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Fostering creativity to design biodiversity-based cropping systems that consider the long term: a participatory framework

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Biodiversity-based cropping systems can address sustainability challenges currently faced by agriculture and provide long-term benefits such as climate-change mitigation and other ecosystem services. However, short-term socio-economic and technical challenges encourage adherence to established paradigms halting the implementation of such systems in farms. In response, we developed a new framework that combines a fictional narrative and information about plant functional ecology to facilitate the co-design of biodiversity-based cropping systems. To demonstrate the interest of this framework, a participatory workshop was conducted in which participants selected crop species based on functional traits and collaboratively designed crop rotations. Both quantitative evaluation of co-designed crop rotations by ecological indices and qualitative evaluation by the satisfaction assessment of the framework by participants were performed. Our approach showed that the two co-designed crop rotations had higher biodiversity than the two reference rotations used in the study: the dominant (maize (*Zea mays*) – wheat (*Triticum aestivum*) – catch crop (white mustard (*Sinapis alba*)) and a highly diversified rotation designed to reduce the use of pesticides (10 taxonomic species). Using a fictional narrative as a trigger event (being stranded on a deserted island) was instrumental in expanding possibilities and stimulating creativity among the participants, which helped them design diverse crop rotations that contained taxonomical and functional diversity. Our framework demonstrated a potential to co-design biodiversity-based cropping systems by abstraction.

KEYWORDS

co-design, ecosystem services, trait-based ecology, fixation effect, diversification

1 Introduction

Food systems are under an unprecedented set of pressures to meet increasing demand for food and decrease competition for natural resources while impacted by climate change and the loss of biodiversity (Global Panel on Agriculture and Food Systems for Nutrition, 2020). Faced with these issues, nature-based solutions in agriculture are promoted based on the narratives of sustainability, resilience, multifunctionality (Keesstra et al., 2018; López Gunn et al., 2021) and long-term development of human societies (Maes and Jacobs, 2017). Long-term evidence of the effectiveness of nature-based solutions in agriculture is acknowledged (Maclaren et al., 2022), as a result of the planned biodiversity and associated biodiversity (Duru et al., 2015). To a certain extent, higher biodiversity provides insurance against climate-change impacts (Costa et al., 2024; Darnhofer, 2021; Renard and Tilman, 2019) and price volatility (Harkness et al., 2021). In addition, nature-based solutions may facilitate a greater sense of fulfilment for farmers, as well as supporting long-term ecosystem and human health (Klebl et al., 2024). However, the expected benefits of nature-based solutions, also known as biodiversity-based solutions, may take up to a decade to manifest (Wagg et al., 2022) and require initial investments (Brooker et al., 2016), especially when ambitious long-term system transformation is sought. Levin et al. (2022) summarized this idea as a trade-off: "how much to sacrifice in immediate return to reduce longer-term hazards". During this extended period, most farmers can accept no sacrifices when they are already struggling with volatile agricultural markets, frequent and unpredictable political changes, low revenues, or well-being issues (Brown et al., 2022). Accordingly, envisioning biodiversity-based solutions is complex, because when designing them, developing "what if" scenarios (Börjeson et al., 2006) that are perceived as "desirable futures" may be obscured by farmers' short-term issues. However, it remains important to identify the most effective biodiversity-based solutions from these long-term perspectives to pave the way for sustainable agriculture.

It is crucial to manage trade-offs between short-term (one year) and long-term issues (up to 50 years), as well as between ecosystem services and disservices (Carof et al., 2022; Seddon et al., 2021). In this context, a systems approach, as practiced in agronomy and ecology, is essential to identify and address connections and dependencies (Stokes et al., 2023). The emergence of functional ecology offers insights for identifying trade-offs, constraints, and synergies among agroecosystem functions that could help support ecosystem services, including food production (Frouz, 2024). In the field of functional ecology, a trait-based approach uses plant traits that quantify a species' performance (e.g., provision of ecosystem services) as a function of their ecological niche, biotic interactions, and functional role in agroecosystems (Lavorel, 2013). Consequently, functional ecology is renewing the agronomic principles behind crop rotations and intercropping (Cortois et al., 2016; Koyama et al., 2022), for example, by predicting results of plant-plant interactions in intercropping (Boudsocq et al., 2022). Recently, functional ecology has been considered as a framework for identifying both short- and long-term ecological processes, with the aim of facilitating agroecosystem management (Ardanov et al., 2023; Brown et al., 2022; Damour et al., 2018). Nonetheless, although functional ecology has made significant progress, these developments remain the exclusive domain of experts who are less inclined to study agroecosystems than other terrestrial ecosystems (Dawson et al., 2021). Co-design is a cognitive process that aims to address new agroecosystem management by involving the knowledge and expectations of different stakeholders (usually farmers, but also scientists and agricultural advisors) (Vereijken, 1997). Co-designing new agroecosystem management is also known to increase their probability of use (Bakker et al., 2022). However, high creativity is required to apply ecological principles in biodiversity-based solutions design (Bezner Kerr et al., 2022). In addition, the co-design of biodiversity-based solutions should avoid the "fixation effect" (Jansson and Smith, 1991), which is a cognitive bias caused by spontaneous activation of already known solutions to a given problem. This bias restricts the exploration of alternative, and sometimes disruptive, solutions (Agogué, 2012). As Hatchuel et al. (2011) demonstrated, individuals tend to retrieve the ideas that are most accessible in their memory, which tends to fix solutions on the habits or deeply held beliefs of designers (Meynard et al., 2012). Co-designing biodiversity-based solutions could benefit from a better interdisciplinary approach between agronomy and functional ecology, which poses strong methodological challenges. Indeed, agricultural stakeholders tend to rely more on empirical knowledge and observation than on theoretical concepts when designing systems (Ardanov et al., 2023; Blanco et al., 2020).

