition, mechanical weeding, selection of resistant or tolerant varieties, the use of decision tools for pest management, sowing of flower strips, and pest monitoring. In contrast, other practices were preferentially tested on other crops, such as the use of a decision tool for fertilisation, mixing varieties, and direct seeding into cover crops.

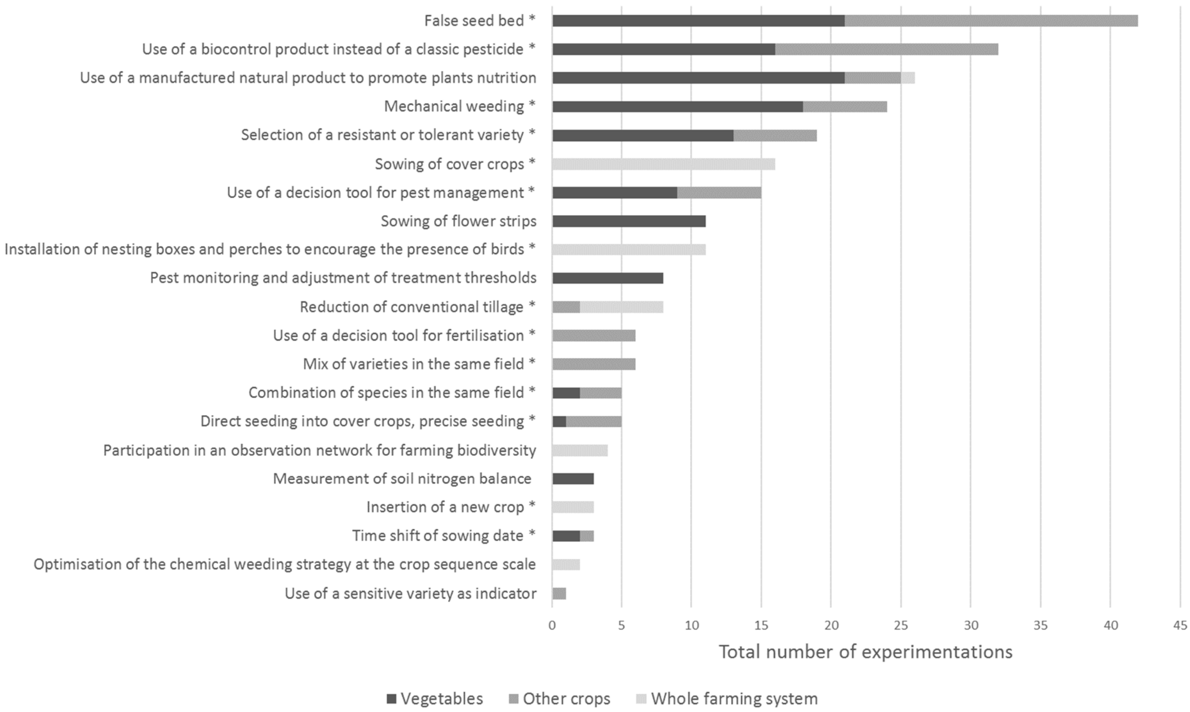

Figure 2. Total number of trials for each agroecological farming practice, based on the detailed categories described in Table 2. One trial is one farming practice used one time by one farmer on one crop during the study. The application scale is specified with different colours, separating practices applied on vegetable crops, on other crops (cereals, oilseed rape, buckwheat, etc.), and at the whole cropping *system scale. Practices trialed by at least one farmer before the study are identified with a star.*

Farmers had varying levels of initial involvement in agroecology, as reflected in the composition of their initial cropping systems (Figure 3). From 13 to 24 innovative agroecological farming practices were proposed during workshops and added to the initial ones. During the workshops, more new farming practices were proposed to the farm with the most intensive initial cropping system (farmer D) than to the others (24 propositions in 2016). The farmers implemented 73% of the farming practices selected for theoretical cropping systems during the study (70% in 2016, 79% in 2017 and 69% in 2018). This mean percentage varied considerably between farmers, reaching 81% for farmers A and C, 68% for farmer B and 59% for farmer D.

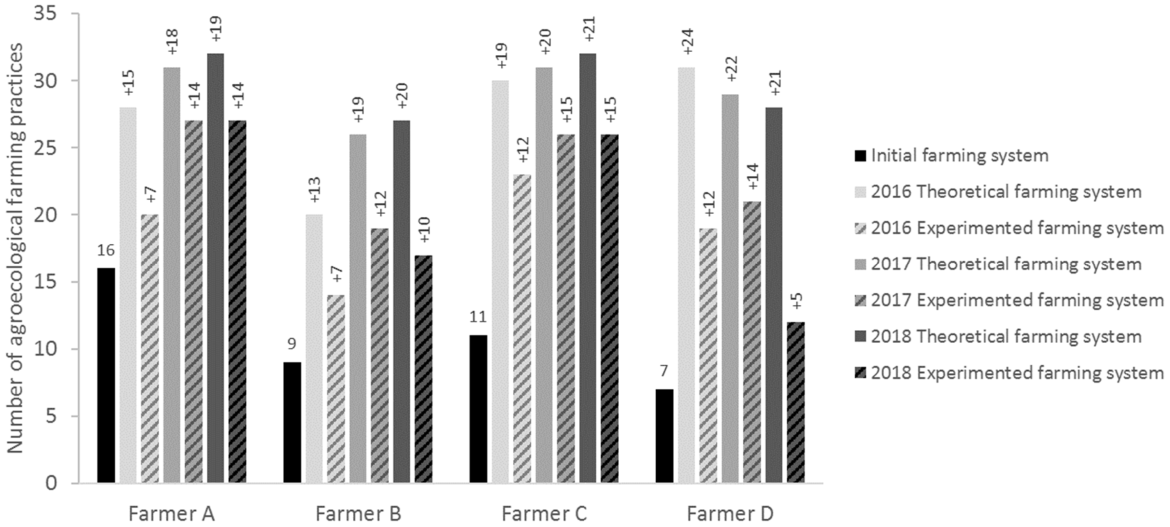

Figure 3. Evolution in the number of agroecological farming practices in the four cropping systems, from the initial approach (before the study) to the last trialed systems (in 2018). Theoretical cropping systems are those designed during workshops. Experimented cropping systems are those actually trialed in fields. Numbers indicated are the initial numbers of agroecological farming practices and the added numbers of innovative agroecological farming practices. Agroecological practices in the initial cropping systems were not always included in the innovative cropping systems.

The main reason for not implementing a proposed agroecological farming practice during the study period was lack of time (Figure 4). This included time-consuming practices such as mechanical weeding and measuring the soil-nitrogen balance. The farmers also found that a significant number of the practices were not effective enough after a first trial, and abandoned them the following years. These practices were diverse (mix of varieties, pest monitoring, use of decision tools, etc.) and were not the same for all farmers. Weather was also a recurrent constraint, especially concerning actions on the soil (*e.g.* mechanical weeding). Both the farmers and their technical advisers were very cautious about any risk to production, and this was consequently a major obstacle to some changes in the cropping systems. For many of the practices, the farmers and cooperative needed to anticipate the steps to implement the change, well in advance, for example to prepare the products (*e.g.* varieties or biocontrol products) and material (*e.g.* mechanical weeding equipment). This was identified as a major weakness of the study since a significant number of agroecological farming practices could not be trialed for this reason. Although economic support was offered to the farmers for testing new practices, costs remained a big concern, especially concerning the use of biocontrol products. Finally some practices were not investigated simply because they were useless in a specific context (*e.g.* when the pest pressure was very low).

