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RESEARCH ARTICLE

A farmer-oriented method for co-designing groundwater-friendly farm management

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Abstract

French and EU policies have been only partially successful in promoting the restoration of groundwater quality. The currently proposed measures are scientifically valid but ineffective in encouraging farmers to change their practices over the longer term. Participatory approaches have been developed for co-designing scenarios at cropping system or catchment area level, to improve groundwater quality. Farmers are one of several types of stakeholders who make contributions in this respect. In this context, we propose a similar participatory approach, although with two key differences: only farmers take part in the co-design process, and a farm-scale systemic perspective is applied. Our method, inspired by co-development, involves five steps, including groundwater quality pressure assessment. Within this method, we generate farmer-to-farmer suggestions aimed at improving farm management from an economic, social, and environmental perspective, with an emphasis on reducing pollution in catchments. The co-design groundwater-friendly farm management combines re-designed elements (e.g., changing agricultural practices or cropping systems or machinery or labor) that are consistent with the project specified by the farmer and that simultaneously decrease pressure on groundwater quality. We tested our method using two groups of farmers from southeastern France, located in areas concerned by groundwater quality issues related to nitrate and pesticide pollution. Our results show that our method based on farmer-to-farmer exchanges with a systemic approach constitutes an interesting and viable solution. In the months following the co-design process, the farmers in the test groups implemented some of the innovations suggested by their peers, thus creating a new groundwater-friendly farm management. This approach could be used in regions with other environmental challenges since the ultimate goal is to encourage sustainable farming practices. However, in the proposed methodology, the knowledge provided only by farmers might be too homogeneous, thus limiting the scope of changes in farming practices.

Keywords Participatory approach · Farm scale · Farmer · Co-design · Water quality

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1 Introduction

Since the 1960s, European agriculture has become increasingly intensive and specialized on farms and within regions. This shift has resulted in the intensive use of synthetic fertilizers and pesticides, and consequently in nitrate and pesticide pollution affecting groundwater quality in sensitive areas (Merrington et al. 2002). Europe has adopted a suite of legislative actions to protect and improve water quality, for instance, the Nitrate Directive of 1991 (Directive (91/676/EEC) and the Water Framework Directive (Directive 2000/60/EEC). These current policies aiming to limit agricultural pollution have not however been entirely successful in improving groundwater quality (Skevas 2019). The "best practices management" proposed to farmers is viewed as unsuitable for variable farm management organizations and has provided inconsistent results until now (Richard et al. 2018).

This diffuse groundwater pollution is difficult to overcome because there is no clearly defined point of entry, and many European farmers remain unconvinced as to the appropriateness of the measures to balance farm management and environmental benefits (Barnes et al. 2011; Macgregor and Warren 2006). Most of the proposed measures are therefore insufficiently adopted by farmers in France to recover groundwater quality (Kuhfuss et al. 2012). In this context, designing farming practices that would be implemented over the long term and likely to improve groundwater quality has become a major challenge. To meet this challenge, this present research is based on three considerations.

First, designing farming practices addressing the environmental impacts of agriculture calls for a systemic approach: each farm's components (cropping system, resources, etc.) and the specific farmer's strategy are taken into account from the beginning of the design process (Fig. 1) (Prost et al. 2017). A systemic analysis is performed to determine explicitly how a shift in practices could affect the use of available labor, land, equipment, and capital, in order to strengthen the adaptive capacity of the farm (Le Gal et al. 2011). This systemic approach at farm scale requires multidisciplinary knowledge and promotes a participatory approach (Thornton and Herrero 2001).

Second, farmer involvement in the participatory approach is key to successfully designing sustainable farm management (Dogliotti et al. 2014). In participatory research, this involvement can take different forms, depending on how much power is given to farmers during the co-design process (Barreteau et al. 2010). Participatory approaches vary according to "who defines the research problems and who analyses, generates, represents, owns, and acts on the information that is sought" (Cornwall and Jewkes 1995). In this study, we will ensure that farmers are involved very early on, as they are the best persons to assess whether an innovation is a good fit for their farm management (Gouttenoire et al. 2013) or to help co-design innovative solutions that foster their spontaneous appropriation (Le Bellec et al. 2012).

Third, co-designing farm management to enhance sustainability is a process that should be exclusively farmer-oriented. As groundwater pollution is a hidden issue that has no direct consequences for farmers, solutions for recovering this pollution should be consistent with each farm management to foster change. Farmers have different perceptions of water quality management, from the "resistors" to the "multifunctionalists" (Barnes et al. 2011), and from the "Beyond regulation" to the "Strong Regulation-constraints" (Richard et al. 2018). These different typologies show that farmers may have a greater or lesser degree of reluctance to adopt new measures for groundwater quality protection, and the "resistors" should be prioritized to participate to this approach, as legislation application is not efficient for them. Many researchers have emphasized that farmers need to exchange interact with their peers, scrutinize the different ideas that arise, and share their experiences in their local contexts (Goulet 2013). In a farmer-oriented co-design process, farmers participate in peer-based discussions where they can share knowledge and receive advice on how to overcome the practical, economic, and social uncertainties when they change their agricultural practices (Cerf et al. 2010; Payette and Champagne 1997).