This literature review highlighted that (i) stakeholders designing biodiversity-based solutions (hereafter, "biodiversity-based cropping systems") have difficulties considering the long term, (ii) the fixation effects sometimes constrain participatory design of biodiversity-based cropping systems, and (iii) farmers and counsellors do not use functional ecology concepts adapted to combine short- and long-term issues. Considering these concerns, we aimed to explore whether encouraging creativity and promoting long-term consideration among participants involved in a participatory approach would facilitate the design of biodiversity-based cropping systems. Such an approach will be valuable for researchers aiming to simulate the benefits of diversification (Meunier et al., 2022) on ecosystem services, as no current rotation generator is able to design such diversified rotations.

To address our research question, we posited two hypotheses. First, we hypothesized that plant functional knowledge could be integrated during the workshop based on a set of cards representing different crops using plant functional ecology concepts. In turn, the potential ecosystem services would be more diverse compared to existing rotations in the Brittany region. Second, we hypothesized that the use of a conditioning phase based on a fictional narrative would help participants to break out of their habits and beliefs and to overcome possible fixation effects. This conditioning step should also help participants to design biodiversity-based cropping systems that could supply multiple ecosystem services and explicitly consider the long term. We defined plant functional knowledge as the roles and functions that plants, and particularly their traits, play in ecosystems. Rather than focusing solely on species identity, functional ecology emphasizes the characteristics (traits) of plants – such as leaf area, root depth, seed size, or drought tolerance – that influence their performance and interactions with the environment and other species that in turn alter ecosystem functions and related services. Through our proposed methodological framework, workshop participants would be able to increase both the taxonomic and functional diversity of cropping systems, potentially providing more ecosystem services.

TABLE 1 The 10 ecosystem services (v. 5.1 of the Common International Classification of Ecosystem Services (CICES)) selected using the trait-based approach implemented before the participatory workshop.

Section	Group	Class
Provisioning	Cultivated terrestrial plants for nutrition	Food provision
Regulation and maintenance	Regulation of baseline flows and extreme events	Erosion control
	Lifecycle maintenance	Maintenance of associated biodiversity
	Pest and disease control	Disease control
		Pest control
		Weed control
	Regulation of soil quality	Supply of nutrients for agroecosystem functioning
	Water conditions	Regulation of water balance for crop development
		Maintenance of water quality
	Atmospheric composition and conditions	Regulation of greenhouse gases

To focus more on field characteristics of cropping system design, the CICES nomenclature was modified when necessary.

2 Materials and methods

We developed a framework based on three steps: (i) tknowledge transfer from functional ecology, (ii) a fictional narrative serving as a spark of creativity, and (iii) a participative co-design workshop with the fictional narrative. The participants were encouraged to design crop rotations that provided a bundle of ecosystem services to address both short- and long-term environmental issues.

2.1 Transfer of a trait-based approach in a participatory workshop

To help combine theoretical concepts of functional ecology with the technical and empirical knowledge of participants, we implemented a trait-based approach before the workshop to select a diverse range of pertinent crop species that participants could use to design crop rotations. This study's trait-based approach was based on the framework of Damour et al. (2018), who adapted the framework of Lavorel and Garnier (2002) to agroecosystems by including two key interactions: (i) those between traits of planned species (i.e., crops) and spontaneous species (i.e., "weeds") and (ii) those between plant traits and farmers' technical decisions. Since plant traits may be associated with the provision of ecosystem services, we selected 10 provisioning or regulating and maintenance ecosystem services from the Common International Classification of Ecosystem Services (Haines-Young and Potschin-Young, 2018) based on their relevance to the main agricultural issues in the region where the workshop took place: Brittany, in western France (Table 1).

We first reviewed the literature to identify plant traits – both effect traits, which influence ecosystem processes and functions, and response traits, which determine a plant's response to its environment – that influence the ecosystem services selected (Figure 1; Appendix 1, Table A1.1). We then consulted the TRY international trait database (Kattge et al., 2020) to select crop species adapted to a temperate oceanic climate, both present and future. Finally, we created a list of 60 crop species that workshop participants could use (Appendix 1, Table A1.2).

