Farmers and agronomists design new biological agricultural practices for organic cropping systems in France

Vincent Lefevre, Mathieu Capitaine, Josephine Peigne, Jean Roger-Estrade

Agron. Sustain. Dev. (2014) 34:623–632
DOI 10.1007/s13593-013-0177-2

RESEARCH ARTICLE

Farmers and agronomists design new biological agricultural practices for organic cropping systems in France

Vincent Lefèvre · Mathieu Capitaine · Joséphine Peigné · Jean Roger-Estrade

Accepted: 6 September 2013 / Published online: 18 October 2013

Abstract New organic cropping systems are needed to keep pace with the growing demand for organic food. Those systems should ideally give more yield and safe for the environment. Current innovations such as non-inversion tillage with cover crops are promising, but investigations usually do not take farmers view into account. Therefore, research work should include farmer participation to maximize success. We present here a method to help farmers in designing innovative cropping systems. This method involves several design workshops with farmers. The first steps of the method foster creativity by changing ways in which farmers thought and worked. The final steps of the method facilitated learning. Participatory tools are used to exchange views and knowledge. System prototypes were developed. The method was applied using groups of six and seven farmers from two French regions. The farmers generated 14 system prototypes. We found that system prototypes differed radically from current practices because prototypes are based on biological rather than mechanical methods. Indeed, cover crop use was almost four times more frequent in prototypes than in current systems. Moldboard plowing and mechanical weeding frequencies were, respectively, two and eight times lower. The main benefits of our method are (1) the involvement of volunteer farmers in the design process, (2) the combination of farmer knowledge and scientific knowledge, and (3) the use of various methodological supports.

Keywords Design method · Farmers' participation · Agricultural innovation · Organic farming · Cover crops · Reduced (or no-) tillage

1 Introduction

Agriculture is facing complex challenges related to environmental (e.g., soil degradation, climate change) and socioeconomic issues (e.g., feeding a growing population, providing a decent income for farmers). Organic agriculture is one developed alternative designed to help preserve the environment. However, the ability of organic farming (1) to increase production to respond to growing demand and (2) to preserve the environment has been called into question (Leifeld 2012). Organic farming professionals are seeking new management practices to improve both soil fertility and their own socioeconomic conditions. New agroecological principles that have recently been developed in conventional agriculture should maintain or increase soil fertility, save labor, and reduce energy costs (Hobbs et al. 2008). These principles are based on (1) diversification of the species used in crop rotations, (2) covering the soil surface with living or dead mulches, and (3) decreasing soil disturbance (Fig. 1). The combination of these agroecological principles represents a deviation from classic organic farming systems. The diversification of crop rotations is already a fundamental aspect of organic farming, but the introduction of reduced tillage (or no-tillage) systems and the frequent use of cover crops represents a major modification of the system, modifying the management of weeds, fertilization, and crop residues (Peigné et al. 2007).

V. Lefèvre · M. Capitaine
VetAgro Sup, UMR AgroParisTech, Inra, Clermont Université, Irstea, VetAgro Sup, 1273 Métafort, 63370 Lempdes, France

V. Lefèvre (✉) · J. Peigné
Agroecology and Environment, ISARA Lyon, 23 rue Jean Baldassini, 69364 Lyon cedex 7, France
e-mail: vlefevre@isara.fr

J. Roger-Estrade
AgroParisTech, INRA, UMR 211 Agronomie, Thiverval-Grignon, France

Fig. 1 Agroecological practices: direct sowing of maize into a rolled rye cover in France. The main advantages of this technique for farmers are (*1*) soil preservation; the soil is undisturbed and covered year-round by crops or residues. This maintains soil fertility by favoring soil biological activity and protecting the soil from degradation. (2) Weed control: the rolled rye creates a mulch that suppresses weed growth. (3) Labor time and fuel consumption: only two passes are required, for rolling and sowing. In classical organic management, plowing, sowing, and numerous mechanical weeding operations are carried out. The main question is, how can direct sowing be incorporated into organic cropping systems, which generally involve plowing?

The design of innovative organic cropping systems involving such agroecological principles so as to favor their effective adoption by farmers is, thus, highly challenging. We describe here a method for supporting farmers in the design of innovative prototype cropping systems with the aim of preserving soil quality. Prototypes are defined here as theoretical cropping systems different from the cropping systems currently used by farmers. Prototypes are characterized by logically defined and structured components (i.e., the nature of the crops, their rotation, planned actions, and decision rules). Prototypes should also meet the objectives defined under a given set of constraints.

Innovation process is based on (1) the introduction of new changes and (2) its attempts to facilitate these changes and to make them sustainable in the long term for farmers (Klerkx et al. 2010). Agricultural innovation is a complex and interactive learning process, in which farmers must play an active role (Sumberg et al. 2003). The participation of farmers in research projects has been shown to be highly beneficial (Chambers et al. 1989; Gouttenoire et al. 2013).

Participatory design approaches are typically based on step-by-step design methods. Such methods progressively integrate specific innovations into current cropping systems (Le Bellec et al. 2012; Cardoso et al. 2001). Current systems are first analyzed to identify the principal limitations faced by farmers. Attempts are then made to identify solutions addressing the limitations identified and easily adaptable to existing systems. Step-by-step methods facilitate the adoption of the innovation through the implementation of a learning process (de Souza et al. 2012). However, radical innovations are rarely generated because the cropping systems in current use are not sufficiently called into question and the objectives set are often limited.

Researchers have recently developed new design methods aiming to introduce radical changes into cropping systems (Meynard et al. 2012). This approach was included in many of the research studies using several methods reviewed by Le Gal et al. (2011). Design modeling is used for the design or assessment of new cropping systems in a wide range of situations (Dogliotti et al. 2005). Expert prototyping is used to design prototypes of integrated farming systems (Vereijken 1997; Lançon et al. 2007). However, the innovative cropping systems generated by these methods are often too far removed from the reality in the field. In most cases, very few, if any, farmers are involved in the design process, resulting in a failure of innovations to be adopted (Sterk et al. 2007).