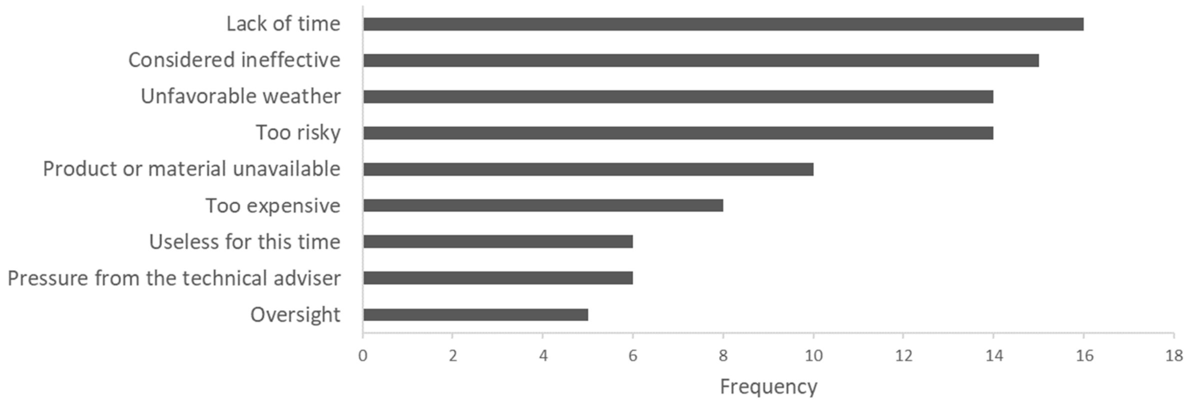

Figure 4. Reasons given by farmers in 2016, 2017 and 2018 for not trialing agroecological farming practices proposed in theoretical cropping systems.

Cropping system sustainability

All farmers reduced their pesticide use during the study (Figure 5), with a mean TFI reduction of 15%. However, the farms had varying trajectories. Farmers A and B had the lowest TFI regardless of the year, showing their commitment to agroecology. Farmer A mostly reduced his pesticide usage in 2016 and then preferred to replace classic pesticides with biocontrol products. The TFI for Farmer B progressively decreased during the study. This change was partly due to the purchase of a seeder in 2018 to carry out direct seeding into cover crops. The high TFI of farm C was mainly due to seed potato crops, which required a high level of pesticide inputs. Indeed, late blight and click beetles are two major pests of this crop, for which few alternative farming practices are actually available, apart from the use of resistant cultivars (for late blight). Nevertheless, farmer C still reduced his TFI by 20% and integrated some biocontrol products into his cropping system. Farmer D was the least experimental and committed to agroecology at the beginning of the study. His high TFI can also be explained by the presence of double crops in his cropping system, i.e. successions of two crops in the same field and during the same year (*e.g.* spinach then carrots). The numerous propositions made to farmer D during his workshop allowed him to reduce pesticide use, especially at the beginning of the project. His TFI increased in 2018, partly because of the use of biocontrol products. This increase was also due to a lower support from advisers and researchers during this year.

In addition to the trials of agroecological farming practices, it is important to note that annual variations in TFI were also related to external and uncontrollable factors such as weather and pest pressure.

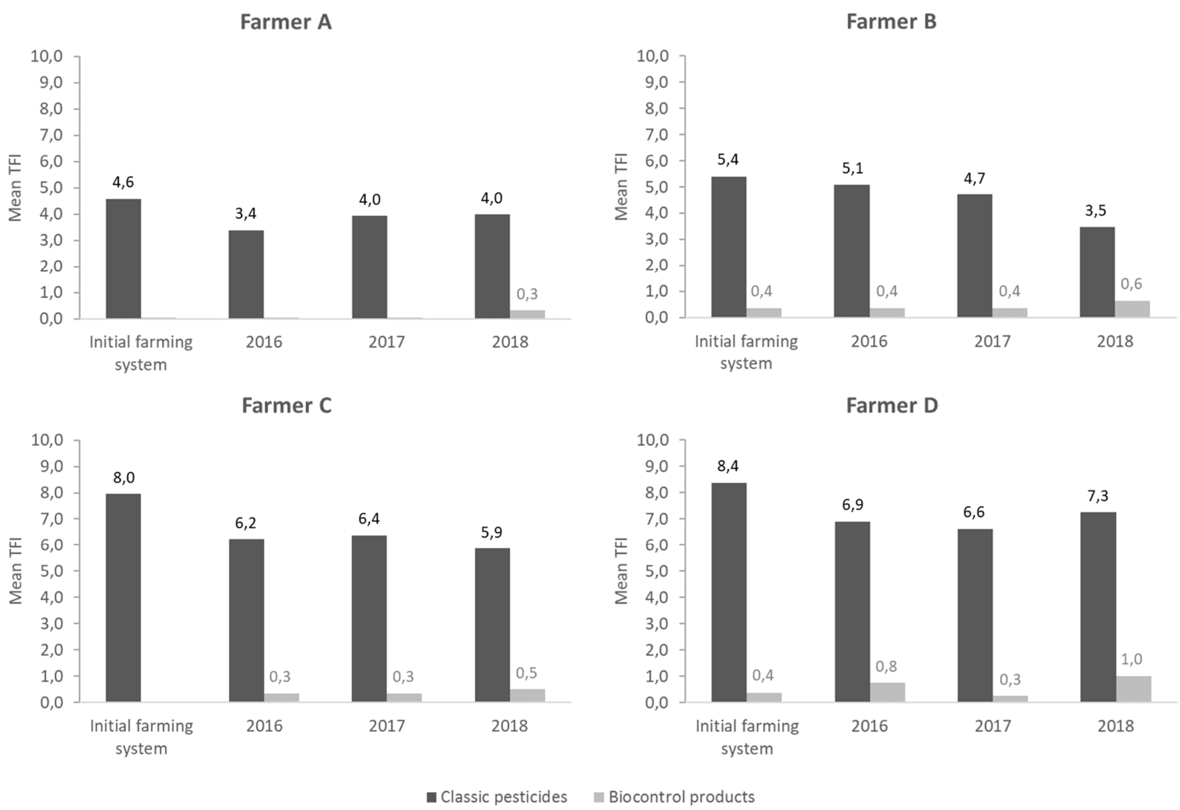

Figure 5. Evolution in mean annual TFI (Treatment Frequency Index) for the four farmers during the study. Initial and trialed cropping systems are shown. The TFI of classic pesticides (in dark grey) and biocontrol products (in light grey) were calculated separately.

Multi-criteria analyses showed that there was no significant change in cropping system sustainability (Figure 6), between the initial and the innovative practices, or between the three experimental years. Only two farmers enhanced their environmental parameters over at least one year. This was related to biodiversity state (farmers B and C), environmental quality (farmer C), and resource use (farmer B). Social parameters only evolved for farmers B and D, for which interactions with society were higher in all innovative cropping systems. On the other hand, the economic profit was lower in all the innovative cropping systems at farms A, B and C.