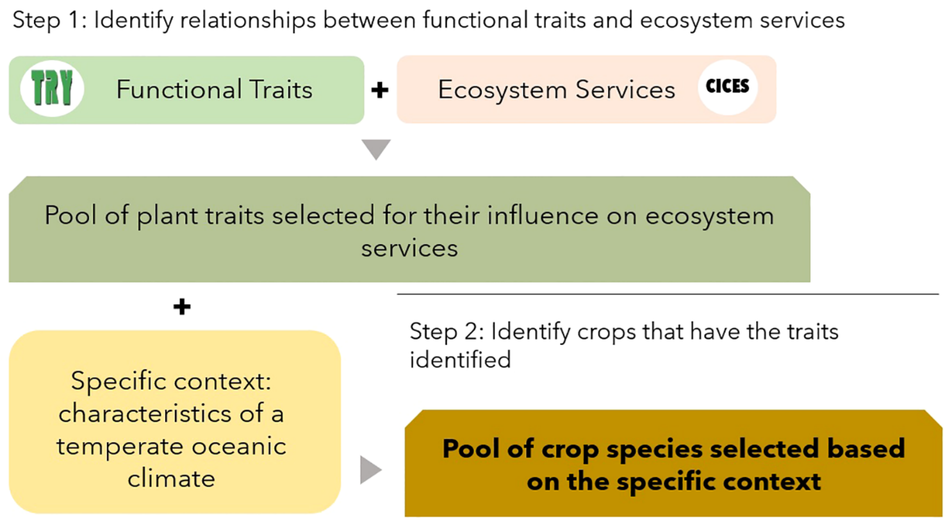
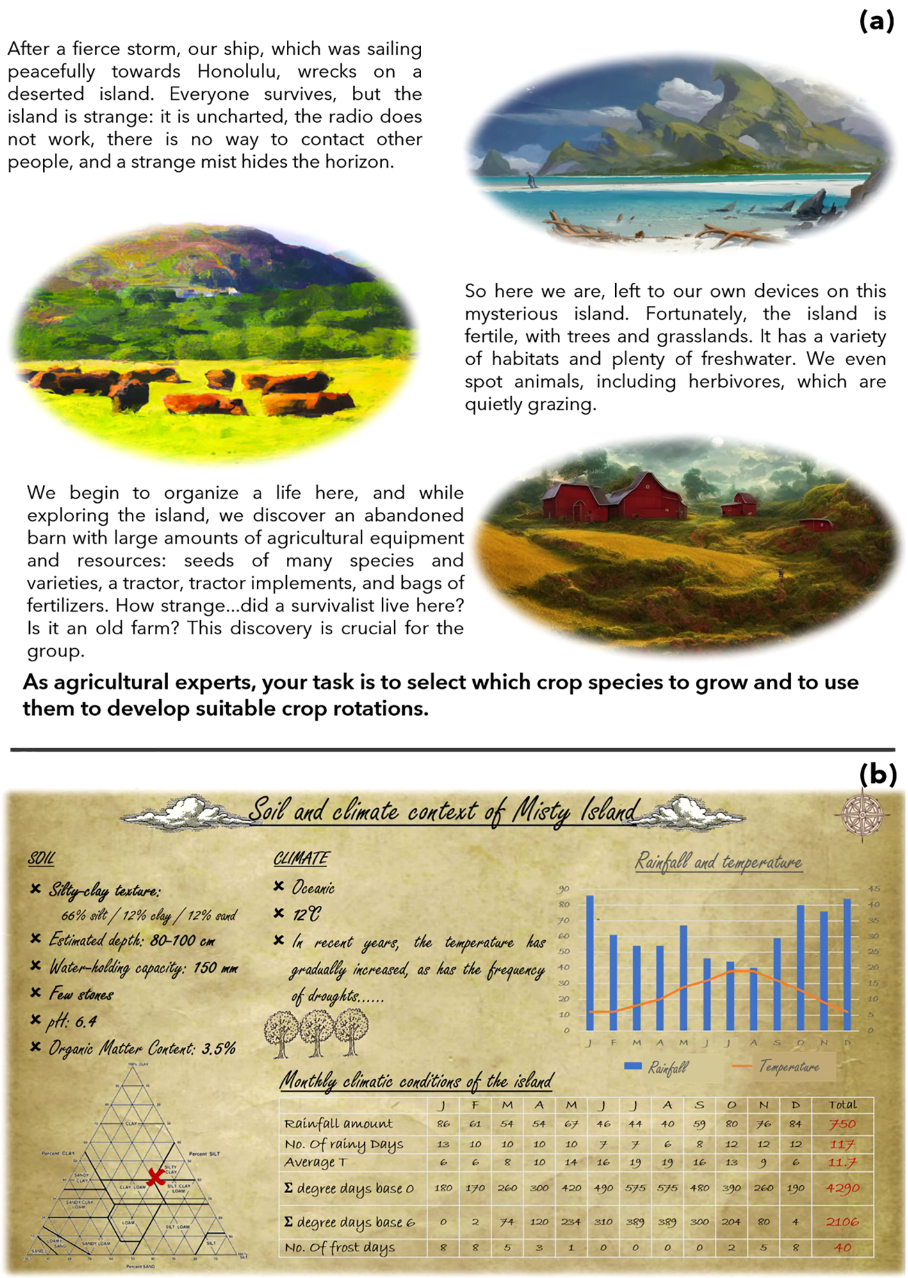


FIGURE 1
The two steps of the trait-based approach implemented before the participatory workshop. TRY stands for plant international trait database, CICES stands for Common International Classification of Ecosystem Services.