Regarding the groundwater quality issue, participatory approaches involving farmers have been developed to co-design (i) cropping systems (Ravier et al. 2015) or (ii) alternative land use on their local watershed (Chantre et al. 2016; De Girolamo and Lo Porto 2012). In view of the three considerations described above, these existing participatory approaches do involve farmers, but farmers (i) are not systematically involved in the early stages, (ii) are not the only stakeholders participating in the design, and (iii) do not consider the farm scale. The objective of this study was therefore to develop a participatory approach in which farmers were the sole co-designers, and to test its ability to yield changes at farm scale that could decrease pressure on groundwater quality. In the first part of the manuscript, we describe the method developed. In the second part, we present and discuss the results from the implementation of this method with two groups of farmers located in southeastern France, in sensitive areas defined by nitrate and pesticide pollution.

2 Materials and methods

2.1 Individual interviews and collective workshops

Our participatory approach was inspired by a co-development method designed by Payette and Champagne (1997) that promotes collective learning. Their method begins by allowing

Fig. 1 Farming landscape picture corresponding to different plots. It includes different cultural systems representing various farming systems

participants to describe their own real-life situations. A guided discussion among peers then helps participants to identify changes to individual objectives or to design plans for achieving goals. In our study, farmers are characterized in two types: (i) *recipient* farmers (further referenced as *recipient*) whose methods in line with current regulations are insufficient to guarantee the quality of groundwater, and present a goal to sustain (meaning, technical challenge or project); and (ii) *adviser* farmers (further referenced as *adviser*), who have expertise and knowledge to help the *recipient*s to design new practices. We organized two types of sessions (Fig. 2): individual interviews with the *recipients* and collective workshops in which *recipients* interacted with *advisers*. In the individual interviews, a facilitator conducted a semi-structured discussion with the *recipients*, which was recorded and partially transcribed (Fig. 2, steps (1) and (3)). The facilitator then analyzed the information gathered (Fig. 2, steps (1) and (3)). Two collective workshops, also recorded, were subsequently held (Fig. 2, steps (2) and (4)), where farmers shared practical knowledge and suggestions. The objective behind alternating individual and collective interactions was to involve farmers during the whole co-design process and to increase their spontaneous appropriation of the proposed modifications. Groundwater quality issue is invisible for farmers, and solutions proposed by regulatory measures find few approvals by farmers. So, we decided that the main objective of co-designing new proposals was to meet the challenge/project of the *recipients* while improving or at least protecting groundwater quality.

2.2 The five steps of the method

2.2.1 Step zero: identifying farmers and their roles for the process

First, we contacted stakeholders to define major challenges regarding the type of groundwater pollution (i.e., nature—nitrates and/or pesticides—and quantity) and to identify farmers cultivating in the vulnerable area, who were subjected to regulatory measures (Fig. 2). During this informal