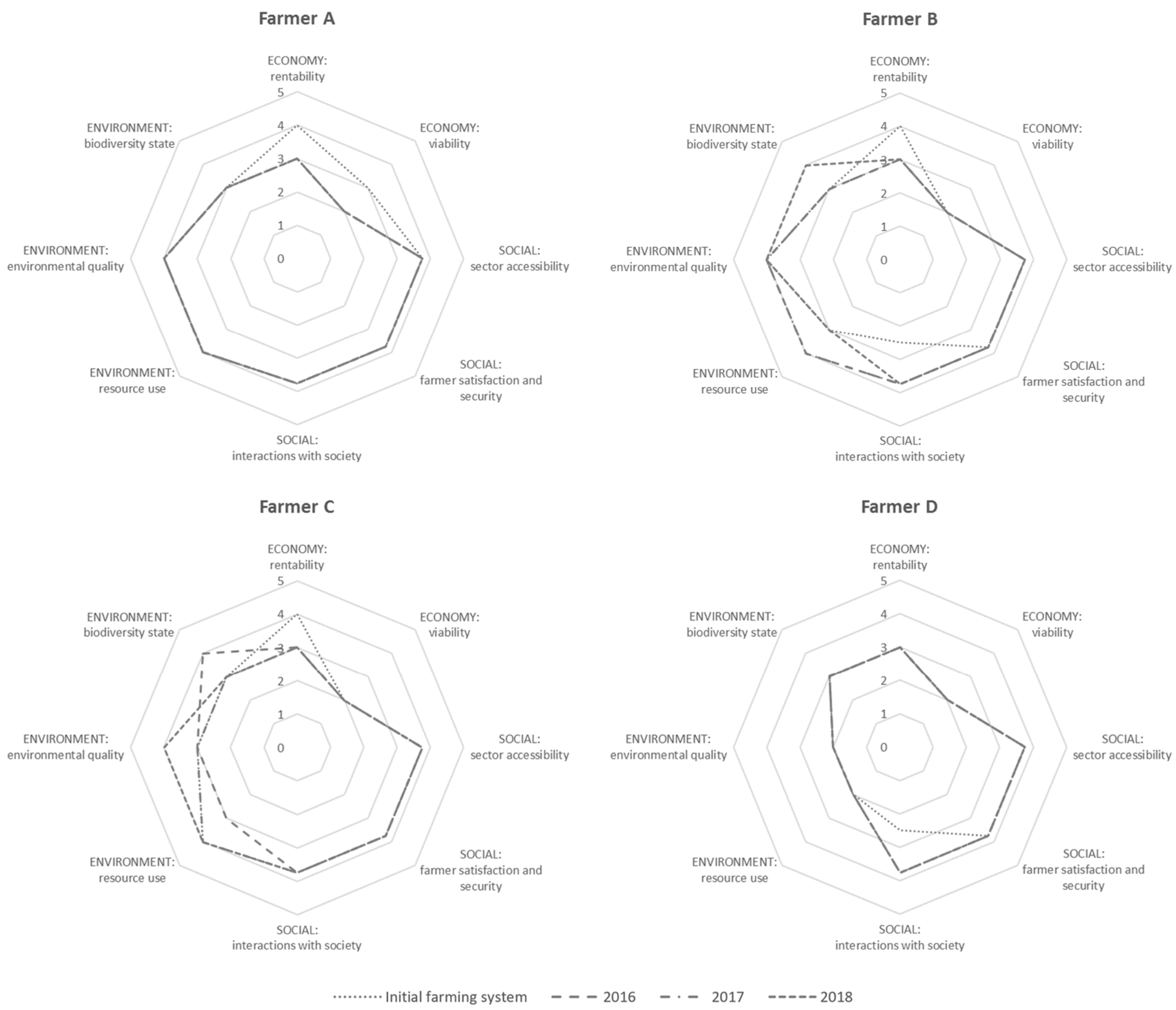

Figure 6. Results of multi-criteria analyses carried out with DEXiPM-FV for the four farmers. Initial and trialed cropping systems are shown. Rentability reflects gross margin and financial aid ; Viability reflects economic independence and efficiency ; Sector accessibility reflects the availability of inputs, workforce, markets and technical advice ; Farmer satisfaction and security reflects the complexity of cropping systems and associated health risks ; Interactions with society reflects contribution to employment, acceptability of farming practices by society, and social value of the surrounding landscape ; Resource use reflects energy consumption and use of water, soil and mineral fertilisers ; Environmental quality reflects water and soil quality, and air pollution ; Biodiversity state reflects the abundance and diversity of terrestrial and aerial species.

<u>Evaluation of the methodology</u>

Based on these results and on discussions with the four farmers, Ardo, Picard and the two researchers from INRAE collectively approved the methodology, since it allowed to design and test cropping systems that can contribute to initial aims. In spite of the mixed results concerning TFI reduction and cropping system sustainability, it was indeed possible to reduce the environmental burdens of farming practices for two of the four farmers involved, and to anticipate the progressive ban of phytosanitary products thanks to the combination of various alternative practices. The three collaborators consequently decided to continue the project by including more farmers.

DISCUSSION

Design of innovative cropping systems for the industrial vegetable sector: what is the outcome?

The 15% mean reduction in TFI obtained from the 21 agroecological practices included in the innovative systems tested by the four pilot farmers is low compared to the aims of current government policies. In France, the “Ecophyto plan” aims to reduce the use of chemical pesticides by 50% by 2025 (French ministry of agriculture agribusiness and forestry, 2015b). Results recently shown by the DEPHY network showed that a reduction of 38% TFI can be reached for vegetable crops (Eckert et al., 2018). At the same time, some studies have shown for other sectors that reducing pesticide usage by 42% can be achieved without negative impacts on productivity and profitability (Lechenet et al., 2017). However, no studies have been published to date on the specific case of the industrial vegetable sector, and the TFI reduction was actually interpreted as a satisfactory result by farmers, Ardo and Picard, given their difficulty in reducing pesticide use. As previously mentioned, the industrial vegetable sector is characterised by strong constraints related to the expectations of consumers, the profitability of distributors, the processing steps of industrial companies, and the agronomic, economic, social and environmental aspects of cropping systems. Such constraints highlight the limits of the industrial model, as already discussed by many authors (D'Souza and Ikerd, 1996; Horrigan et al., 2002; Woodhouse, 2010), and could indicate that a strong TFI reduction in such systems is actually not possible because of lock-in effects (Fares et al., 2012; Lamine, 2011).

Meynard et al. (2017) explain that when a socio-technical system is well-established, few innovations have a chance of emerging because dominant actors do not want to question their successful strategies. In this study, dominant actors (Picard and Ardo) were directly involved in the design of innovative cropping systems and ready to question their strategies. However, although Ardo and Picard mentioned possible adaptions of their strategies during workshops (*e.g.* for Ardo, improvement of optical sorting, and for Picard, creation of a new agroecological product range), none of these suggestions led to actual decisions during the three years. This is because the duration and the scope of the study were too short to make such decisions, which can have strong economic consequences and would require a long and collective consideration within each company.

The multi-criteria analyses carried out as part of the study did not show a significant improvement in cropping system sustainability, unlike in other co-design studies (Berrueta et al., 2021; Dogliotti et al., 2014). Although some farmers increased the environmental and social parameters of their systems, economic performance was identified as a major weakness. This is due to the cost of alternative biocontrol products (often much more expensive than conventional pesticides), to the investment needed in specific farming tools, and to the higher risk of yield losses. In the same way, the practices most often tested during the study were the least risky ones, *i.e.* those not strongly related to the operation of the whole cropping system and unlikely to lead to a reduction in production quality or quantity (*e.g.* false seed bed or choice of resistant/tolerant varieties). This selection shows the natural reluctance of farmers and technicians to take risks because of potential economic losses (Chantre and Cardona, 2014). Such observations have already been made in other studies (Jacquet et al., 2011; Lien et al., 2007; Pardo et al., 2010; Smith et al., 2011), underlying the difficulty of obtaining satisfactory economic results during transitions to organic or agroecological farming systems. Fares et al. (2012) demonstrate that the organisational structure of agrifood systems can indeed be a lock-in for transition and innovation, because economic investments are hampered by downstream actors.

Based on these observations, Ardo, Picard and INRAE finally approved the cropping system design methodology, arguing that the TFI reduction observed is promising and is the first step in a potentially larger movement in which other farmers and cooperatives could be involved. They collectively decided to continue the project for another three years second phase, with the target to involve more and more farmers. An essential point is that Ardo and Picard concluded that farmers cannot be asked to change their systems without increasing the purchase price of their vegetables. Together, they set a percentage increase in the purchase price of the vegetables produced as part of the study.

Design of innovative cropping systems for the industrial vegetable sector: what lessons can be learned?

The integration of agroecological practices within the current cropping systems relied on the co-design methodology proposed by Launais et al. (2014). All collaborators in the study appreciated this framework and it was considered successful since it allowed the assimilation of various agroecological farming practices and the reduction in pesticide use, in spite of the low flexibility of the sector and of mixed economic results. Four methodological aspects were identified as key points, which should be taken into consideration in farm system design for industrial sectors: farm system scale, collective work, farm systems flexibility, and farm systems uniqueness.

Farm system scale

The first initiatives for farm system redesign date back to the 1990s (Spiertz et al., 1996). The systemic approach has been highly encouraged for the last decade because, compared to an analytical approach, it can facilitate innovation and transition toward more sustainable systems (Berrueta et al., 2021; Darnhofer et al., 2012; Meynard et al., 2012; Probst et al., 2012; Wigboldus et al., 2016). During this project, the innovative systems were designed considering all crops in the sequences, with 55% of new practices targeting vegetables and 45% the other species. Discussions during workshops and representation in the form of decision sketches aimed to take into account interactions between crops and techniques. For instance, when a winter cover crop containing species susceptible to *Sclerotinia* root rot and damping-off was selected, a biocontrol product was also placed in the sequence to prevent the development of the disease. As for all approaches based on collective design of innovating cropping systems, this coherent combination of farming practices was essential to create robust and credible cropping systems and relied on in-depth technical knowledge (Meynard et al., 2012; Reau et al., 2012). Moreover, the systemic approach led farmers and their technical advisers to analyse cropping systems in a different way, since ‘contract’ crops (vegetables and seed crops) and ‘non-contract’ crops are usually managed separately (with different technical advisers and for different markets). Working at the crop sequence scale allowed to make modifications in the management of vegetables, which is usually locked by specifications. For instance, the composition of crop sequences can be changed to better manage weeds and reduce herbicide use on vegetables.