	J	F	M	A	M	J	J	A	S	O	N	D	Total
Rainfall amount	86	61	54	54	67	46	44	40	59	80	76	84	750
No. Of rainy Days	13	10	10	10	10	7	7	6	8	12	12	12	117
Average T	6	6	8	10	14	16	19	19	16	13	9	6	11.7
Σ degree days base 0	180	170	260	300	420	490	575	575	480	390	260	190	4290
Σ degree days base 6	0	2	74	120	234	310	389	389	300	204	80	4	2106
No. Of frost days	8	8	5	3	1	0	0	0	0	2	5	8	40

FIGURE 2
(a) The fictional narrative presented at the beginning of the participatory workshop conducted with five participants on 21 April 2022, and **(b)** the document provided to participants that contained relevant data about the island's soil and climate conditions. The latter's design was inspired by a pirate theme to increase participants' abstraction from reality and involvement in the workshop.

2.2 A narrative to co-design biodiversity-based cropping systems

After explaining the workshop's objective (co-designing crop rotations to preserve either short- and long-term ecosystem services) and the housekeeping guidelines to the participants, we presented a brief fictional narrative (Figure 2a).

The narrative was the core of the workshop, extracting participants from their usual techno-economic constraints by including figurative and imaginative elements, while maintaining a credible local context for the ultimate objective of the design process: designing biodiversity-based cropping systems that could be implemented in Brittany (Figure 2b).

The narrative asked participants to imagine a scenario in which they were isolated castaways on a remote deserted island, with a fragile yet fertile ecosystem that needed to be conserved while providing a bundle of both provisioning, regulating, and maintenance ecosystem services (Table 1). To ensure participants' suspension of disbelief (Frittaion et al., 2010), fundamental aspects of farming practices were introduced in a logical manner within the

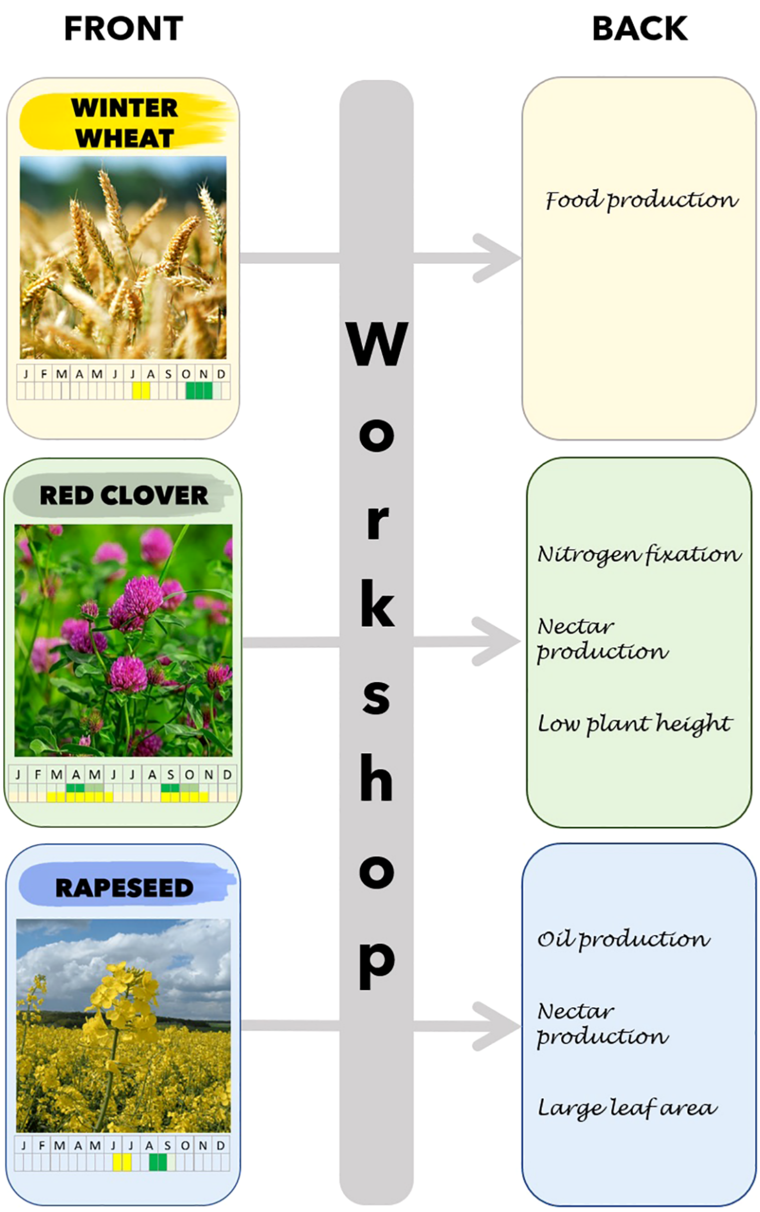


FIGURE 3
Example of three playing cards for crop species made using the trait-based approach and used in the workshop. The front of each card shows the common name, image, and corresponding sowing (green cells) and harvest (yellow cells) times for each. The back allowed participants to write down their reasons for selecting the species.