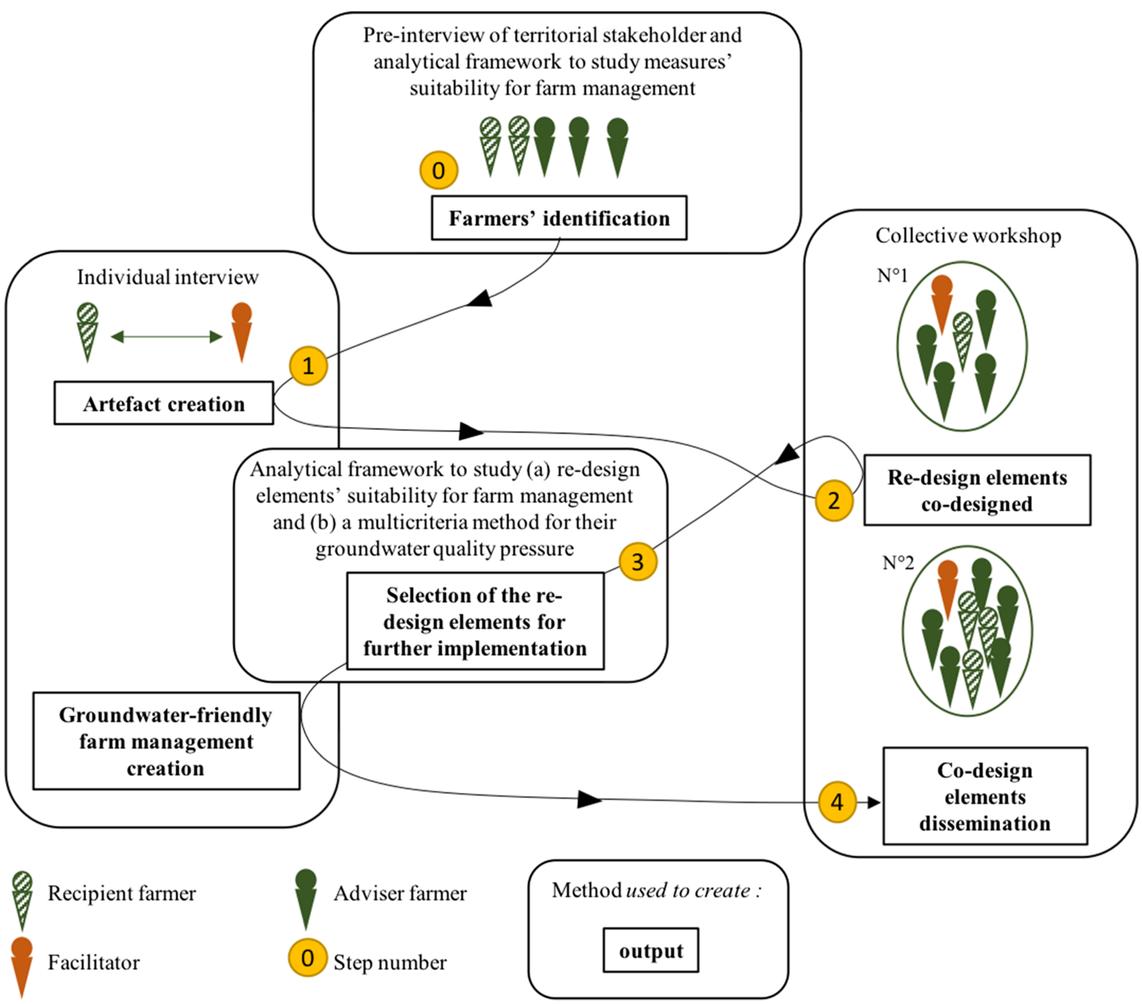

Fig. 2 Five steps of the participatory approach balancing between individual (steps (1) and (3)) and collective sessions (steps (2) and (4)). Each step presents output for co-designing groundwater-friendly farm management

exchange, we defined, with the stakeholders, consistent indicators for monitoring groundwater quality. Second, we initiated dialogs with farmers and studied how they implemented the regulatory measures for recovering groundwater quality (Richard et al. 2018). A typology made, the "Strong Regulation-constraints" type, presents resistance for regulatory measures application. So, they were prioritized to encourage them to participate in our study for co-designing change consistent with their farm management. Promising candidates were chosen to be *recipients* after clarifying their goal, technical challenge, or project, to develop sustainable practices. The *advisers* were then chosen according to their expertise with regard to the *recipient*'s goal.

2.2.2 Step one: representing the recipients' farm management

The objective of the first step was to create a visual depiction of the *recipients*' farm management, i.e., an artifact support for the design process. This step is important to enhance a systemic approach during the co-design process. First, during the individual interview, the *recipient* described their farm management and detailed their technical challenge or project aligned with the groundwater quality recovery intention. On this basis, we generated the artifact of the *recipient* farm management. It contained information about the farmer's family, hired labor, equipment, land use, and cropping systems, noting any instances of interdependence (e.g., exchange of seeds) (Fig. 3). Then, the proposed artifact was presented to the *recipient*, in order to (i) refine/complete the representation and (ii) encourage them to take ownership of it, as it would serve as the basis for exchanges between farmers during the design workshop. These two interviews were thus essential precursors to the collective workshop n°1 (Fig. 2, step (2)).

2.2.3 Step two: exchanging knowledge and proposing re-design elements

The second step consisted of the collective workshop n°1: *recipients* presented (i) their farm depictions (Fig. 3) and (ii) their technical challenge or project, to three or four *advisers*. The *advisers* relied on the artifact when suggesting re-design elements during the consultation stage. Re-design elements could be either the improvement of techniques already in use (e.g., hoeing at a higher speed to control the weed population) or the adoption of new agricultural practices (e.g., weeding with biocontrol) or changed to a cropping system by exploiting available equipment/labor or making additional investments (e.g., implementing an inter-row frost-sensitive cover crop between lavender). During the co-design process, improving groundwater quality was not treated as an objective but rather as a constraint. This means that re-design elements