Collective work

Farmers, researchers, technicians and engineers from a cooperative, an industry and a distributor conducted this study for three years. This kind of collaboration is rare, and farmers are more used to a top-down information flow from technical advisers, agribusiness actors, or politicians (Coquil et al., 2018; Darnhofer et al., 2012; Duru and Therond, 2015). However, as explained by Lamine (2011), collective dynamics are better at supporting robust transitions toward agroecological systems. In this study, working collectively allowed consensual cropping systems to be designed, and solutions to promote agroecology in the industrial vegetables sector to be thought about collectively. This was possible because the risk associated with agroecological transition was distributed among stakeholders.

With the development of co-design approaches, farmers, technical advisers and researchers are now commonly involved in the design of innovative cropping systems (Berrueta et al., 2021; Falconnier et al., 2017; Le Bellec et al., 2012; Lesur-Dumoulin et al., 2018; Moraine et al., 2016; Reckling et al., 2020). The strong originality of this study is the participation of a processing company and a distributor. Discussions during workshops showed that Picard was actually not completely aware of agronomic, economic and social issues inherent to the vegetable production phase, as well as technical limits inherent to the processing phase. They realised that specifications are sometimes very hard to reach with these constraints and with a possible transition toward agroecology. For instance, the complete lack of dead insects in vegetable bags can actually be incompatible with the promotion of biological control in crops and with the performance of optical sorters used in processing factories. As explained in the previous section, this awareness did not lead to actual modifications of specifications requested by Picard. However, they initiated a real questioning about products from agroecological production, especially with the quality and marketing departments of the company, which could lead to modifications of their sales strategy in the years to come. Consumers education campaigns aiming to explain how farmers produce agroecological vegetables can for instance help in supporting the development of agroecology (Francis et al., 2003).

The presence of Ardo during workshops had a significant impact on the design of innovative cropping systems. Indeed, the contractual system imposes on farmers precise specifications defined by industries in order to optimise the processing procedure (Henson and Humphrey, 2012). Without Ardo, few innovations would have concerned the vegetable crops themselves, because farmers could not fully exploit all agroecological measures envisioned during the workshops. For instance, the management of pests is defined in a precise and collective program that leaves little latitude to farmers, and that has been modified thanks to the presence of Ardo. In the same way, sowing of vegetables being organised at the scale of production areas, changing the sowing date of their own crops could not have been possible without Ardo. This observation raises the problem of the scale at which design methods are conducted. The management unit for industrials is actually the batch, and not the crop, the field or the farm (Meynard et al., 2017). In such a context, collective design should consequently be ideally conducted at the collecting area scale, as it was already done for other crops (Le Bail and Meynard, 2003; Navarrete et al., 2006). Discussion about innovative cropping systems also led Ardo to question their process. Their main challenge concerns the sorting of foreign bodies collected during harvest (plant debris and animals). This can have strong repercussions on consumers satisfaction, but also on health. Some weeds, such as *Datura stramonium*, are indeed very toxic and can cause death if stems, leaves or fruits are left and consumed with the vegetables. However, several agroecological farming practices (*e.g.* direct seeding into cover crops, promotion of natural enemies) may increase the amount of exogeneous materials that cannot be properly sorted during the process. As for Picard, this questioning did not lead to concrete decisions during the study, partly because an improvement of optical sorters would require significant investments. However, they could consider it seriously if the continuation of the project results in the processing of a sufficient tonnage of “agroecological vegetables”.

During the study, farmers learned about industrial processes and the need for Picard to meet customer’s expectations. As explained by Bos et al. (2009), an essential aspect of design methods is the collective learning, leading everyone to increase their knowledge. In this study, exchange between collaborators allowed the recognition and consideration of the constraints of each participant. It helped to create a climate of trust during workshops and to collectively define the limits of innovation. The four farmers were also very satisfied to have the opportunity to express their concerns and issues to downstream actors. Discussions between such different stakeholders are indeed rare, which contributes to the imbalanced power relationships observed in food industry (Duru and Therond, 2015; Stuart and Worosz, 2012). The four farmers had contrasting experiences and were initially interested in different farming techniques. During workshops, they naturally shared advice and knowledge, which highly enriched their innovating cropping systems. Indeed, this kind of “farmer-to-farmer” learning has already been identified as an efficient way to expand agroecology (Mier y Terán Giménez Cacho et al., 2018; Rosset and Martínez-Torres, 2012; Sumane et al., 2018).

Collaboration between farmers and technical advisers was also decisive because farmers needed strong support to implement their innovative systems, and especially in planning and anticipating the needed material, varieties and products. Lack of anticipation was indeed identified as one of the main weaknesses, leading some practices to not being tested when advisers were not present enough. Discussions with farmers also revealed that advice from technicians is widely followed in vegetable crops. The strong influence of cooperatives on farmer choices is due to the fact that industrial vegetable crops are grown under contracts, and regularly subjected to important yield losses. Farmers do not want to risk losing a crop and prefer to delegate the main technical decisions. Indeed, technical advisers involved in the study were used to make their decisions with a ‘safety first’ strategy, for instance with a preventive use of pesticides. Based on this observation, we argue that involving agricultural cooperatives and technical advisers in the design and testing of innovative contract cropping systems is essential, since farmers decisions are closely related to advisers decisions. Technical advisers need to be trained in systemic approach and in the use of alternative farming practices. The importance of cooperatives during the agroecological transition has already been highlighted by other authors, questioning the top-down organisation of advisory systems widely used since the agricultural modernisation period (Brives et al., 2015; Coquil et al., 2018; Del Corso et al., 2015).

Researchers finally played a strategic role in the testing of the new cropping systems, especially the highly innovative practices needing a particular type of monitoring (*e.g.* the combination of species to control a pest), or time-consuming practices needing specific knowledge (*e.g.* participation in a biodiversity observation network). Without their support, farmers would not have attempted some tricky practices (for instance, the combination of broccoli and Chinese cabbage to control the cabbage root fly was proposed and supervised by a researcher and a PhD student). Moreover, involving researchers in farmers' transition to agroecology is essential, since it can provide a scientific evaluation of the practices (Coquil et al., 2018). During the study, farmers and their technical advisers indicated that some agronomical issues constitute technical dead-ends and that they are waiting for innovations, sometimes in an urgent way because of the upcoming ban on several phytosanitary products. For instance, banning glyphosate in France will require the development of suitable machinery to manage weeds in vegetable crops. Organic farmers producing industrial vegetables are indeed faced with difficult weed management, resulting in lower and more fluctuating yields than conventional farmers, and higher risk of contamination by toxic species. Similarly, the promotion of conservation biological control at various scales is a complex issue that still needs specific recommendations to be used by farmers (Wezel et al., 2014). Duru and Therond (2015) underlined that knowledge produced by scientists about biodiversity and ecosystem services is currently too general to be used in the design and the management of agroecological farm systems. They argue that a great challenge for research is to develop operational knowledge to help stakeholders in agroecological transition.