narrative (Figure 2a), such as remnants of past human activities, including agricultural machines, gas, seeds, inorganic fertilizers, and the ability to use manure from herbivores left on the island as another fertilizer. Participants were notified that they all had the same role throughout the sequence of events described in the following sections. To reinforce the narrative, intermediate elements were proposed to encourage interactions and exchanges between participants (Jeuffroy et al., 2022). These elements took the form of cards that described the crop species that had been selected using the trait-based approach (section 2.1; Figure 3). These cards captured the most advanced information about functional crop ecology, which could be considered herein as a knowledge transfer with participants.

2.3 Implementation of the participatory workshop

2.3.1 Panel of participants

The participatory workshop, entitled "TomorRot" (for "tomorrow" and "rotation"), used these two words to highlight a long-term perspective on rotations. The workshop was held on 21 April 2022 in a 3h session. Five participants (a common number for a participatory workshop in agriculture to ensure sufficient speaking time for all participants (Chieze et al., 2021)) were recruited by the authors, for whom descriptions are outlined below. None of the participants had theoretical or empirical experience in plant functional ecology, but all had experience in cropping system design. The first socio-professional category – farmers – consisted of two local farmers who managed mixed crop-livestock farms. One farmer had practiced organic farming for nearly 30 years, since the beginning of his career, and was a member of an agricultural association for organic soil conservation. The second farmer had been converting his farm to organic production for two years. The second category – scientists – consisted of an agronomist from INRAE (the French National Research Institute for Agriculture, Food and Environment) who had expertise in innovation and diversification of cropping systems that support multifunctionality of farmlands. The third category – agricultural advisors – consisted of two advisors with expertise in biodiversity-based cropping systems and regional-scale crop management. The participants in the study were as follows:

- Participant 1 – farmer 1: male, 50 < age < 55 y-old, BSc degree
- Participant 2 – farmer 2: male, 45 < age < 50 y-old, BSc degree
- Participant 3 – advisor 1: female, 35 < age < 40 y-old, MSc and PhD degree
- Participant 4 – advisor 2: female, 30 < age < 35 y-old, MSc and PhD degree
- Participant 5 – scientist: male, 35 < age < 40 y-old, MSc and PhD degree

Farmer 1 could be considered a “pioneer” in organic conservation agriculture due to his extended experience. Farmer 2 had been converting his mixed crop-livestock farm to organic farming for the previous two years and had expressed a willingness to innovate his farming practices. Farmer 1 had never participated in co-design workshops before, whereas all the other participants had participated at least once. Participants are located in Brittany, so they were aware of the conventional rotations. Advisor 1 was in charge of the “low pesticide” rotation. However, no description of these two rotations were described at the beginning of the workshop. As recommended by Nyumba et al. (2018), a facilitator (the first author) kept the discussion on track and ensured fair participation, while a note taker (the third author) observed participants’ behaviors during the entire workshop. Participants were invited to express their opinions freely within the limits of goodwill and suspension of criticisms.

2.3.2 Sequence of events for the “TomorRot” participatory workshop

After presentation of the narrative, the “TomorRot” participatory workshop was divided into two phases. During the first phase (30 min), each participant had to select the cards for at least six crop species to grow on the island and provide reasons why they selected each species. Participants were allowed to select the same species as each other. Blank cards were also provided to allow participants to add species not on the initial list of 60 species. Participants also had to justify why they added new species, based on the plant traits that influence the provision of ecosystem services. For all species selected or added, they had to describe the species’ characteristics they considered interesting and explain how the species contributed to at least one ecosystem service. It was expected that participants would base their proposals primarily on the ecosystem services presented in the initial list (Table 1), but they may also propose other services they consider relevant. To help them remember, the participants wrote each reason on the back of the cards, as well as the source of the knowledge: theoretical (i.e., agronomic theory and education), experiential (e.g., practical experience or experiments), or speculative (i.e., beliefs or hypothetical explanations not grounded in theory or experience). After the “TomorRot” workshop, all information given by participants was translated into English, compiled, and represented in the form of two word clouds generated using R software (R Core Team, 2021) with the package *wordcloud2* (Lang and Chien, 2018). The first word cloud illustrated the main characteristics that explained why participants selected the species. The second word cloud illustrated which ecosystem services, influenced by these characteristics, influenced selection of the species the most.

During the second phase (120 minutes), participants were encouraged to collectively design one or more crop rotations that included at least six crop species and had a duration of at least six years. They were also encouraged to consider trade-offs between the provisioning ecosystem service and regulation and maintenance ecosystem services. For each species added to a rotation, the participants discussed and noted the rules they used to select the species and determine its place in the rotation. Although it was not required, all decisions were made by consensus.