We have developed a method based on specific methodologies encouraging farmers to be creative and reflective. These methods present similarities with those already developed in animal production systems (Bos et al. 2009).

We will begin by describing the eight-step method and its use with two groups of farmers in central France. This paper focuses on the first seven steps, and is restricted to a presentation of the prototypes designed, highlighting their degree of innovation and discussing the determinants of such innovations in relation to the method.

2 Materials and methods

2.1 The participants

This method was run in parallel, with two groups of farmers, in two different regions of France as follows: a group of six farmers in Rhône-Alpes and a group of seven farmers in Auvergne. The two groups of farmers represented various farming systems, differing mostly in terms of the availability of organic matter (pure arable vs. mixed crop–livestock farms). During the design process, we asked the farmers to design prototype cropping systems.

Three researchers specializing in organic farming, soil science, agroecological practices, and systemic approach-based research were involved in the study. The researchers instigated the design process, with the aim of developing more sustainable organic cropping systems taking society's expectations into account. They supported farmers by providing them with relevant tools to encourage the dynamic generation of ideas and to stimulate exchanges. They also provided state-of-the-art expertise concerning various agroecological practices and soil mechanisms, in response to the questions raised by the farmers during the design process.

2.2 Overview of the design method

The method used for the design and assessment of prototype cropping systems encompassed eight steps (Fig. 2). We present here the steps corresponding to the cropping system design phase (steps 1 to 7). The two groups of farmers each went through these seven steps. The ex ante assessment step is not presented here.

2.2.1 Step 1: seeking volunteer farmers

The first step was to find participants with an awareness of soil preservation issues who were interested in being part of a collective project. We targeted a wide diversity of farmer profiles in terms of experience in farming, organic farming, and agroecological management. This made it possible to include numerous complementary skills and diverse local knowledge in the collective work.

Contacts were provided by local advisors or organic farming associations. After discussions over the telephone and the sending of a brochure, an individual meeting was set up with each interested farmer for an initial face-to-face discussion of the project.

2.2.2 Step 2: institutionalizing the project

The second step involved the holding of a meeting designed to generate cohesion within the group and to construct a shared idea of the objectives and functioning of the project. The main point of this meeting was to promote exchanges within the group. The participants shared personal expectations and came to agreements concerning the organization of the work (schedule, collective rules). Dynamic tools, such as “icebreakers” and brainstorming, were employed. “Icebreakers” were intended to help the members of the group to get to know each other through imaginative exercises designed to break the links between the individuals and the realities in which they are generally anchored. Brainstorming was used as a way of gauging the expectations of the participants. Rephrasing and the development of an overall consensus about the question addressed enabled farmers and researchers to build a common language, providing all the participants with a sense of legitimacy.

2.2.3 Step 3: identifying objectives

This third step was designed to define an exhaustive set of objectives that the participants wished to achieve to satisfy their expectations. Soil fertility was a matter of particular concern, as this was the main focus of the research. We used the Metaplan method to facilitate the selection of objectives. This exercise made it possible for participants to share, approve, and prioritize ideas. Each farmer initially defined his or her own expectations and objectives. They then wrote these objectives on cards, with one idea per card. Finally, all of the cards were collected, pinned onto a board, and organized as a function of the topic concerned (e.g., agronomic aspects, work organization, and economic aspects).

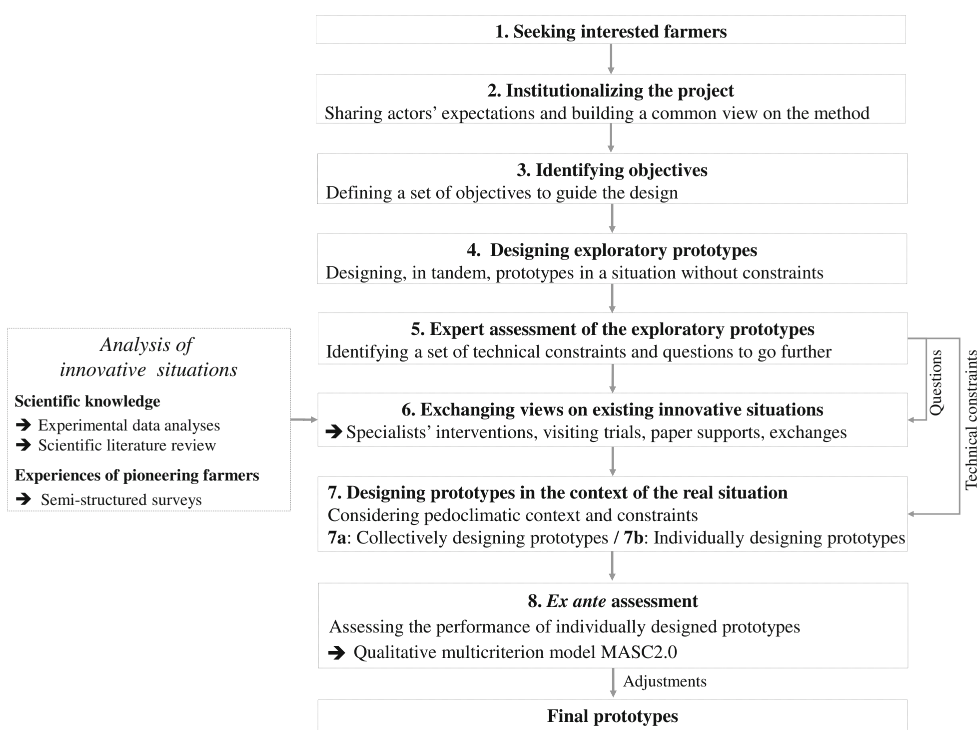

Fig. 2 Overall method developed for designing innovative prototypes of cropping systems. The method encompasses eight steps and makes use of various types of methods (*rightwards arrow*). After seeking interested farmers and institutionalizing the project (steps 1 and 2), the method involves identifying objectives and holding several design workshops (steps 3, 4, 7a, and 7b). The analysis of existing innovations (step 6) aims to provide a platform of knowledge for the design of new cropping systems. Step 8 involves the evaluation of the designed prototypes (according to the objectives defined) to obtain the final prototypes. We present only steps 1 to 7 in this article