Farm system flexibility

Two major types of approach regarding the design of innovative cropping systems have been described in the literature: *de novo* design refers to the design of systems that break away immediately from existing ones, whereas step-by-step design refers to more progressive, incremental transitions (Meynard et al., 2012; Meynard and Casabianca, 2011). In this study, in order to obtain operational and strongly innovative cropping systems in a short time, the initial desire was to implement a *de novo* design. During workshops, participants were encouraged to propose strong innovations, breaking with initial systems. Farmers were then asked to test innovative systems in their entirety from the first year, *i.e.* implementing all alternative farming practices as soon as possible. However, the three years of observation showed that only 73% of the agroecological farming practices proposed to farmers were enforced, with significant variations between years for each farmer. The reasons for not testing or implementing specific practices were multiple, but mainly related to available means, organisation and annual context. This result suggests that a *de novo* design is actually difficult to achieve in this kind of context and short time frame. It is probably further hindered by the strong regulations associated with industrial production which hampered transition, and must have contributed to the farmers' path-dependency. This concept explains that farmers have often difficulties to make their production systems evolve because of the high costs of converting from a dominant model to a new innovative one (Chantre and Cardona, 2014; Vanloqueren and Baret, 2009). As mentioned before, the context of this study may also explain the slow progression of farmers. *De novo* approach is indeed more suitable for model-based design, since it allows a very wide exploration of technical combinations to be carried out (Meynard et al., 2012). When *de novo* systems are tested, they are preferentially implemented in experimental platforms where there is no risk to jeopardise a farmer's production (Havard et al., 2017). In this study, working directly in the production context seemed finally more suited to a step-by-step approach. It means that in such systems, a progressive transition is unavoidable. Innovation is more careful but cropping systems remain more flexible, which facilitates their adoption by farmers (Meynard et al., 2012). Farmers indeed need time and insurance to adopt new combinations of practices and check that their system makes sense and is economically secure. In the long term, it was shown that modifying practices progressively helps create systems that are more robust and avoid reversible transitions (Lamine, 2011).

Farm system flexibility is essential to face annual and inter-annual variations in weather, pest pressure, and market prices (Darnhofer et al., 2010; Lev and Campbell, 1987). Due to global warming, ecosystem disruption, and market globalisation, farmers are increasingly challenged with these types of fluctuations and need to anticipate them. The contract system and the sensitivity of vegetables to many pests and diseases make farmers involved in the study particularly concerned with this kind of economic and agronomic risks. This was highlighted by significant variation in the number of farming practices tested between years for each farmer. This finding is important since it suggests that agroecological farm systems cannot be built as unique and static assemblies. Each pest must be managed considering the varying situations that can be encountered. Although it was not done during this study, taking time to determine decision-making rules when innovative cropping systems are designed can strongly help reaching this aim (Launais et al., 2014). Continuously adapting farming practices to context also requires that crops are observed very regularly and farmers have access to surveillance networks. In France, farmers can, for example, read a public bulletin dedicated to pest pressure evolution at a regional scale several times a week. These tasks are time-consuming and must be taken into account in the evaluation of agroecological farm system sustainability.

During workshops, participants could design innovative and consistent cropping systems thanks to a large panel of agroecological farming practices. It shows there is actually some scope to make industrial vegetable cropping systems more sustainable. This diversity in available practices is important since it increases the possibility for farmers to select and combine a set of techniques adapted to their aims and to the agronomic and economic specifications of their farms. During the study, some practices were however abandoned by farmers because they found them either inefficient or too risky (*e.g.* the combination of broccoli and Chinese cabbage to control the cabbage root fly). In the same way, some technical dead ends were identified during workshops, related to material, tools and knowledge that were not yet available (e.g. the lack of direct seeding equipment for vegetable crops). Thus, some innovative techniques actually need additional research and may not be fully operational for periods ranging from a few years to decades. In the long term, cropping systems need consequently to remain flexible to integrate technical innovations from research and development. Farmers must be able to easily swap some practices for others. This relies on a continuous learning process and monitoring of outcomes. Such skills were indeed identified as a major strategy for strengthening the adaptive capacity and sustainability of farm systems (Darnhofer et al., 2010).

Farm system uniqueness

One of the interesting points of this study is the heterogeneity in the farmer pilot group. The diversity in their profiles was a continuous reminder that each cropping system is built within a specific context, and for specific objectives. First, the localisation of the farm implies specific soil and climatic conditions, affecting crops directly (*e.g.* concerning nutrients availability) or indirectly (*e.g.* concerning pest pressure) (Altieri and Nicholls, 2003; Tamburini et al., 2018). Landscape parameters, such as the abundance and accessibility of semi-natural elements, can also strongly affect ecological processes related to crops (biological control, pollination) (Martins et al., 2015; Veres et al., 2013). Otherwise, the innovative farming practices selected during workshops were often related to the priorities and preferences of each farmer. Some authors indeed showed that farmers personality, experience and knowledge can largely determine farm system composition, functioning and evolution (Edwards-Jones, 2006; Shrapnel and Davie, 2001; Willock et al., 1999). All these parameters led to contrasted cropping systems, whose heterogeneity is increased in the industrial vegetable context. Indeed, in the region where the study was conducted, this sector is characterised by big farms and diversified farm systems, with a minimum of three different activities such as livestock farming or cereal production (Pierron, 2016). Farmers integrate industrial vegetable in their systems in order to diversify their crop sequences and to increase their income.

This heterogeneity must be considered during a design process because it is not possible to directly transpose a farm system from farmer to farmer. A unique and perfect sustainable agroecological system does not exist, because "*no single package of practices is able to fit the dynamics of every ecosystem*" (Pretty, 2018). On the contrary, there are as many farms and farmers as good agroecological farm systems to build. This suggests that innovative cropping system design processes should be organised as much as possible at the farmer scale to take individualities into account (Lacombe et al., 2018). This is especially true for the industrial vegetable sector because of the high heterogeneity in cropping systems.

CONCLUSION

In this study, we showed that designing and testing innovative agroecological cropping systems for the industrial vegetable sector is possible, and can help finding new ways to comply with value chain demands, related to the expectations of consumers, the profitability of distributors and the processing steps of industrial companies. However, some precautions must be taken to ensure the success of the design process:

- Time is needed to build cropping systems adapted to each farmer and compatible with specifications. There is a time lag from the design of theoretical systems and the period necessary for farmers to adopt new practices and gradually select the best combination.
- Human resources and training are needed to assist farmers, especially during the first years. They need help planning and anticipating the equipment needed and training to increase their technical knowledge.
- Money is needed, to compensate for the extra time needed to implement new systems, the rising costs and the higher risk of yield losses.

Such recommendations can be hard to follow because time and money are often two missing parameters when agroecological transitions are initiated, and that is why such processes must be taken on collectively. In this study, the collaboration of Picard, Ardo, INRAE, the cooperative and the farmers was essential for making decisions at the sector scale, spread the risks and create an enduring dynamic. Indeed, in 2019, it was decided to extend the study to twenty farmers in the sector. Agroecological regulations were developed, which will have to be followed by farmers who want to join the project and benefit from an economic revaluation of their vegetables (increase in purchase price). For Picard, this could be the first step in a broader process, their ambition being to deploy agroecology on a large scale and meet consumer expectations by offering healthier products. For Ardo, it will be a good opportunity to make their technical equipment evolve toward the processing of a larger amount of agroecological products. For INRAE, it presents the possibility to learn more about transition process in the specific context of industrial farming. To go further, it will be essential to measure the impact of innovative cropping systems on the marketing aspects of production, for instance with a monitoring of product quality, production costs and commercial yields.

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REFERENCES

Agreste, 2016. Mémento de la statistique agricole - Bretagne. Direction régionale de l'Alimentation, de l'Agriculture et de la Forêt, 13p.

Altieri, M.A., 1989. Agroecology: A new research and development paradigm for world agriculture. Agriculture, Ecosystems & Environment 27, 37-46.

Altieri, M.A., Nicholls, C.I., 2003. Soil fertility management and insect pests: harmonizing soil and plant health in agroecosystems. Soil and Tillage Research 72, 203-211.

Aubertot, J.-N., Guichard, L., Jouy, L., Mischler, P., Omon, B., Petit, M.-S., Pleyber, E., Reau, R., Seiler, A., 2011. Guide pratique pour la conception de systèmes de culture plus économes en produits phytosanitaires. Réseau Mixte Technologique Systèmes de Culture Innovants, 115p.

Barbier, J.M., Constant, N., Davidou, L., Deliere, L., Guisset, M., Jacquet, O., Lafond, D., Panon, M.-L., Sauvage, D., 2011. CEPviti: co-conception de systèmes viticoles économes en produits phytosanitaires.

Bernardin, A., 2018. Les légumes en conserve et surgelés en 2017. Unilet - Bilan économique 2017, 27p.