2.4 Evaluation of the framework used for the “TomorRot” participatory workshop

After the collective design ended, participants were asked to provide immediate feedback to assess their perceptions and feelings. To this end, each participant answered 30 multiple-choice questions (Appendix 2) in a questionnaire based on recommendations of the companion modeling method (Hassenforder et al., 2020). The first six questions inquired the “TomorRot” workshop itself, including the clarity of the discussion, the group atmosphere, and the degree of personal involvement. The next six questions asked about the method, focusing on the importance of the narrative and the utility of supplemental elements such as the crop cards or the “island map” with climate and soil information. The next five questions asked about the outcomes, considering the relevance and feasibility of the rotations designed. The last seven questions asked about participants’ perspectives on the co-design process itself and their willingness to participate in future workshops.

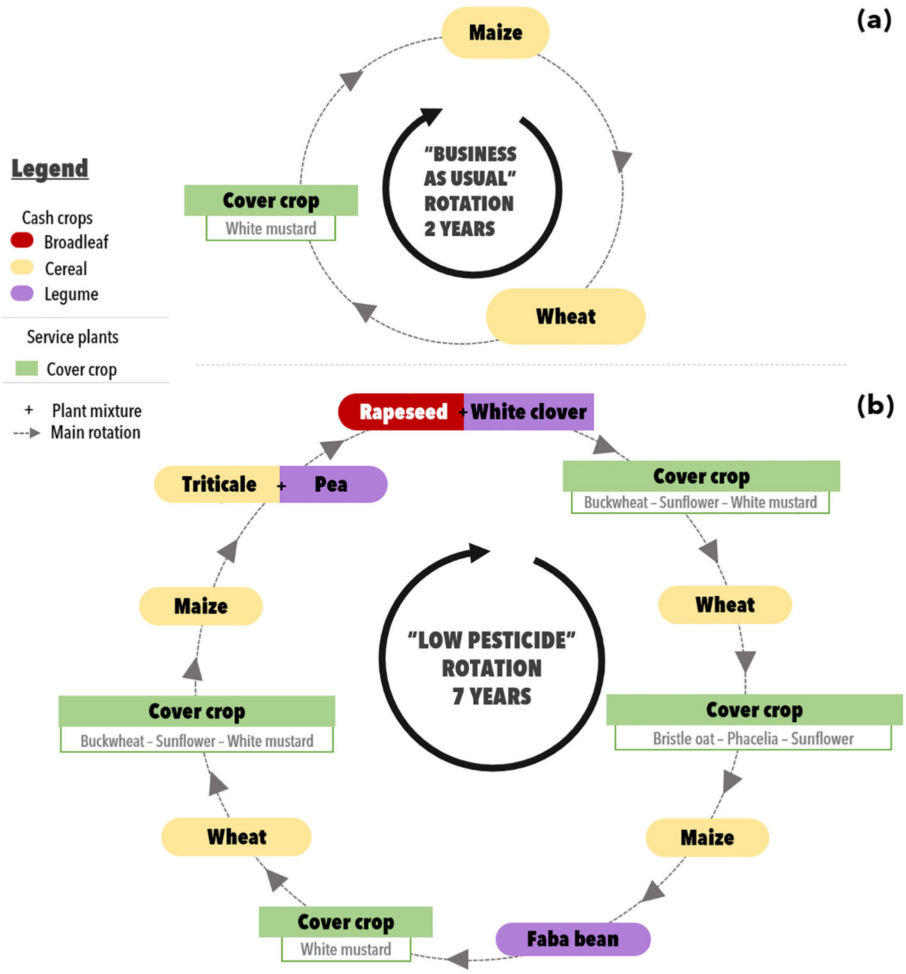


FIGURE 4
(a) The "business as usual" and **(b)** the "low pesticide" crop rotations in the study to compare their diversity to those of the rotations co-designed during the workshop. Service plant: a species used to improve agroecosystem functions, without being harvested or grazed.

After the "TomorRot" workshop, the co-designed crop rotations were compared to both a mainstream "business as usual" low-diversity crop rotation and a more diversified agroecological crop rotation, hereafter the "low pesticide" crop rotation (Figure 4). The former was a maize (*Zea mays*) – wheat (*Triticum aestivum*) – catch crop (white mustard (*Sinapis alba*)) rotation, which is the dominant crop rotation in Brittany, covering 20-30% of arable land in the region (Therond et al., 2017). The objective of this rotation is food production, which is driven by short-term commercial expectations of local agricultural sectors. The "low pesticide" rotation, which included 10 species (Figure 4), was the subject of an experiment in Brittany that aimed to decrease pesticide use by increasing planned biodiversity, while maintaining some consistency with mainstream crop rotations (Pourias et al., 2019). The rotations were quantitatively compared by calculating crop rotational diversity (Costa et al., 2024) and functional richness (Smith et al., 2023). Crop Rotational Diversity (CRD) is a modified version of Simpson's reciprocal diversity index (*D*) (Simpson, 1949) that reflects both the number of species and their relative abundance over the duration of the rotation, considering the temporal proportion of species (Equation 1):

$$CRD = \frac{1}{\sum_{i=1}^{c} Pi^2} \tag{1}$$

Crop Rotational Diversity indicator calculation

Where C is the number of species, and Pi is the proportion of the duration of the rotation (in years) that the i^{th} *species is present.*

For intercrops, Pi was divided by the number of intercropped species, which increased CRD.