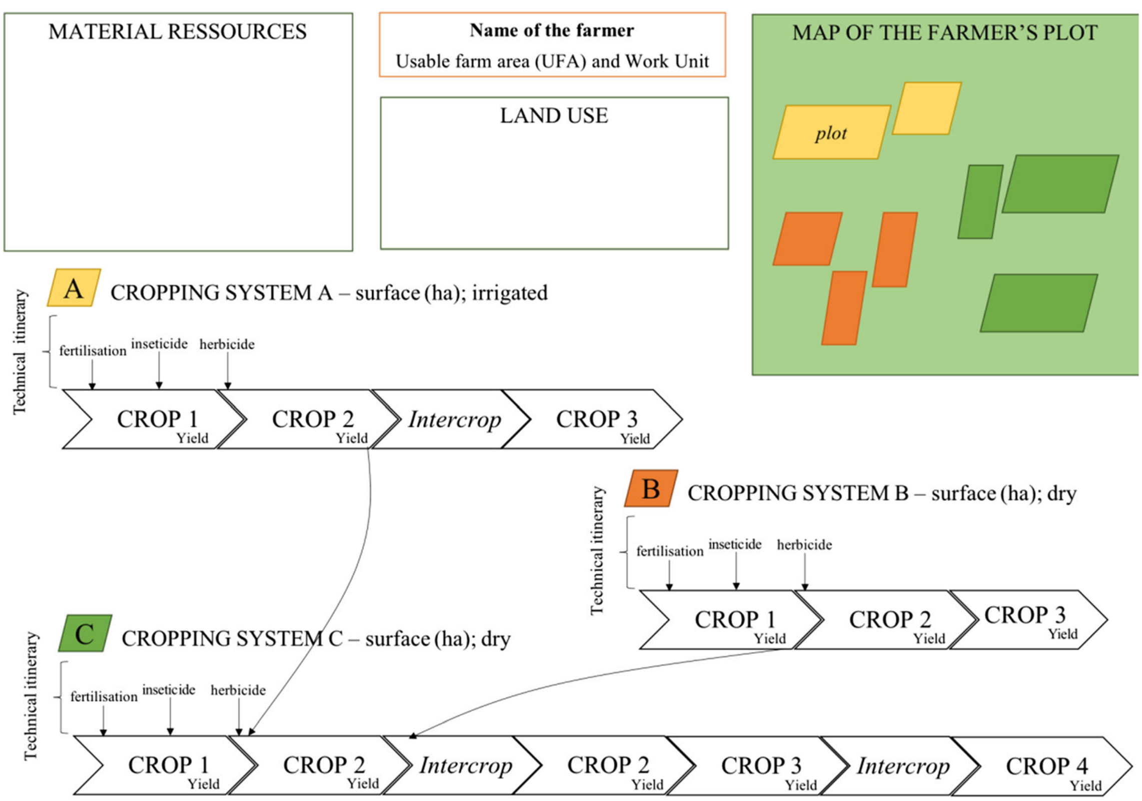

Fig. 3 Artifact of *recipient* farmer's management. It represents the farm's equipment, usable farm area (UFA), land use (in hectares), and cropping systems ((A), (B), and (C); locations shown on map). Crop sequences, cover crops, and key actions are indicated for each cropping system

were proposed regarding the *recipient*'s goal and were excluded if not consistent with groundwater quality recovery (e.g., chemical treatment of seeds).

The facilitator adopted a neutral position during this workshop; no additional knowledge was given but the discussion was stimulated or the focus shifted if necessary. The facilitator used the artifact as a tool for promoting a farm-scale systemic approach throughout the co-design process (the facilitator made the *adviser* detail the resources used, such as machinery or seeds) and write down in green the proposals on the artifact.

2.2.4 Step three: pre-selecting re-designed elements and assessing the impact of customized re-designed farm management on groundwater quality pressure

The third step consisted of designing new groundwater-friendly farm managements (Fig. 2). First, we classified the optional changes suggested by the *advisers* according to their suitability to the *recipient's* farm management. We used an integrative analysis (Richard et al. 2018) involving (i) an ex ante assessment of the structural impact of implementing the re-designed elements and (ii) an evaluation of how well the structural modifications fit with the farmer's objectives. The structural impact refers to structural modifications at different levels of farm management, i.e., input, crop rotation, or changes to the machinery. We considered that the structural impact was large when it affected at least the cropping system, and that it was minimal when it did not.

The re-designed element's suitability was then defined by its structural impact and its strategic consistency. For example, it was considered to be highly suitable when it had a slight structural impact and a strong strategic consistency.

Thereafter, the suitable re-designed elements were evaluated at farm scale, according to their potential impact on groundwater quality pressure, as a basis for selecting them in relation to the constraint concerning groundwater quality. The objective of this second stage was to develop a method that was easy to use to assess ex ante the co-designed farm management capacity for protecting groundwater quality.

To assess pressure on groundwater quality, a large range of methods exist, from operational models (e.g., MASC) (Sadok et al. 2009) to simulation models (e.g., SWAT, CO'CLICK'EAU) (Chantre et al. 2016; Ullrich and Volk 2009). However, the objective of this whole participatory method is to be operational and easy to use for groundwater stakeholders, which is not the case for most models. So, we chose to use indicators that can be simple to assess.

Regarding pressure on nitrate content of groundwater, we used a common indicator, widely employed in the literature (Foissy et al. 2013): the nitrogen balance (N) which compares N-inputs, including N fertilizer and N2 fixation by legumes, and N-outputs during the whole crop rotation (Carlsson and Huss-Danell 2003). Nitrogen balance should be calculated, at least, in a rotation scale, to take into account symbiotic nitrogen fixation by legumes. N fertilizer values for each crop (name and quantity) of each cropping system were given by the *recipient* during the first interview, and N2 fixation values for legumes grown by the farmer were derived from the scientific literature.