Berrueta, C., Giménez, G., Dogliotti, S., 2021. Scaling up from crop to farm level: Co-innovation framework to improve vegetable farm systems sustainability. Agricultural Systems 189, 103055.

Boccaletti, S., Nardella, M., 2000. Consumer willingness to pay for pesticide-free fresh fruit and vegetables in Italy. International Food and Agribusiness Management Review 3, 297-310.

Bos, A., Koerkamp, P.G., Gosselink, J., Bokma, S., 2009. Reflexive interactive design and its application in a project on sustainable dairy husbandry systems. Outlook on agriculture 38, 137-145.

Brives, H., Riousset, P., de Tourdonnet, S., 2015. Chapitre 7. Quelles modalités de conseil pour l'accompagnement vers des pratiques agricoles plus écologiques?, Conseil privé en agriculture. Educagri éditions, pp. 133-148.

Bruchon, L., Le Bellec, F., Vannière, H., Ehret, P., Vincenot, D., De Bon, H., Marion, D., Deguine, J.P., 2015. Guide Tropical – Guide pratique de conception de systèmes de culture tropicaux économes en produits phytosanitaires. Le Bellec F. (Ed.), CIRAD, Paris, 210 p.

Carvalho, F.P., 2017. Pesticides, environment, and food safety. Food and Energy Security 6, 48-60.

Chantre, E., Cardona, A., 2014. Trajectories of French Field Crop Farmers Moving Toward Sustainable Farming Practices: Change, Learning, and Links with the Advisory Services. Agroecology and Sustainable Food Systems 38, 573-602.

Coquil, X., Cerf, M., Auricoste, C., Joannon, A., Barcellini, F., Cayre, P., Chizallet, M., Dedieu, B., Hostiou, N., Hellec, F., Lusson, J.-M., Olry, P., Omon, B., Prost, L., 2018. Questioning the work of farmers, advisors, teachers and researchers in agro-ecological transition. A review. Agronomy for Sustainable Development 38.

D'Souza, G., Ikerd, J., 1996. Small Farms and Sustainable Development: Is Small More Sustainable? Journal of Agricultural and Applied Economics 28, 73-83.

Darnhofer, I., Bellon, S., Dedieu, B., Milestad, R., 2010. Adaptiveness to enhance the sustainability of farming systems. A review. Agronomy for Sustainable Development 30, 545-555.

Darnhofer, I., Gibbon, D., Dedieu, B., 2012. Farming Systems Research: an approach to inquiry. In: Darnhofer I., Gibbon D., Dedieu B. (eds) Farming Systems Research into the 21st Century: The New Dynamic. Springer, Dordrecht, 3-31.

Debaeke, P., Munier-Jolain, N., Bertrand, M., Guichard, L., Nolot, J.-M., Faloya, V., Saulas, P., 2009. Iterative design and evaluation of rule-based cropping systems: methodology and case studies. A review. Agronomy for sustainable development 29, 73-86.
Del Corso, J.-P., Kephaliacos, C., Plumecocq, G., 2015. Legitimizing farmers' new knowledge, learning and practices through communicative action: Application of an agro-environmental policy. Ecological Economics 117, 86-96.
Dogliotti, S., García, M., Peluffo, S., Dieste, J., Pedemonte, A., Bacigalupe, G., Scarlato, M., Alliaume, F., Alvarez, J., Chiappe, M., 2014. Co-innovation of family farm systems: A systems approach to sustainable agriculture. Agricultural Systems 126, 76-86.
Duru, M., Therond, O., 2015. Designing agroecological transitions; A review. Agronomy for Sustainable Development 35, 1237-1257.
Eckert, C., Rougier, M., Abjean-Uguen, A., Lusetti, A., Castel, L., Deslandes, T., Faloya, V., Genty, C., Lecompte, F., Lefèvre, A., Pelletier, B., Pommier, J.J., Pottiez, B., Tormin, P., Trottin Caudal, Y., Chartier, N., Emonet, E., Brun, V., 2018. DEPHY EXPE network : Summary of results at the national scale - vegetable sector. Cellule d'Animation Nationale DEPHY Ecophyto, 88 p.
Edwards-Jones, G., 2006. Modelling farmer decision-making: concepts, progress and challenges. Animal science 82, 783-790.
Estorgues, V., Lecuyer, G., Allainguillaume, J., Fayola, V., 2017. DEXiPM – Field Vegetables : un modèle d'analyse ex ante de la durabilité des systèmes légumiers. Innovations Agronomiques 61, 91-98.
Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Adam, M., Sogoba, B., Giller, K.E., 2017. Co-learning cycles to support the design of innovative farm systems in southern Mali. European Journal of Agronomy 89, 61-74.
Fares, M.H., Magrini, M.-B., Triboulet, P., 2012. Transition agroécologique, innovation et effets de verrouillage: le rôle de la structure organisationnelle des filières. Cahiers Agricultures 21, 34-45 (31).
Francis, C., Lieblein, G., Gliessman, S., Breland, T.A., Creamer, N., Harwood, R., Salomonsson, L., Helenius, J., Rickerl, D., Salvador, R., Wiedenhoeft, M., Simmons, S., Allen, P., Altieri, M., Flora, C., Poincelot, R., 2003. Agroecology: The Ecology of Food Systems. Journal of Sustainable Agriculture 22, 99-118.
French ministry of agriculture agribusiness and forestry, 2015a. Liste des produits entrant dans le calcul du NODU "vert" Biocontrôle au titre de l'année 2014 - actualisation au 13 février 2015. available on http://agriculture.gouv.fr/.
French ministry of agriculture agribusiness and forestry, 2015b. Plan Ecophyto II. Available on http://agriculture.gouv.fr/, 67 pages.
Geels, F.W., 2005. Processes and patterns in transitions and system innovations: Refining the co-evolutionary multi-level perspective. Technological forecasting and social change 72, 681-696.
Gliessman, S.R., 2014. Agroecology: the ecology of sustainable food systems. CRC press.
Gregory, P.J., Ingram, J.S.I., Andersson, R., Betts, R.A., Brovkin, V., Chase, T.N., Grace, P.R., Gray, A.J., Hamilton, N., Hardy, T.B., Howdenj, S.M., Jenkins, A., Meybeckm, M., Olsson, M., Ortiz-Monasterio, I., Palm, C.A., Payn, T.W., Rummukainen, M., Schulze, R.E., Thiemr, M., Valentin, C., Wilkinson, M.J., 2002. Environmental consequences of alternative practices for intensifying crop production. Agriculture, Ecosystems and Environment 88, 279–290.
Guichard, L., Dedieu, F., Jeuffroy, M.-H., Meynard, J.M., Reau, R., Savini, I., 2017. Le plan Ecophyto de réduction d'usage des pesticides en France: décryptage d'un échec et raisons d'espérer. Cahiers Agricultures 26, 1-12.
Havard, M., Alaphilippe, A., Deytieux, V., Estorgues, V., Labeyrie, B., Lafond, D., Meynard, J.M., Petit, M.S., Plénet, D., Picault, S., Faloya, V., 2017. Guide de l'expérimentateur système : concevoir, conduire et valoriser une expérimentation "système" pour les cultures assolées et pérennes. GIS PICLég, GIS Fruits, Réseau ECOVITI, RMT Systèmes de culture innovants, GIS Relance Agronomique, 172p.
Hebel, P., 2008. Synthèse des baromètres sur l'alimentation. Centre de Recherche pour l'Etude et l'Observation des Conditions de vie, 9p.

Henson, S., Humphrey, J., 2012. Private standards in global agri-food chains, Private Standards and Global Governance. Edward Elgar Publishing.

Hill, S.B., MacRae, R.J., 1995. Conceptual Framework for the Transition from Conventional to Sustainable Agriculture. Journal of Sustainable Agriculture 7, 81-87.

Horrigan, L., Lawrence, R.S., Walker, P., 2002. How Sustainable Agriculture Can Address the Environmental and Human Health Harms of Industrial Agriculture. Environmental Health Perspectives 110, 445-456.

Huang, I.B., Keisler, J., Linkov, I., 2011. Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. Science of the Total Environment 409.