Functional richness (FR) equals the total number of functional groups in the rotation. Modeling our calculation after Smith et al. (2023), we used four functional groups: legumes (able to fix nitrogen through symbiosis with bacteria), broadleaf non-legumes (unable to fix nitrogen), cereals, and grassland plants. To complete the assessment of rotation diversity, we also counted the number of taxonomic families in each rotation and calculated the ratio between the number of service plants and cash crops. Service crops are defined as crops grown to improve agroecosystem functions and enhance the environmental performance of the system (Gardarin et al., 2022) rather than for production purposes; this is contrary to cash crops, which are meant to be harvested and then traded.

3 Results

The participants co-designed two desirable crop rotations that contained at least six crop species over six years (R1 and R2, Figure 5).

3.1 Higher diversity of the co-designed crop rotations than the two reference crop rotations

The "business as usual" crop rotation had the lowest diversity (CRD = 2.7) of all rotations (Table 2), which reflected its focus on short-term economic objectives through optimizing food production using a few high-yielding crop species. In contrast, co-designed rotations R1 and R2 had the highest diversity (CRD = 10.1 and 12.5, respectively) (Table 2) because they included more intercrops and cover crops in order to provide ecosystem services besides only food provision. The "low pesticide" rotation had an

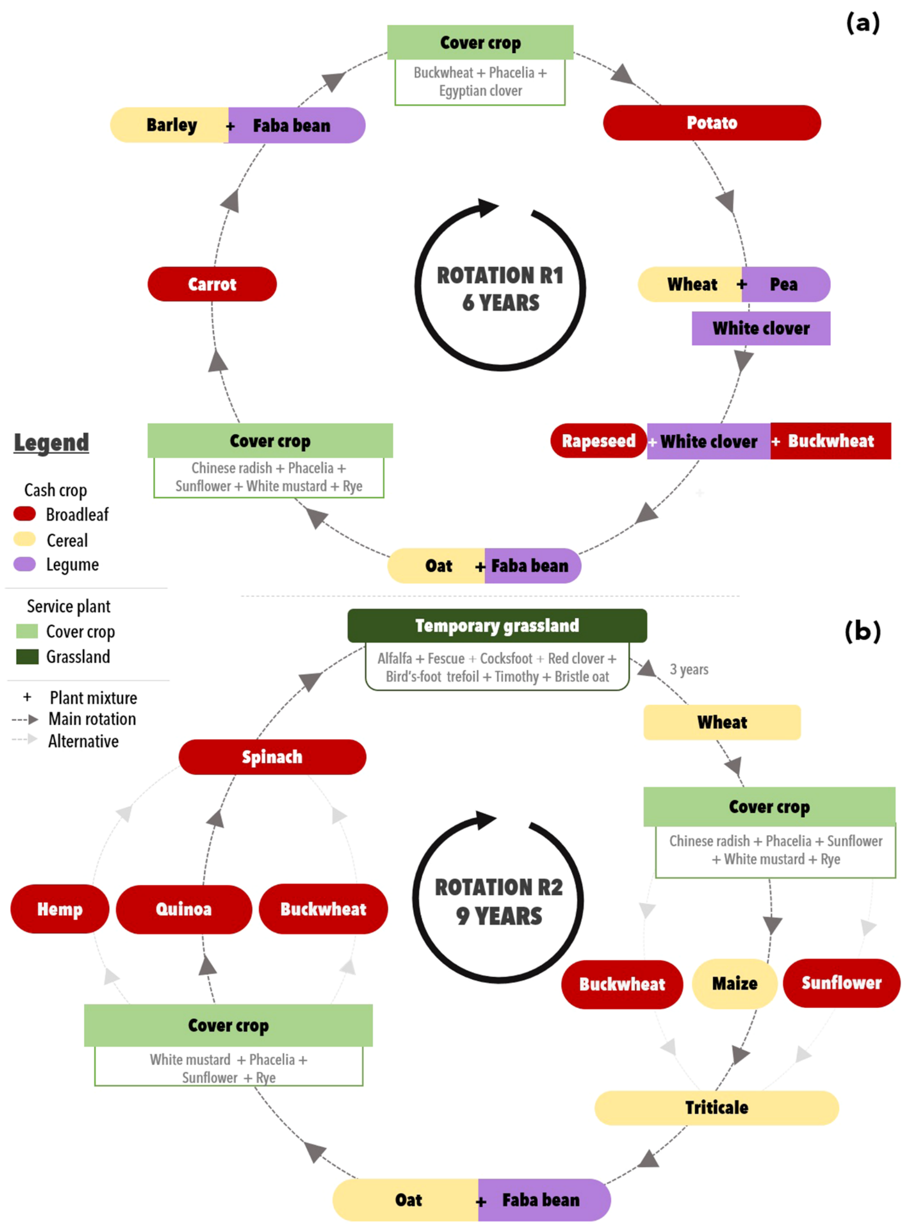


FIGURE 5
The crop rotations **(a)** R1 and **(b)** R2 co-designed by workshop participants. Service plants refer to species used to improve agro-ecosystem functions, without being harvested or grazed.

intermediate diversity (CRD = 6.9) despite its important length and number of crop species. This was due to the lower number of intercrops (both for crops and cover crops) compared to the R1 and R2 rotations.