Regarding pressure on groundwater quality by pesticides, the common indicator is treatment frequency index (TFI). However, it does not give information on the active molecules, found in groundwater, on which the pesticides are based (e.g., METAREX® is made up of 40 g/kg of metaldehyde, a molecule monitored in groundwater catchment). So, we used the TFI of active molecules (TFIam) that measures the amount of active molecules included in the pesticides used. We calculated the ratio of the concentration of each active molecule contained in a pesticide, to a registered rate of application. The pesticide applications for every crop on the farm (name and quantity) were given by the *recipient* farmer during the first interview.

Differences in the values of these indicators revealed the impact of re-designed farm management on the reduction of risks of pollution. These two indicators were calculated at farm scale. We first evaluated the differences between the *recipient* farmer's current management and these re-designed versions of the farm management in which single re-designed elements had been implemented (e.g., one new practice had been incorporated). Second, we evaluated the current farm management and the customized one, incorporating changes of the combination of re-design elements.

The last stage was an interview with the *recipients*. After a presentation of the set of re-designed elements, their suitability for the management of each farm, and their potential impact on groundwater quality, they selected the re-designed elements they intended to implement in their farm. Once the final combination of choices was made by the *recipient*, the objective was to allow them to spontaneously take up these recommendations and to discuss the targeted result of this combination on groundwater quality pressure. Finally, it was to agree about it in order to present them to other farmers during the final collective workshop n°2. At the end, a customized re-design farm management was created.

2.2.5 Step four: producing collective levers

The fourth and last step was a collective workshop n°2, in which all the *recipients* presented to other farmers of the territory, one by one, the different re-designed elements they intend to implement and their final combination. The presentation was based on the artifact, to keep the systemic approach so that the other farmers could more easily compare their own farm management and potentially appropriate some re-designed elements for further implementation. The objectives of this step were (i) to allow farmers to compare strategies to encourage their implementation in the modified farm management and (ii) to disseminate the re-design elements to other farmers in the territory.

2.3 Method testing

We tested our method using two groups of farmers from two counties in southeastern France: (1) an area next to Oraison municipality in Val de Durance (O; 43°54′ N; 5°55′ E) and (2) an area next to Quincieux in Rhône-Alpes (A; 45°54′ N, 4°46′ E). These two counties are defined as sensitive areas with regard to nitrate and pesticide pollution, and farmers are subjected to regulatory measures. We involved respectively 12 and 6 farmers during the co-design process, who had various farming systems with grain, forage, and "speciality crops" (e.g., lavender) with or without livestock, under conventional, organic, or conservation systems (Table 1). In Val de Durance, we organized two n°1 collective workshops in order to have more *recipient* farmers in the co-design process and to exchange roles between *recipient* and *adviser* (Table 1).

3 Results and discussion

3.1 Diversity of re-designed elements during the collective workshop n°1

3.1.1 Various strategies of re-design elements

The seven *recipient* farmers described various goals, technical challenges, or projects, from "reducing input use" to "developing an agro-forestry system" (Table 1). Two *recipients* (V3 and V4) did not receive any proposed re-design element because, during consultation time, they discussed only their current farm management without describing a specific goal. Thus, we will not further mention these two *recipients* in the results.

Over all the workshops, the re-design elements proposed centered around (i) increasing diversity within the cropping systems; (ii) enhancing natural biodiversity; and (iii) improving autonomy (Table 2). Several strategies were recommended for increasing cropping system diversity. The most common was adding a new crop in the rotation (*recipients* V1, V5, A1, and A2). The goal was to manage weed resistance, to improve soil fertility, or to produce organic mixed fodder for sheep (Table 2). For example, *recipient* V1 was faced with a problem of resistance of rye grass in wheat, and *adviser* V6 suggested that he diversify his rotation. Once this strategy had been suggested, another *adviser* V7 proposed that he reuse the faba bean seeds, already grown in another cropping system on the *recipient's* farm, and to sow them as a main crop between two wheat crops. Likewise, implementing a new crop in his current short-term succession was proposed to the *recipient* A1 to address the problem of resistant Bermuda grass (Table 2). Less common suggestions involved intercropping or planting orchard crops, cover crops, or diverse varieties to increase field crop diversity (*recipient*s V1, A1, A2; Table 2). The agro-forestry project of *recipient* V5 was discussed with *adviser*s V7, V10, and V12 (Table 2). They proposed different species of trees: pistachio, as *adviser* V12 had been growing this species on his farm for 3 years; pomegranate and persimmon, as *adviser* V7's neighbor grew them; and fig, as it is a native species. Spatial diversification strategies were also proposed: intercropping rapeseed was proposed to *recipient V1* (Table 2) either with vetch (inspired by the experience of *adviser* V6) or a mix of barley and rye to control slugs or alfalfa (because the crop was already cultivated on the farm and on-farm seeds were therefore available). Two strategies for enhancing natural biodiversity were mentioned. First, it was suggested that synthetic pesticides be replaced by organic biocontrol (*recipient* V1; Table 2). Second, it was suggested that chemical weed treatments be replaced by mechanical weed control (*recipients* V1 and A1; Table 2). Finally, one solution for improving farm autonomy was to use farm-saved seeds for wheat and rapeseed, in order to reduce costs and to avoid buying treated seeds (the local cooperative did not offer untreated seeds), which were not necessary (Table 2).