2.2.4 Step 4: exploratory prototype design

This step corresponds to the first design workshop. Pairs of farmers designed prototype cropping systems, ignoring all constraints other than the achievement of the objectives defined. During this step, role-play exercises were developed to help farmers to change the ways in which they thought and reacted. Technical, pedoclimatic, and socioeconomic factors were all assumed to be favorable to promote creativity. Pep talks and parallel thinking activities were used to stimulate the work of the farmers. The researchers gave pep talks to encourage the farmers and to incite them to explore new ideas rather than focusing on the situations they encountered in real life. Parallel thinking activities allowed farmers to identify the strengths and weaknesses of their prototypes by responding to a number of questions on worksheets.

Each prototype was developed by completing a table describing the planning of crop rotations and crop management operations.

2.2.5 Step 5: peer assessment of exploratory prototypes

This step involved the assessment of the exploratory prototypes by farmers, making use of their own expertise. At the end of the exploratory design workshop, each pair of farmers presented their prototype to the group for peer review and to argue their case. A collective debriefing then took place to outline the strengths and weaknesses of each prototype with respect to the defined objectives. The groups were also asked (1) to identify the main technical constraints hindering the adoption of the proposed innovations, and (2) to define a set of questions making it possible to advance in the subsequent steps.

2.2.6 Step 6: exchange of views on existing innovative situations and scientific knowledge

This step aimed to provide an overview of existing innovative knowledge and experiences. It helped farmers to find solutions for technical constraints and answers to the questions raised during the debriefing of the previous step. This review was based on international scientific knowledge, the analysis of data from experimental trials, and the experiences of farmers pioneering particular cropping practices across France. The state-of-the-art was defined for several topics, and results from French trials were used (Peigné et al. 2009; Vian et al. 2009; Amossé et al. 2013). A survey was previously conducted in France to collect the experiences of pioneering organic farmers concerning the adoption of new agroecological practices (Lefèvre et al. 2012). The researchers shared this knowledge with the farmers, through the development of worksheets summarizing the principal results of the trials carried out and describing innovative management practices (e.g., reduced tillage, cover crops). In addition, two technical days were organized, combining theoretical (e.g., lectures on soil function, soil tillage, and cover cropping) and practical (e.g., visit to trials and interventions by pioneering farmers) sessions.

2.2.7 Step 7: designing prototypes, including constraints

This step involved a return to reality at the field scale. Considering the defined objectives (identified in step 3), the farmers designed new prototypes by looking for solutions to deal with constraints (pedoclimatic and technical constraints identified in step 5). Economic and organizational constraints were not taken into account, as they had already been considered in the objectives. Farmers analyzed the feasibility of the innovative prototypes developed for application in the real conditions they encountered on their farms, at the scale of the cropping system. Two different design workshops were used.

The first (step 7a) involved all the farmers of the group in a role play situation inspired by the "exquisite corpse" paradigm; individual farmers were asked to make successive contributions to the development of a management system for one crop in the rotation, such that the entire cropping system fulfilled the defined objectives (i.e., farmer A designed the first crop management system, farmer B analyzed it and then designed the second crop management system, etc.). This tool enabled farmers to identify their constraints and to react to feedback from their peers concerning the management systems they proposed. It also forced farmers to find a set of solutions concerning (1) the defined objectives, (2) the constraints given by the first farmer, and (3) the combinations of practices imposed by the preceding farmers. This set of solutions involved choices concerning the relevant crops, crop management, and decision rules.

The second design workshop (step 7b) involved farmers working individually (i.e., without peers and researchers). They designed a prototype cropping system, including soil management innovations, which they were ready to manage in their own conditions. Each farmer completed a table providing detailed information about the prototype.

2.2.8 Step 8: ex ante assessment

This step aimed to provide an ex ante assessment of the individual prototype cropping systems designed (step 7b) with respect to the defined objectives (step 3). Researchers used a qualitative multicriterion model for ex ante assessment of the performance of the innovative prototype cropping system in terms of their sustainability. The results obtained with the model were discussed with farmers (1) to favor exchanges, (2) to inform farmers about the potential performances of their innovative prototypes, and (3) to make improvements, as necessary. The results of the assessment step are not presented here.

3 Results and discussion

The design process began in March 2011 and finished in June 2012. For each group, seven collective meetings were held. In addition, two interviews and several exchanges of electronic messages or telephone calls were necessary between each farmer and the researchers.

During step 3, farmers formulated four general objectives for the design process as follows: (1) the long-term maintenance or improvement of soil quality (e.g., increasing soil organic matter content, protecting and promoting soil biodiversity, and obtaining a favorable soil structure), (2) ensuring production (e.g., control of weeds), (3) achievement of economic expectations (e.g., obtaining a sufficiently high gross margin, reducing energy consumption), and (4) optimizing work efficiency (e.g., increasing work efficiency and well-being at work). Our design method focused on improving soil fertility in organic farming. Objectives relating to improvements in soil fertility were, therefore, given priority during the design process.

The 13 farmers designed 28 prototypes, seven of which were developed in the first workshop (step 4). Another seven prototypes were developed collectively by farmers during the second workshop (step 7a). The remaining 14 prototypes were developed individually by farmers (one farmer designed two prototypes) during the third workshop (step 7b). Only these 14 final cropping system prototypes were fully complete. We, therefore, limited our subsequent analysis to these 14 cropping system prototypes.