Jacquet, F., Butault, J.-P., Guichard, L., 2011. An economic analysis of the possibility of reducing pesticides in French field crops. Ecological Economics 10, 1638-1648.

Kemp, R., Schot, J., Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. Technology analysis & strategic management 10, 175-198.

Lacombe, C., Couix, N., Hazard, L., 2018. Designing agroecological farming systems with farmers: A review. Agricultural Systems 165, 208-220.

Laget, E., Guadagnini, M., Plénet, D., Simon, S., Assié, G., Billote, B., Borioli, P., Bourgouin, B., Fratantuono, M., Guérin, A., Hucbourg, B., Lemarquand, A., Loquet, B., Mercadal, M., Parveaud, C.-E., Ramade, L., Rames, M.-H., Ricaud, V., Rousselou, C., Sagnes, J.-L., Zavagli, F., 2015. Guide pour la conception de systèmes de production fruitière économes en produits phytopharmaceutiques. GIS Fruits et Ministère de l'agriculture, Paris, 264 p.

Lamichhane, J.R., Messéan, A., Ricci, P., 2019. Research and innovation priorities as defined by the Ecophyto plan to address current crop protection transformation challenges in France, Advances in Agronomy. Elsevier, pp. 81-152.

Lamine, C., 2011. Transition pathways towards a robust ecologization of agriculture and the need for system redesign. Cases from organic farming and IPM. Journal of Rural Studies 27, 209-219.

Lamprinopoulou, C., Renwick, A., Klerkx, L., Hermans, F., Roep, D., 2014. Application of an integrated systemic framework for analysing agricultural innovation systems and informing innovation policies: Comparing the Dutch and Scottish agrifood sectors. Agricultural Systems 129, 40-54.

Lançon, J., Reau, R., Cariolle, M., Munier-Jolain, N., Ornon, B., Petit, M.-S., Viaux, P., Wery, J., 2008. Elaboration à dire d'experts de systèmes de culture innovants. In R. Reau & T. Doré (Eds.), Systèmes de culture innovants et durables Dijon: Educagri, 91-108.

Lançon, J., Wery, J., Rapidel, B., Angokaye, M., Gérardeaux, E., Gaborel, C., Ballo, D., Fadegnon, B., 2007. An improved methodology for integrated crop management systems. Agronomy for Sustainable development 27, 101-110.

Launais, M., Bzdrenga, L., Estorgues, V., Faloya, V., Jeannequin, B., Lheureux, S., Nivet, L., Scherrer, B., Sinoir, N., Szilvasi, S., Taussig, C., Terrentroy, A., Trottin-Caudal, Y., Villeneuve, F., 2014. Guide pratique pour la conception de systèmes de culture légumiers économes en produits phytopharmaceutiques. Ministère chargé de l'agriculture, Onema, GIS PICLég, 178 pages.

Le Bail, M., Meynard, J.-M., 2003. Yield and protein concentration of spring malting barley: the effects of cropping systems in the Paris Basin (France).

Le Bellec, F., Rajaud, A., Ozier-Lafontaine, H., Bockstaller, C., Malezieux, E., 2012. Evidence for farmers' active involvement in co-designing citrus cropping systems using an improved participatory method. Agronomy for sustainable development 32, 703-714.

Le Gal, P.-Y., Dugué, P., Faure, G., Novak, S., 2011. How does research address the design of innovative agricultural production systems at the farm level? A review. Agricultural Systems 104, 714-728.

Lechenet, M., Dessaint, F., Py, G., Makowski, D., Munier-Jolain, N., 2017. Reducing pesticide use while preserving crop productivity and profitability on arable farms. Nature Plants 3, 1-6.

Lefèvre, V., Capitaine, M., Peigné, J., Roger-Estrade, J., 2014. Farmers and agronomists design new biological agricultural practices for organic cropping systems in France. Agronomy for sustainable development 34, 623-632.

Lesur-Dumoulin, C., Laurent, A., Reau, R., Guichard, L., Ballot, R., Jeuffroy, M., Loyce, C., 2018. Co-design and ex ante assessment of cropping system prototypes including energy crops in Eastern France. Biomass and Bioenergy 116, 205-215.

Lev, L., Campbell, D.J., 1987. The temporal dimension in farming systems research: the importance of maintaining flexibility under conditions of uncertainty. Journal of Rural Studies 3, 123-132.

Lien, G., Hardaker, J.B., Flaten, O., 2007. Risk and economic sustainability of crop farming systems. Agricultural Systems 94, 541-552.

Martin, G., Martin-Clouaire, R., Duru, M., 2013. Farming system design to feed the changing world. A review. Agronomy for Sustainable Development 33, 131-149.

Martins, K.T., Gonzalez, A., Lechowicz, M.J., 2015. Pollination services are mediated by bee functional diversity and landscape context. Agriculture, Ecosystems & Environment 200, 12-20.

Méndez, V.E., Bacon, C.M., Cohen, R., 2012. Agroecology as a Transdisciplinary, Participatory, and Action-Oriented Approach. Agroecology and Sustainable Food Systems 37, 3-18.

Meynard, J.-M., Dedieu, B., Bos, A.B., 2012. Re-design and co-design of farming systems. An overview of methods and practices, Farming Systems Research into the 21st century: The new dynamic. Springer, pp. 405-429.

Meynard, J.-M., Jeuffroy, M.-H., Le Bail, M., Lefèvre, A., Magrini, M.-B., Michon, C., 2017. Designing coupled innovations for the sustainability transition of agrifood systems. Agricultural systems 157, 330-339.

Meynard, J.M., Casabianca, F., 2011. Agricultural systems and the innovation process. In R. Bouche, A. Derkimba, & F. Casabianca (Eds.), New trends for innovation in the Mediterranean animal production. Wageningen: Wageningen Academic Publishers., 17-26.

Mier y Terán Giménez Cacho, M., Giraldo, O.F., Aldasoro, M., Morales, H., Ferguson, B.G., Rosset, P., Khadse, A., Campos, C., 2018. Bringing agroecology to scale: key drivers and emblematic cases. Agroecology and Sustainable Food Systems 42, 637-665.

Ministry of Ecological and Solidarity Transition, 2018. Plan Ecophyto II+. 66 pages.

Moraine, M., Grimaldi, J., Murgue, C., Duru, M., Therond, O., 2016. Co-design and assessment of cropping systems for developing crop-livestock integration at the territory level. Agricultural Systems 147, 87-97.

Navarrete, M., Le Bail, M., Papy, F., Bressoud, F., Tordjman, S., 2006. Combining leeway on farm and supply basin scales to promote technical innovations in lettuce production.

Olesen, J., Schelde, K., Weiske, A., Weisbjerg, M., Asman, W., Djurhuus, J., 2006. Modelling greenhouse gas emissions from European conventional and organic dairy farms. Agriculture, Ecosystems & Environment 112, 207-220.

Pardo, G., Riravololona, M., Munier-Jolain, N., 2010. Using a farming system model to evaluate cropping system prototypes: Are labour constraints and economic performances hampering the adoption of Integrated Weed Management? European Journal of Agronomy 33, 24-32.

Pelzer, E., Fortino, G., Bockstaller, C., Angevin, F., Lamine, C., Moonen, C., Vasileiadis, V., Guérin, D., Guichard, L., Reau, R., Messéan, A., 2012. Assessing innovative cropping systems with DEXiPM, a qualitative multi-criteria assessment tool derived from DEXi. Ecological Indicators 18, 171-182.

Pierron, D., 2016. Profil des exploitations cultivant des légumes d'industrie. Unilet infos 154, 14-16.

Pimentel, D., Lehman, H., 1993. The Pesticide Question: Environment, Economics and Ethics. Springer.

Pretty, J., 2018. Intensification for redesigned and sustainable agricultural systems. Science 362.

Probst, L., Adoukonou, A., Amankwah, A., Diarra, A., Vogl, C.R., Hauser, M., 2012. Understanding change at farm level to facilitate innovation towards sustainable plant protection: a case study at cabbage production sites in urban West Africa. International Journal of Agricultural Sustainability 10, 40-60.

Prost, L., Berthet, E.T., Cerf, M., Jeuffroy, M.-H., Labatut, J., Meynard, J.-M., 2017. Innovative design for agriculture in the move towards sustainability: scientific challenges. Research in Engineering Design 28, 119-129.