3.1.2 As described above, various re-design elements were proposed during the collective workshop n°1 to help recipients address their objectives (Table 2): re-design elements' suitability for farm management, their implementation, and dissemination to other farmers

Among the *recipients*, V2 received re-design elements that were only moderately suitable for his farm management. He therefore chose not plan to implement them (Table 2).

The other *recipients* were given between 2 and 12 re-design elements. However, some changes displayed either low or very low suitability. Others, while moderate suitable, were not implemented (Table 2). *Recipients* V1, V5, A1, and A2 implemented, respectively, 50%, 100%, 40%, and 50% of the changes proposed to them (Table 2). These included highly and moderately suitable elements, with strategic consistency (e.g., planting a new crop such as faba bean had an important structural impact but was consistent with the farmer's goal, so was considered as moderately suitable with regard to his farm management; Table 2). *Recipients* V1, A1, and A2 quickly incorporated into their farm management some of the highly suitable re-design elements they had selected. Others were to be implemented later, when climatic conditions, such as rainfall, called for it. These were mainly designated to one particular farmer, but could sometimes be used by the other farmers participating to the farmer-to-farmer discussion (Table 2). For example, farmer V3 adopted "planting pistachio trees" to his farm, whereas it was first proposed to *recipient* V5 (Table 2).

Table 1 Characteristics of farmers who participated to the participatory approach developed in two zones and their roles accorded to each for the collective workshop(s). *ABS* absent

Zone	Farm code	Total area (ha)	Type of farms	Farming system	Role for collective workshop n°1	Role for collective workshop n°1 bis	Design goal
Val de Durance	V1	270	Mixed production system (cereal, lavanda)	Conventional system	Recipient	Adviser to V3 and V4	Reducing inputs
	V2	170	Mixed beef production system	Conservation tillage system	Recipient	ABS.	Converting a conventional system into an organic system for 1 plot
	V3	38	Mixed sheep production system	Conservation tillage system	Adviser to V2	Recipient and adviser to V4	Converting a conventional system into an organic system
	V4	120	Mixed production system (cereal, olive, tulip)	Conventional system	Adviser to V2	Recipient and adviser to V3	Reducing inputs
	V5	140	Cereal production system	Conservation tillage system	ABS.	Recipient	Designing agro-forestry system for a non-irrigated plot
	V6	65	Cereal production system	Conservation tillage system	Adviser to V1	ABS.	
	V7	109	Cereal production system	Conservation tillage system	Adviser to V1	Adviser to V5	
	V8	120	Cereal production system	Conventional system	Adviser to V2	ABS.	
	V9	55	Cereal production system	Organic system	Adviser to V1	ABS.	
	V10	60	Cereal production system	Conservation tillage system	ABS.	Adviser to V5	
	V11	45	Cereal production system	Organic system	Adviser to	ABS.	
	V12	30	Mixed production system (lavanda and pistachio)	Agro-forestry system	ABS.	Adviser to V5	
Amberieux (North of Lyon)	A1	125	Mixed beef production and market gardening	Conservation tillage system	Recipient and adviser to A2		Improving soil quality
	A2	69	Mixed plant production (cereal and tree crops)	Conventional system	Recipient and adviser to A1		Increasing crop rotation
	A3	82	Cereal production	Conventional system	Adviser to A1 and A2		
	A4	95	Mixed sheep production	Conventional system	Adviser to A1 and A2		
	A5	40	Mixed poultry production	Conventional system	Adviser to A1 and A2		
	A6	80	Cereal production	Conventional system	Adviser to A1 and A2		

Table 2 Re-design elements proposed to *recipient* and *adviser* farmers according to different strategies, the results of their suitability for farm management explaining the future implementation by the farmer, and their farm-scale evaluation assessing potential pressure on groundwater quality by nitrates and pesticides