3.1 Innovative aspects of the 14 cropping system prototypes

3.1.1 Which innovations were included in the prototypes

Several new crops or crop management practices were introduced into the prototype cropping systems (Tables 1 and 2). Prototypes 1 to 9 (Table 1) were innovative principally in (1) their use of occasional intercropping and (2) the combination of frequent cover crops with minimal or no-tillage systems. These prototypes frequently involved non-inversion tillage, and some included no tillage at all or the possibility of plowing only once per crop sequence (except for prototype 1, which involved plowing twice, and prototype 9, in which there was no plowing at all).

Prototypes 10 to 14 (Table 2) included more radical innovations, such as (1) systematically maintaining soil surface cover, (2) very low levels of soil tillage, (3) a complete absence of fertilizer application, and (4) the incorporation of ley residues into the soil. Prototype 10 used strip-tillage in permanent living mulch. Prototypes 11, 12, and 13 were based on direct drilling (Fig. 1) or occasional strip-tillage without mechanical weeding. Prototype 13 also involved the use of double crops (i.e., two harvests in 12 months due to the sowing of buckwheat or millet after the winter wheat harvest). Prototype 14 involved the systematic broadcast of rustic crops (e.g., heirloom cultivars of winter wheat) into a permanent living mulch. The soil was, thus, protected and never disturbed.

All the designed protocols differed radically from current organic farming management practices (Fig. 3); plowing and mechanical weeding frequencies were much lower (decreasing from 48 % currently to 5 % in the prototypes for plowing, and from 75 to 37 % for mechanical weeding). Conversely, the frequency of no-tillage practices and cover cropping were higher in the prototypes than in current practice (increasing from 4 to 42 % and from 25 to 85 %, respectively).

In classical organic cropping systems, such as those described by Colomb et al. (2012), non-inversion tillage is usually carried out in the period between two main crops to limit weed infestation (Bàrberi 2002). Annual plowing is also frequently used to manage weeds and to incorporate organic surface residues (Teasdale et al. 2007). Finally, for economic reasons, leys are not systematically cultivated and, when they are, the hay is exported for sale. Furthermore, classical crop rotations involve frequent cash-crop cereals (e.g., maize or winter wheat) and a smaller proportion of secondary cereals (e.g., triticale or oat) or legumes to increase the gross margin (Darnhofer et al. 2010).

This design method, thus, resulted in several prototype cropping systems differing markedly from existing forms of organic farm management, principally in terms of the integration of crop management practices based on biological regulation rather than mechanical methods.

3.1.2 Are these innovations likely, in principle, to represent a suitable response to constraints

The concept of innovation involves adapting novelty to local conditions to ensure that it is widely used. Innovative prototypes must, therefore, take farmers' constraints and objectives into account.

During step 5, farmers identified four main technical constraints, relating to soil conservation innovations (e.g., non-inversion tillage, the use of living mulches), as follows: weed infestation, lack of nitrogen availability, competition with living mulch, and the removal of perennial leys. Throughout the method, the farmers sought appropriate ways to work around these constraints. Prototypes 1 to 9 managed weeds through soil tillage (frequent low-level tillage, a single annual moldboard plowing, and mechanical weeding) and the use of leys or competitive cover crops. Prototypes 10 to 14 were almost exclusively based on biological regulation (e.g., the use of living mulches or cover crops, weed-suppressing crops or cultivars, and decreasing the length of the crop rotation to ensure the more frequent inclusion of leys), although prototype 10 also included mechanical weeding. The farmers improved nitrogen supply by increasing the proportion of

Table 1 Characterization of prototypes 1 to 9, involving occasional intercropping, frequent cover crops, and low-level soil disturbance by tillage

Name	Crop rotation (*in italics*, *current cropping system of the farmers*)	% cover crops	% plowing	% no-tillage	% mechanical weeding	Ley cutting and hay removal	Organic fertilizer
1	*No current cropping system—in conversion* 3y LU-WW-TR-FB-WW-OA	60	15	15	80	3	Occasional
2	*No current cropping system—in conversion* 3y LU-WW-TR-FB-WW-(SF+LU)	60	15	15	80	3	Occasional
3	*Current*: *2y LU-WW-SP-(RY+PE)-SF-SP-VE-WW-WB*	*10*	*60*	*0*	*80*	*4*	*Occasional*
	2y LU-WW-SP-SF-SP-(RY+VE)-WW-WB	60	15	25	75	3	Occasional
4	*No current cropping system—in conversion* LU-(RY+LU)-(TR+LU)-MA-(SF+EC)-WW	60	15	15	50	2	Never
5	*Current*: *4y (LU-OG)-WW-TR-RY-SB*	*30*	*80*	*0*	*80*	*3*	*Occasional*
	5y (LU-OG)-WW-TR-(FB+RY)-H-WW-(TR+PE)-SB	75	25	25	25	3	Occasional
6	*No current cropping system—in conversion* 3y LU-WW-OA-(SF+RC)-(WW+RC)-SB	75	15	35	50	3	Occasional
7	*No current cropping system—in conversion* 2y LU-WW-WW-SF-SO-(MA+WC)-MA-WW	75	15	15	90	3	Occasional
8	*No current cropping system—in conversion* 2y (LU+OG)-WW-WW-(SF+LU+OG)	75	25	50	60	3	Occasional
9	*Current*: *3y LU-WW-SO-TR-OA-FB-SF-WW-PE-WB*	*30*	*0*	*0*	*90*	*4*	*Frequent*
	3y LU-MA-WB-(WB+PE)-WW-TR-SO-OA-SP	60	0	10	65	4	Occasional

Prototypes *1*, *2*, *4*, *6*, *7*, and *8* were designed by farmers either converting to organic farming or only recently installed as organic farmers. No current cropping system was therefore available in these cases