Reau, R., Doré, T., 2008. Systèmes de culture innovants et durables - Quelles méthodes pour les mettre au point et les évaluer? Éducagri éditions / AgriParisTech, 176 pages.

Reau, R., Monnot, L.A., Schaub, A., Munier-Jolain, N., Pampoul, I., Bockstaller, C., Cariolle, M., Chabert, A., Dumans, P., 2012. Les ateliers de conception de systèmes de culture pour construire, évaluer et identifier des prototypes prometteurs. Innovations Agronomiques 20, 5-33.

Reckling, M., Bergkvist, G., Watson, C.A., Stoddard, F.L., Bachinger, J., 2020. Re-designing organic grain legume cropping systems using systems agronomy. European Journal of Agronomy 112, 125951.

Rosset, P.M., Martínez-Torres, M.E., 2012. Rural Social Movements and Agroecology: Context, Theory, and Process. Ecology and Society 17, 17.

Sadras, V.c., Roget, D., Krause, M., 2003. Dynamic cropping strategies for risk management in dry-land farming systems. Agricultural systems 76, 929-948.

Schaub, A., Toupet, A.L., Deytieux, V., Toqué, C., Petit, M.S., Cadoux, S., Minette, S., Vivier, C., Geloen, M., Massot, P., Fonteny, C., Reau, R., 2016. Décrire un système de culture expérimenté, pour aider à son pilotage, faciliter son analyse et communiquer. Guide méthodologique du réseau expérimental du Réseau Mixte Technologique « Systèmes de culture innovants ». 68 pages.

Shrapnel, M., Davie, J., 2001. The influence of personality in determining farmer responsiveness to risk. The Journal of agricultural education and extension 7, 167-178.

Smith, R.G., Barbercheck, M.E., Mortensen, D.A., Hyde, J., Hulting, A.G., 2011. Yield and Net Returns during the Transition to Organic Feed Grain Production. Agronomy Journal 103, 51-59.

Spiertz, J., Haverkort, A., Vereijken, P., 1996. Environmentally safe and consumer-friendly potato production in The Netherlands. 1. Development of ecologically sound production systems. Potato Research 39, 371-378.

Stuart, D., Worosz, M.R., 2012. Risk, anti-reflexivity, and ethical neutralization in industrial food processing. Agriculture and Human Values 29, 287-301.

Sumane, S., Kunda, I., Knickel, K., Strauss, A., Tisenkopfs, T., des los Rios, I., Rivera, M., Chebach, T., Ashkenazy, A., 2018. Local and farmers' knowledge matters! How integrating informal and formal knowledge enhances sustainable and resilient agriculture. Journal of Rural Studies 59, 232-241.

Tamburini, G., Van Gils, S., Kos, M., Van der Putten, W., Marini, L., 2018. Drought and soil fertility modify fertilization effects on aphid performance in wheat. Basic and Applied Ecology 30, 23-31.

Vanloqueren, G., Baret, P.V., 2009. How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. Research policy 38, 971-983.

Veres, A., Petit, S., Conord, C., Lavigne, C., 2013. Does landscape composition affect pest abundance and their control by natural enemies? A review. Agriculture, Ecosystems & Environment 166, 110-117.

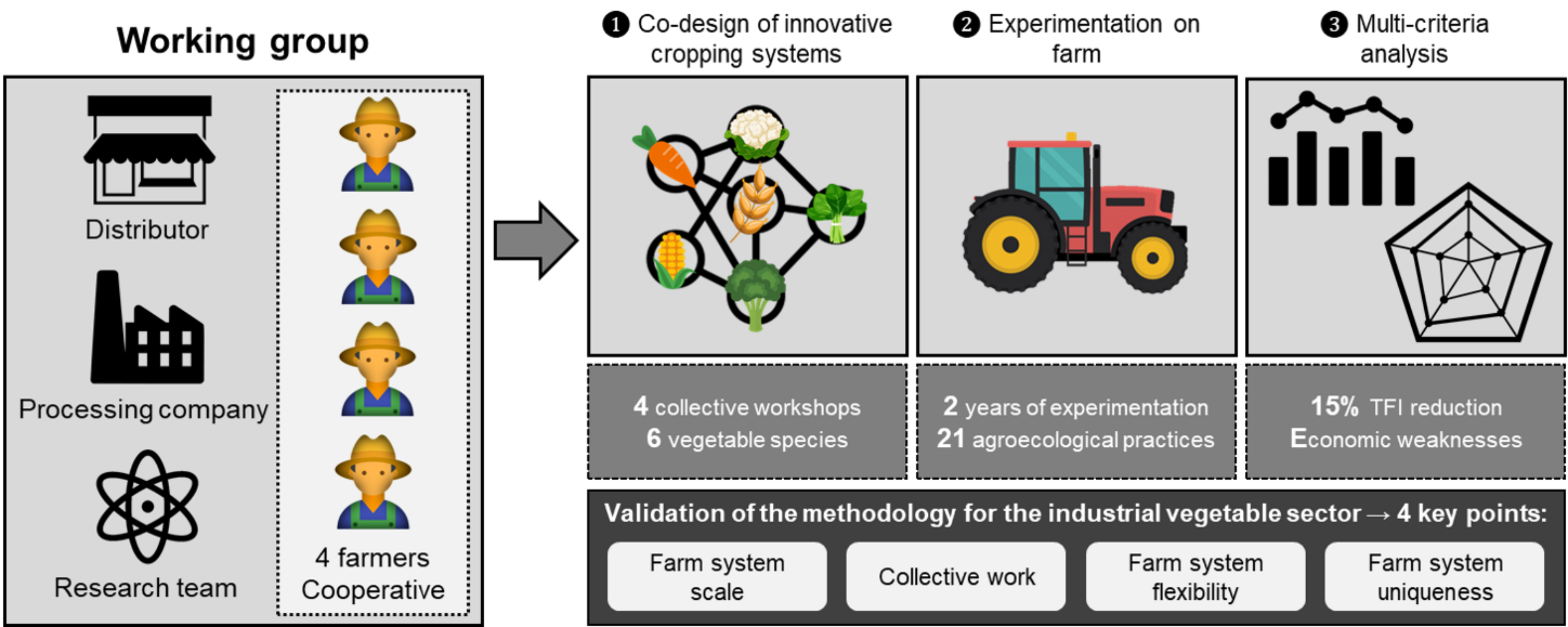
Wezel, A., Casagrande, M., Celette, F., Vian, J.-F., Ferrer, A., Peigné, J., 2014. Agroecological practices for sustainable agriculture. A review. Agronomy for Sustainable Development 34, 1-20.

Wigboldus, S., Klerkx, L., Leeuwis, C., Schut, M., Muilerman, S., Jochemsen, H., 2016. Systemic perspectives on scaling agricultural innovations. A review. Agronomy for Sustainable Development 36, 20p.

Willock, J., Deary, I.J., McGregor, M.M., Sutherland, A., Edwards-Jones, G., Morgan, O., Dent, B., Grieve, R., Gibson, G., Austin, E., 1999. Farmers' attitudes, objectives, behaviors, and personality traits: The Edinburgh study of decision making on farms. Journal of Vocational Behavior 54, 5-36.

Woodhouse, P., 2010. Beyond Industrial Agriculture? Some Questions about Farm Size, Productivity and Sustainability. Journal of Agrarian Change 10, 437-453.

Zingore, S., González-Estrada, E., Delve, R.J., Herrero, M., Dimes, J.P., Giller, K.E., 2009. An integrated evaluation of strategies for enhancing productivity and profitability of resource-constrained smallholder farms in Zimbabwe. Agricultural systems 101, 57-68.


Working group
Distributor
Processing company
Research team
4 farmers
Cooperative
❶ Co-design of innovative cropping systems
❷ Experimentation on farm
❸ Multi-criteria analysis
4 collective workshops
6 vegetable species
2 years of experimentation
21 agroecological practices
15% TFI reduction
Economic weaknesses
Validation of the methodology for the industrial vegetable sector → 4 key points:
Farm system scale
Collective work
Farm system flexibility
Farm system uniqueness