Re-design elements	For who ?	Strategy			Suitability	implementation (surface)	Groundwater quality Pressure	
		System diversification	Natural biodiversity	Autonomy			TFIam	[*N*]
Harvesting farm-saved seed for wheat and rapeseed	V1			x	High	Yes (35 ha)	4.4 (− 9%)	36.1 (0%)
Using low-volume treatments	V1		x		High	Yes (270 ha)	4.8 (− 3%)	36.1 (0%)
Planting faba bean between wheat in non-irrigated fields	V1	x			Mod	Yes (5 ha)	4.6 (− 5%)	32 (− 12%)
Planting frost-sensitive inter-row cover crop between lavender	V1	x			Mod	Yes (not yet, 60 ha)	4.6 (− 5%)	37.9 (+ 5%)
Planting pistachio trees	V3	x			na	Yes (5 ha - 100 trees)	na	na
	V5				High	Yes (22 ha - 300 trees)	1.56 (0%)	41 (+ 5%)
Planting pomegranate trees	V5	x			Mod	Yes (22 ha - 200 trees)		
Planting persimmon trees:	V5	x			Mod	Yes (22 ha - 200 trees)		
Planting fig trees	V5	x			Mod	Yes (22 ha - 200 trees)		
Using buckwheat as the rotation's second crop	A1 A2	x			Mod Mod	Yes (10 ha) Yes (15 ha)	6.4 (− 8%) 1.6 (− 14%)	8.6 (− 5%) 26 (− 15%)
Using faba bean as a pre-corn cover crop	A1	x			Mod	Yes (not yet)	6.8 (− 1%)	9 (− 1%)
Intercropping rapeseed with alfalfa	V1	x			Mod	Yes (not yet,	4.8 (− 3%)	33.6 (− 7%)
Employing conservation tillage	A1	x			Mod	Yes (not yet)	na	na
Intercropping rapeseed with vetch	V1	x			Mod	No	na	na
Intercropping rapeseed with barley and rye	V1	x			Mod	No	na	na
Replacing chemical pesticides with organic ones	V1		x		Mod	No	na	na
Using alfalfa as fodder	V2	x			Mod	No	na	na
Using trefoil as fodder	V2	x			Mod	No	na	na
Using dwarf clover as fodder	V2	x			Mod	No	na	na
Adding triticale	A1	x			Mod	No	na	na
Mixing two rapeseed varieties	A1		x		Mod	No	na	na
Hoeing corn at a higher speed (6–7 miles per hour)	A1			x	Mod	No	na	na
Adding triticale	A2	x			Mod	No	na	na
Treating alfalfa with castor bean meal to fight wireworms	V1		x		Low	No	na	na
Using buckwheat as a main crop, planted after corn	A1	x			Low	No	na	na
Adding chickpea	A1	x			Low	No	na	na
Adding flax	A1	x			Low	No	na	na
Spreading compost/ramial chipped wood	V2		x		Very low	No	na	na
Using a Rodenator® system in alfalfa to fight wireworms	V1		x		Very low	No	na	na
Implementing a mixed cover crop of rye and hairy vetch	V1	x			Very low	No	na	na

3.1.3 Impact of these re-design elements' implementation on groundwater quality pressure

Every re-design element has been assessed as reducing pesticide use (cf. Table 2; TFIam% [− 14; − 1]). They are associated with the three different strategies described above: even in the autonomy strategy, farm-saved seed enables a farmer to reduce the pesticides used for seed treatments. As these results are at farm scale, we find variations of TFIam results between farmers, who have different farm management systems, from cereal production to mixed beef production (Table 1). Likewise, we find that most re-design elements can reduce nitrogen balance (cf. balance N (%) [− 15; − 1]). Here, the N balance increased because of the addition of orchard crops and the use of an undersown cover crop (Table 2). For *recipient* V5, fruit trees may reduce nitrate leaching because (i) the tree roots can absorb nitrogen from below the zone occupied by the annual crops' root systems; and (ii) water uptake increases, thus decreasing drainage (Reisner et al. 2007). For *recipient* V1, the addition of a cover crop in lavender can increase soil organic matter and decrease nitrate leaching (Garcia et al. 2018). Overall, we can conclude that the *recipient* farmers can improve groundwater quality through increases in soil organic matter, or decreases in TFIam, or in nitrogen losses.

We can conclude that all the tailored re-design elements intended to be implemented by farmers are able to decrease pressure on groundwater quality. New groundwater-friendly farm management was thus co-designed. However, we need to consider these results with caution, as our indicators give only information trends on the impact on groundwater quality pressure that would need to be discussed, since groundwater quality may vary in a more complex way, depending on the local factors that affect leaching.

3.2 Effectiveness of this participatory method in fostering change

Our participatory method exclusively involved farmers and was based on a systemic approach at farm scale. In this section, we discuss the impact of these two methodological choices on fostering the change implemented by farmers to reduce pressure on groundwater quality.

In our test groups, we found that the knowledge shared was mainly technical, relating to local condition. For example, one *adviser* suggested a change that he had recently made on his farm: "last year, I sowed my own farm-saved rapeseed seeds, and I didn't see any change in yield compared with commercial seeds. You should try it too!" Such knowledge was routinely brought up during interviews and workshops and encouraged other farmers to do likewise. We found that such local proposals, already tested by a peer, are an incentive to others to adopt them: "with V5, we've got the same seeder, so if it works with him, I would go for it more confidently" (*recipient* V1). This emphasizes the fact that it is more risky for every farmer to adopt practices proposed by socially distant outsiders than by farmers closer to them (Hoffmann et al. 2007). Thus, the exclusive participation of farmers was able to foster change, even with *recipients* who were averse to risk and whose regulatory measures were not able to make them change, such as V1 and A1.