% *cover crops* period (in months) with a cover crop between two mains crops/sum of periods (in months) between two mains crops during the crop sequence, % *plowing* sum of crop sowing with mouldboard plough/sum of crop sowing during the crop sequence, % *no-tillage* sum of crop sowing without tillage/sum of crop sowing during the crop sequence, % *mechanical weeding* sum of crops managed by mechanical weeding/sum of crops during the crop sequence, *Ley cutting and hay removal* number of leys cut from which the hay is exported per year, *organic fertilizer* (manure or commercial fertilizer), *frequent* inputs for all cereals, *occasional* inputs for primary cereals (e.g., wheat and maize), *never* no input, (*X* + *Y*) intercropping, *EC* Egyptian clover, *FB* faba bean, *H* hemp, *LU* lucerne, *MA* maize, *OA* oat, *OG* orchard grass, *PE* pea, *RC* red clover, *RY* rye, *SF* sunflower, *SB* spring barley, *SO* soya, *SP* spelt, *TR* triticale, *VE* vetch, *WB* winter barley, *WC* white clover, *WW* winter wheat, and *y* year

legume crops in the crop rotation, including legume cover crops and applying organic inputs or incorporating ley residues into the soil. The removal of perennial leys was managed by plowing or frequent non-inversion tillage. Farmers managed the competition between crop and living mulches through the use of strip-tillage, sowing crops into dead mulch, choosing rustic crops or cultivars (e.g., heirloom cultivars or secondary cereals), or using less competitive living mulches.

Pedoclimatic constraints were identified principally in steps 6 and 7. These constraints were related to the lack of moisture during the summer for cover crop growth and the risk of soil structure degradation (i.e., crop harvest or cover crop removal at a time of high soil humidity; poor natural capacity for soil structure development due to factors such as soil types with low clay content). Farmers proposed solutions to overcome these local constraints, including the maintenance of adequate cover crop during the sowing period (e.g., early in spring, by relay sowing) and cultivating appropriate crops and cultivars, using occasional deep soil tillage or developing soil structure by growing plants with vigorous and extensive root systems (e.g., lucerne).

This method, thus, generated a number of prototype cropping systems. These prototypes took into account an initial set of requirements for the future adoption of innovations by anticipating technical and pedoclimatic constraints and providing solutions to these problems. A second set of requirements will be considered in the results of the assessment steps.

3.2 The determinants favoring agricultural innovation in relation to the method

At the start of the design process, this method favors the exploration of innovation by diversifying support tools and encouraging abstraction and a distancing of thought processes from the current situation. At the end of the process, the method favors the adaptation of these innovations to local conditions by anticipating technical and pedoclimatic constraints.

Figure 4 illustrates a current cropping system and the associated final prototype designed by a mixed crop–livestock farmer from Rhône-Alps. It relates the crop sequence and the principal actions planned to the objectives and constraints.

Table 2 Characterization of prototypes 10 to 14, including more radical innovations (i) systematic maintenance of soil surface cover, (ii) very low-level soil disturbance, and (iii) incorporation of ley residues into the soil

Name	Crop sequence (*in italics*, *current cropping system of the farmers*)	% cover crops	% plowing	% no-tillage	% mechanical weeding	Ley cutting and hay removal	Organic fertilizer
10	*Current: 2y LU-WW-SF-SO-WW-MA*	*20*	*70*	*0*	*80*	*3*	*Occasional*
	WC-(WW+WC)-(MA+WC)-(WW+WC)-(SF+WC)	100	0	20	80	0	Never
11	*Current:4y (LU + OG)-MA-MA-WB-(TR+OA+PE)*	*10*	*60*	*0*	*80*	*4*	*Frequent*
	4y (LU+OG)-(MA+WC)-(TR+OA+PE+WC)-(MA+WC)-(RY+PE)	100	0	60	10	3	Occasional
12	*Current: 3y (LU)-SP-OA-SF-FB-SP-OA*	*50*	*0*	*30*	*40*	*0*	*Never*
	3y LU-(SP + LU)-FL-SF-SP-BE-SP-OA	100	0	60	10	0	Never
13	*No current cropping system—in conversion* 2y LU-WW/(BW+MI)-(OA-WL)-(SF+BW+LU)	100	0	100	0	2	Occasional
14	*Current: 2y LU-WW-SF-SO-WW-MA*	*20*	*70*	*0*	*80*	*3*	*Occasional*
	LU-(WW*+LU)-(TR+LU)-(RY+LU)-(WW*+LU)	100	0	100	0	0	Never

Prototype 13 was designed by a farmer converting to organic farming. Thus, no current cropping system was available. A permanent living mulch is maintaining in prototypes 10 and 14

% *cover crops* period (in months) with cover crop between two main crops/sum of periods (in months) between two mains crops during the crop sequence, % *plowing* sum of crop sowing with mouldboard plowing/sum of crop sowing during the crop sequence, % *no-tillage* sum of crop sowing without tillage/sum of crop sowing during the crop sequence, % *mechanical weeding* sum of crops managed by mechanical weeding/sum of crops during the crop sequence, *ley cutting and hay removal* number of leys cut from which the hay is exported per year, *organic fertilizer* (manure or commercial fertilizer) *frequent* inputs for all cereals, occasional inputs for primary cereals (e.g., wheat and maize), *never* no input, ($X + Y$) intercropping, *BE* bean, *BW* buckwheat, *FL* flax, *FB* faba bean, *LU* lucerne, *MA* maize, *MI* millet, *OA* oat, *OG* orchard grass, *PE* pea, *RY* rye, *SF* sunflower, *SO* soya, *SP* spelt, *TR* triticale, *WB* winter barley, *WC* white clover, *WL* white lupin, *WW* winter wheat, *WW** heirloom cultivars of winter wheat, and *y* year