However, when farmers are the only participants, the knowledge provided may be somewhat too homogeneous or not original enough to apply to unpredictable conditions (Prost et al. 2017). Hence, we can argue that multi-stakeholder workshops should be added as a complementary step. Farmer-to-farmer exchange should nevertheless be maintained, as it is a key to (i) exchanging some local and empirical knowledge; (ii) facilitating the systemic approach; and (iii) fostering spontaneous appropriation of the suggestions made by their peers. But bringing in other stakeholders at a subsequent workshop, such as groundwater managers, local technicians, and researchers, with their different points of view, may ensure that more innovative propositions are made (Le Bellec et al. 2012). And it is likely to allow the emergence of local multi-stakeholder dynamics that could facilitate dialog (Le Bellec et al. 2012). Furthermore, farmers are not the only actors influencing farm management decisions, and involving stakeholders having such influence could facilitate the implementation of the innovation. For example, in the case of *recipients* V1 and A1, some re-design elements were suitable for their farm management but were ultimately refused because the farmer's father or the usual adviser offered opposing contradictory opinion after the workshop. It would have been helpful to include the *recipient*'s father in the collective workshop n°1 (step 2).

Participatory approaches involving farmers have been developed to co-design (i) cropping systems (Ravier et al. 2015) or (ii) alternative land use on their local watershed (Chantre et al. 2016; De Girolamo and Lo Porto 2012). They also proposed that groundwater quality issues could be dealt with by increasing the use of biodiversity-enhancing techniques such as planting cover crops or diversifying rotations. But farmers' implementation of new practices encountered various difficulties such as work calendar constraints and the cost or unavailability of new resources. Farmers often fail to adopt more sustainable agricultural practices because they lack the proper resources, and/or the practices are inappropriate (Dorward et al. 2003). A systemic approach at farm scale is able to take into account the complex farm management components during the design process and even their interdependency. Some *advisers* made suggestions that clearly encompassed the whole combination of cropping systems at farm scale, such as saving alfalfa seeds from one cropping system to intercrop alfalfa with rapeseed in another cropping system (Table 2). Overall, the recommendations were tailored to account for each *recipient* farmer's challenge or objective and their current farm management regime (e.g., crop number, cropping systems, and available equipment). Ultimately, four of the seven *recipients* implemented at least some of the proposed changes. At the end of the workshop n°1, some farmers agreed about this approach that gather only farmers working to address each farmer's objectives. One said "we are not used to this type of workshop, and sharing tips between farmers is very interesting."

3.3 Keys to success: the facilitator and *recipient* and *adviser* farmers

During the consultation stage of the collective workshop n°1, the facilitator played an essential role by guiding the discussion between the *recipient* and *adviser* farmers, thus promoting interactions and knowledge exchange. In the workshop focusing on *recipient* V3, the facilitator let the *advisers* ask numerous questions about the current farm management and did not refocus the exchange on the farmer's objective. As a result, no re-design elements were suggested by the *advisers*. Additionally, the facilitator was responsible for ensuring that the discussions had a systemic approach. In the workshop focusing on *recipient* V2, the suggestions made during the consultation stage did not adequately fit with his farm management regime, resulting in no further discussion.

It is moreover important for the *recipient* to be engaged in the process; he must have a well-identified, significant goal. *Recipient* V4 had a major project, which was revealed during the pre-workshop interviews. However, as prior to the workshop he had completed a training program to address his project, the consultation stage was of little additional use. It therefore appears pointless to have consultations with a *recipient* who has no further questions about his objectives. Finally, the *advisers* need to be the driving force of the workshop: they should have enough expertise to make original and relevant proposals to further the objectives of *recipients*.

4 Conclusion

In France like in other EU countries, dealing with non-point pollution stemming from intensive agriculture remains a significant challenge. Unlike usual "one size fits all" approach to design the catchment-level action plan, our approach includes original and key components of participatory approach to restore groundwater quality. First, farmers are the only contributors to take part in the co-design process to foster knowledge exchange among peers. Second, a systemic approach was applied at farm scale to co-design tailored propositions that could easily be implemented by farmers. These methodological choices support farmers to design farming practices that would be implemented over the long term to improve groundwater quality.

We ran individual sessions and collective workshops with two groups of farmers. This approach was successfully applied to a diversity of farm management systems and local conditions because farmers could come up with innovative recommendations on their own. They shared relevant local and scientific knowledge, as they discussed suitable changes based on agroecological practices that could help their peers work towards a given objective. Most of the participants of the workshops found this farmer-oriented method interesting and unusual. Ultimately, four of the seven focal *recipients*, but also *advisers*, implemented at least one of the re-design elements, showing the impact of such a farmer-oriented approach.

A major limitation of the described method is that it requires a large investment from *recipients* (interviews and workshops). However, we assume that this investment is a key to success in implementing the proposed changes. Compared with other co-design approaches for protection of groundwater quality, our method required the same investment but over a shorter time span.

Finally, our results suggest that this method could improve groundwater quality even though groundwater concerns were a constraint rather than an objective during the co-design process in our study. This participatory approach could also be used in regions with other environmental challenges such as groundwater quantity or erosion as long as the goal is to encourage more sustainable farming practices. This work supports the need to take into account the variability in farm management when making suitable recommendations for farmers. Regulation incentives clearly have an important role to play in improving water quality, but the long-term, chronic forms of diffuse pollution associated with agriculture will only be reduced significantly with the active cooperation of farmers. This farmer-to-farmer method can be an option for water management stakeholders that need to make some farmers change their practices in longer term.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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