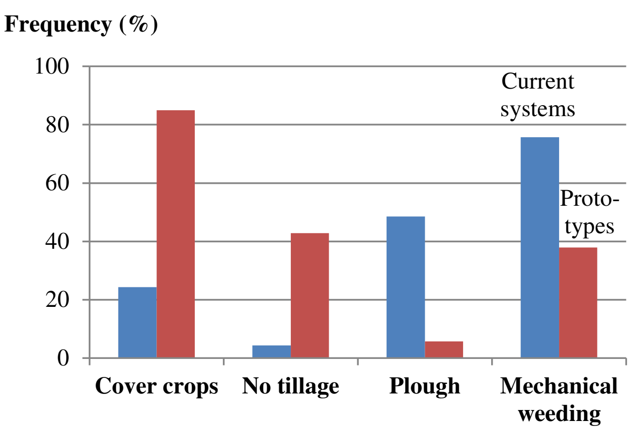

Fig. 3 Mean frequency of the main soil management techniques in the current cropping system of the farmers and the designed prototypes. *Current systems* are the cropping systems managed by farmers 3, 5, 9, 10, 11, 12, and 14. *Prototypes* are the final prototypes designed by farmers in step 7b (Tables 1 and 2). *Cover crops frequency* period (in months) with cover crops between two main crops/sum of periods (in months) between two mains crops during the crop sequence. *Plough frequency* sum of crop sowing with mouldboard plough/sum of crop sowing during the crop sequence. *No-tillage frequency* sum of crop sowing without tillage/sum of crop sowing during the crop sequence. *Mechanical weeding frequency* sum of crops managed with mechanical weeding/sum of crops during the crop sequence. The mean frequency was calculated by averaging the frequencies for all prototypes or all current cropping systems

3.2.1 A method for facilitating the exploration of innovation

When researchers study ways of integrating radical changes into cropping systems, they generally make use of expert knowledge (Vereijken 1997; Lançon et al. 2007) or models (Dogliotti et al. 2005). Unlike these existing prototyping methods, our method favored profound changes by helping farmers to distance themselves from their current situation. Our findings corroborate those of previous studies by highlighting the need to establish specific methodologies favoring creativity and interactions between participants (Bos et al. 2009). In our method, the collective dimension of the work led farmers to explore new approaches by comparing their skills, convictions, or intuitions. Collective work also fostered emulation in the groups. The first design workshop, completed without constraint (step 4), facilitated the exploration of innovation because it allowed farmers to distance themselves from their own situations (and thus to free themselves from their constraints). This point is illustrated in the final prototype shown in Fig. 4. This approach resulted in the implementation of radical innovations, such as direct drilling or the sowing of relay cover crops into maize, in the final prototype.

The sharing of experiences with and knowledge of innovations (step 6) and, to a lesser extent, the collective design workshop (step 7a) also provided farmers with a broader view and allowed them to explore new ideas. This is illustrated by the use of strip-tillage and the sowing of crops into a living mulch (Fig. 4).

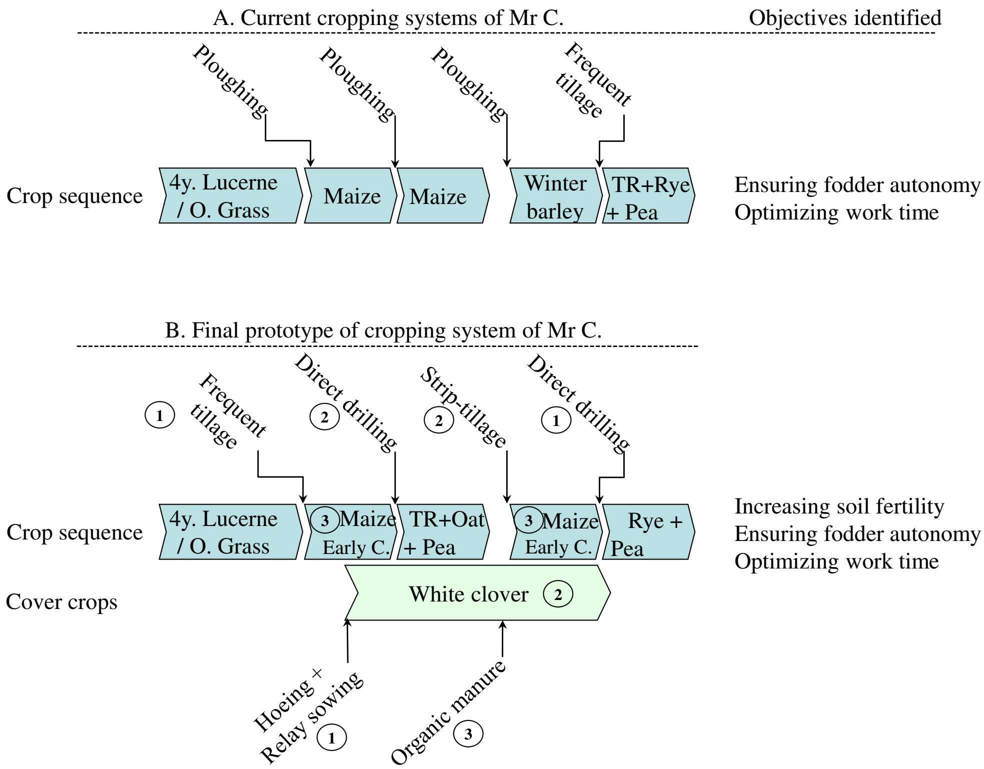

Fig. 4 Illustration of the current cropping system and final prototype designed by a farmer from Rhône-Alpes (Mr C), taking into account the objectives identified, the pedoclimatic context, and technical constraints. Mr C. is a mixed crop–livestock farmer from Rhône-Alpes. The figure shows, in a simplified manner, **a** the cropping system currently managed by Mr. C and **b** the final prototype produced in step 7b, corresponding to prototype 11 in Table 2. The crop sequence, cover crop management, and the main planned actions relative to the farmers' defined objectives are described. The numbers correspond to planned actions designed in different workshops: *1* Exploratory design (step 4), step favoring farmer creativity. *2* Collective design in context (step 7a), step favoring exchanges and the taking into account of local constraints. For instance, it is difficult to manage the direct drilling of maize into a living mulch. The use of strip tillage is more appropriate. *3* Individual design in context (step 7b), step favoring the use of the farmer's local knowledge, taking into account the constraints specific to his farm. For instance, due to the particular mountainous climate of the farm, the farmer chose to use an early maize cultivar. He also retained white clover in the rotation because water was not a limiting factor. *O Grass* orchard grass, *MC* mixed cover crops, *TR* triticale, and *y* year

3.2.2 A method for anticipating an initial set of local constraints

Unlike existing innovative participatory design studies (Bos et al. 2009), our method involved several collective or individual design workshops, carried out with the same group of farmers. This enabled the participants to focus their reflections on anticipating the adoption of innovation. Despite differences in the design methods used (i.e., step-by-step design studies with the use of field experimentation), de Souza et al. (2012) and Le Bellec et al. (2012) also reported the development of adaptable cropping systems through the creation of strong dynamic relationships between farmers and researchers.

Throughout the method, the farmers gradually appropriated their innovative prototype cropping systems by identifying technical and pedoclimatic constraints and solutions to get around them. This learning process resulted from exchanges with researchers, specialists, or peers. The mixing of local and scientific knowledge is a highly successful way to create a learning environment (Pretty 1997) and to deal with complex cropping systems (Fumagalli et al. 2012). Farmers made good use of their (1) holistic point of view, developed through their experience in managing complex interactions, and (2) operational and local knowledge (e.g., pedoclimatic context, crop management). Local knowledge proved particularly important in the individual design workshop (step 7b). Researchers, for their part, brought generic knowledge (e.g., biological mechanisms involved in cover crops or soil tillage) and empirical knowledge from a previous survey of pioneering farmers. Knowledge and ideas circulated between researchers and farmers throughout the design process, through formal (e.g., during a design workshop or a technical day) and informal (e.g., during breaks or lunch time) discussions.

In addition, the involvement of farmers, from the beginning of the design process onwards, enabled them to be fully involved and aware of the practical final objective (i.e., to test the designed cropping systems).

The final prototypes were, therefore, highly detailed and essentially "ready to be tested". In the example shown in Fig. 4, the farmer used many planned actions to deal with the identified constraints as follows: weeds were managed by (1) the use of 4-year leys, (2) the maintenance of white clover, and (3) the cultivation of intercrops. Nitrogen availability was optimized through the use of leys or intercropping with legumes and manure applications. The farmer dealt with pedoclimatic constraints (i.e., clay soil, medium-sized mountain climate, and sloping topography), through the choice of an early maize cultivar, to reduce the risk of soil degradation during harvest while leaving time for the white clover to grow. The use of strip-tillage and the 4-year ley with lucerne should favor the development of soil structure.

Learning conditions can facilitate the future adoption of prototypes by farmers (Cerf et al. 2012; Coughenour 2003). Initial feedback supports the following hypothesis: some farmers have already spontaneously begun testing some innovations and others have expressed a desire to move toward assessment.

4 Conclusion

The prototypes generated by this method involving farmers in the innovation process differed markedly from current organic cropping systems, in the use of biological rather than mechanical regulation. The combination of various sources of knowledge and skills and sincere efforts to provide methodological support are decisive factors in the implementation of innovations in cropping systems. The diversity of methodological support tools appeared to be crucial, allowing (1) farmers to distance themselves from their personal framework, (2) promotion of the dynamic generation of ideas, (3) the stimulation of exchanges and reflection, and (4) farmers to make their reasoning explicit.

Furthermore, the final prototypes remained connected to real conditions. This was made possible by the promotion of a learning environment throughout the process. Indeed, by exchanging information with peers or researchers, farmers were able to take technical and pedoclimatic constraints into account. Assessment steps, such as ex ante model or trials managed by farmers on their own farms and researchers at experimental stations, are now required to pursue studies of the adoption of these processes.

Working alongside farmers and connecting different bodies of knowledge allowed researchers (1) to identify new questions relating to the understanding of complex mechanisms (resulting from innovative combinations of biological regulation methods), (2) to increase their awareness of farmers' needs and realities, and (3) to understand how to favor innovation in agricultural system by combining scientific and local knowledge. Additional case studies are required to confirm and clarify our findings. Lessons from our innovative design method could open up new perspectives for the promotion of sustainable cropping systems.

Acknowledgments We would like to thank the farmers for their involvement in this study and for having designed the prototypes. Without their active participation, this study would not have been possible. We gratefully acknowledge funding from the French Agency of Energy Control and Environmental Protection (ADEME) and the "Pôle ESTIVE", competence center for Education, Sciences, Technology, Innovation in Life and Environment Sciences. We thank Lorène Prost, Marion Casagrande, and the anonymous reviewers who provided valuable comments on previous versions of this paper. We also thank Donald White, Jennifer Kendzior, and Julie Sappa for English revision.

References

Amossé C, Jeuffroy M-H, David C (2013) Relay intercropping of legume cover crops in organic winter wheat: effects on performance and resource availability. Field Crop Res 145(0):78–87. doi:10.1016/j.fcr.2013.02.010

Bàrberi P (2002) Weed management in organic agriculture: are we addressing the right issues? Weed Res 42(3):177–193. doi:10.1046/j.1365-3180.2002.00277.x

Bos AP, Groot Koerkamp PWG, Gosselink JMJ, Bokma S (2009) Reflexive interactive design and its application in a project on sustainable dairy husbandry systems. Outlook Agric 38:137–145

Cardoso IM, Guijt I, Franco FS, Carvalho AF, Ferreira Neto PS (2001) Continual learning for agroforestry system design: university, NGO, and farmer partnership in Minas Gerais, Brazil. Agric Syst 69(3):235–257. doi:10.1016/s0308-521x(01)00028-2

Cerf M, Jeuffroy M-H, Prost L, Meynard J-M (2012) Participatory design of agricultural decision support tools: taking account of the use situations. Agron Sustain Dev 32(4):899–910. doi:10.1007/s13593-012-0091-z

Chambers R, Pacey A, Thrupp LA (1989) Farmer First: farmer Innovation and Agricultural Research. The Bootstrap Press, New-York

Colomb B, Carof M, Aveline A, Bergez J-E (2012) Stockless organic farming: strengths and weaknesses evidenced by a multicriteria sustainability assessment model. Agron Sustain Dev:1–16. doi:10.1007/s13593-012-0126-5

Coughenour CM (2003) Innovating conservation agriculture: the case of no-till cropping. Rural Sociol 68(2):278–304. doi:10.1111/j.1549-0831.2003.tb00138.x

Darnhofer I, Lindenthal T, Bartel-Kratochvil R, Zollitsch W (2010) Conventionalisation of organic farming practices: from structural criteria towards an assessment based on organic principles. A review. Agron Sustain Dev 30(1):67–81

de Souza H, Cardoso I, de Sá Mendonça E, Carvalho A, de Oliveira G, Gjorup D, Bonfim V (2012) Learning by doing: a participatory methodology for systematization of experiments with agroforestry systems, with an example of its application. Agrofor Syst 85(2):247–262. doi:10.1007/s10457-012-9498-4

Dogliotti S, van Ittersum MK, Rossing WAH (2005) A method for exploring sustainable development options at farm scale: a case study for vegetable farms in South Uruguay. Agric Syst 86(1):29–51. doi:10.1016/j.agsy.2004.08.002

Fumagalli M, Acutis M, Mazzetto F, Vidotto F, Sali G, Bechini L (2012) A methodology for designing and evaluating alternative cropping systems: application on dairy and arable farms. Ecol Indic 23(0):189–201. doi:10.1016/j.ecolind.2012.03.028

Gouttenoire L, Cournut S, Ingrand S (2013) Participatory modeling with farmer groups to help them redesign their livestock farming systems. Agron Sustain Dev 33(2):413–424. doi:10.1007/s13593-012-0112-y

Hobbs PR, Sayre K, Gupta R (2008) The role of conservation agriculture in sustainable agriculture. Phil Trans R Soc B Biol Sci 363(1491):543–555. doi:10.1098/rstb.2007.2169

Klerkx L, Aarts N, Leeuwis C (2010) Adaptive management in agricultural innovation systems: the interactions between innovation networks and their environment. Agric Syst 103(6):390–400. doi:10.1016/j.agsy.2010.03.012

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. Agron Sustain Dev 27(2):101–110. doi:10.1051/agro:2006037

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. Agron Sustain Dev 32(3):703–714. doi:10.1007/s13593-011-0070-9

Le Gal PY, Dugué P, Faure G, Novak S (2011) How does research address the design of innovative agricultural production systems at the farm level? A review. Agric Syst 104(9):714–728. doi:10.1016/j.agsy.2011.07.007

Lefèvre V, Capitaine M, Peigné J, Roger-Estrade J (2012) Soil conservation practices in organic farming: overview of French farmers' experiences and contribution to future cropping systems design. Paper presented at the 10th European IFSA Symposium, Aarhus, 1–4 July

Leifeld J (2012) How sustainable is organic farming? Agric Ecosyst Environ 150:121–122. doi:10.1016/j.agee.2012.01.020

Meynard JM, Dedieu B, Bos B (2012) Re-design and co-design of farming systems: an overview of methods and practices. In: Darnhofer I, Gibbon D, Dedieu B (eds) Farming Systems Research into the 21st century: the new dynamic. Springer, pp 407–431

Peigné J, Ball BC, Roger-Estrade J, David C (2007) Is conservation tillage suitable for organic farming? A review. Soil Use Manag 23(2):129–144. doi:10.1111/j.1475-2743.2006.00082.x

Peigné J, Cannavaciuolo M, Gautronneau Y, Aveline A, Giteau JL, Cluzeau D (2009) Earthworm populations under different tillage systems in organic farming. Soil Tillage Res 104(2):207–214. doi:10.1016/j.still.2009.02.011

Pretty JN (1997) The sustainable intensification of agriculture. Nat Res Forum 21(4):247–256. doi:10.1111/j.1477-8947.1997.tb00699.x

Sterk B, van Ittersum MK, Leeuwis C, Wijnands FG (2007) Prototyping and farm system modeling: partners on the road towards more sustainable farm systems? Eur J Agron 26(4):401–409. doi:10.1016/j.eja.2006.12.006

Sumberg J, Okali C, Reece D (2003) Agricultural research in the face of diversity, local knowledge, and the participation imperative: theoretical considerations. Agric Syst 76(2):739–753. doi:10.1016/s0308-521x(02)00153-1

Teasdale JR, Brandsæter LO, Calegari A, Skora Neto F (2007) Cover Crops and Weed Management. In: Mahesh K. Upadhyaya REB (ed) Non-chemical weed management: principles, concepts and technology. CABI, pp 49–64

Vereijken P (1997) A methodical way of prototyping integrated and ecological arable farming systems (I/EAFS) in interaction with pilot farms. Eur J Agron 7(1–3):235–250. doi:10.1016/s1161-0301(97)00039-7

Vian JF, Peigne J, Chaussod R, Roger-Estrade J (2009) Effects of four tillage systems on soil structure and soil microbial biomass in organic farming. Soil Use Manag 25(1):1–10. doi:10.1111/j.1475-2743.2008.00176.x