The R2 and "low pesticide" rotations had a higher FR (4 each) than R1 did (FR = 3) because R1 had no grassland plants. However, R1 had the most "service plants" (including cover crops), which were used to improve agroecosystem functions without being harvested or grazed (service plant:cash crop ratio = 0.90) and the most taxonomic families.

3.2 Selection of crop species for the co-designed crop rotations

In the first phase of the "TomorRot" workshop, to co-design R1 and R2, participants selected 39 crops (Appendix 1, Table A1.2), 37 of which came from the original panel of 60 crops and two of which were added by participants – Egyptian clover (*Trifolium alexandrinum*) and Chinese radish (*Raphanus sativus* var. *longipinnatus*) – due to their potential as cover crops. In total, 32 species were annuals and seven were perennials: alfalfa (*Medicago sativa*), bird's-foot trefoil (*Lotus corniculatus*), white clover (*Trifolium repens*), and red clover (*Trifolium pratense*) and grassland grass species such as orchardgrass (*Dactylis* spp.), English ryegrass (*Lolium perenne*), and timothy (*Phleum pratense*). Furthermore, more broadleaf non-legumes were selected (36% of the total) than any other functional group. The broadleaf species selected most often was buckwheat (by four participants) due to its allelopathic properties. Legumes were the second most selected functional group (31%), with faba bean (*Vicia faba*) selected most often (also by four participants). The cereal species selected most often were wheat (by all participants) and common oat (*Avena sativa*) (by two participants) for their grain as a food source. For the grassland species, all were selected once each and only by the two farmers.

TABLE 2 Indicators for the two co-designed crop rotations (R1 and R2), the "business as usual" crop rotation (BAU), and the "low pesticide" crop rotation (LP).

Crop rotation	R1	R2	BAU	LP
Number of crop species (including cover crops)	16	19	3	11
Number of taxonomic families	8	7	3	7
Service plant:cash crop ratio	0.90	0.60	0.33	0.83
Crop rotational diversity (CRD)	10.1	12.5	2.7	6.9
Functional richness (FR)	3	4	2	4

Service plant: a species used to improve agroecosystem functions, without being harvested or grazed.

3.3 Justifications of crop species selection

To explain the selection of these species, participants identified 139 different species characteristics (Appendix 3), as represented in the associated word cloud (Figure 6). The most mentioned characteristic was the food and feed that a species could provide. However, analysis of relationships between species characteristics and ecosystem services in the second word cloud revealed that food provision was not the service mentioned the most (Figure 6). Instead, regulation of soil quality was mentioned most often (48 times), followed by food provision (45 times) and regulation of crop pests, weeds and pathogens (35 times). For this last service, participants focused more on managing weeds (17 times) than pests (13 times) or pathogens (5 times).

To a much lesser extent, participants selected species based on characteristics related to regulation of the water balance for crop development (9 times). Participants rarely considered ecosystem services that did not benefit the agroecosystem directly, such as maintenance of water quality (7 times) and regulation of greenhouse gases (5 times). In contrast, cultural ecosystem services, such as gastronomy and heritage, were not initially requested but were spontaneously mentioned (5 times). Finally, most participants' justifications (88 out of 139; 63%) (Figure 6) were based on theoretical knowledge, indicating that the three categories of participants (advisors, farmers, and scientists) were informed by a comprehensive theoretical background and not only empirical knowledge.

3.4 Spatial and temporal diversification to increase planned biodiversity and ecosystem services

The participants first designed rotation R1, which was oriented mainly towards food provision, since participants expressed the "urge to produce a large amount of food" soon after they arrived on the island, because it was isolated from the rest of the world. For this reason, they started the rotation with potato (*Solanum tuberosum*), which was perceived by participants as "a major source of nutrients […] we could store easily in case of challenging periods" (Figure 7a). In addition to food provision, participants also mentioned potato's taxonomic family (Solanaceae), which is known to disrupt pathogen and pest cycles of several crop species: "including potatoes will allow a succession of summer and winter crops to break cycles of fungal pathogens of cereals". One farmer also mentioned potato's ability to improve soil conditions for subsequent crops, since "the potato harvest will aerate and prepare the soil for the following crop".

Participants included other crop species in the rotation mainly to produce food, such as (i) rapeseed (*Brassica napus* var. *napus*) for its production of oil and (ii) a mixture of buckwheat, rapeseed, and white clover, which also controls weeds (ecosystem service: regulation of weeds). Furthermore, since the participants

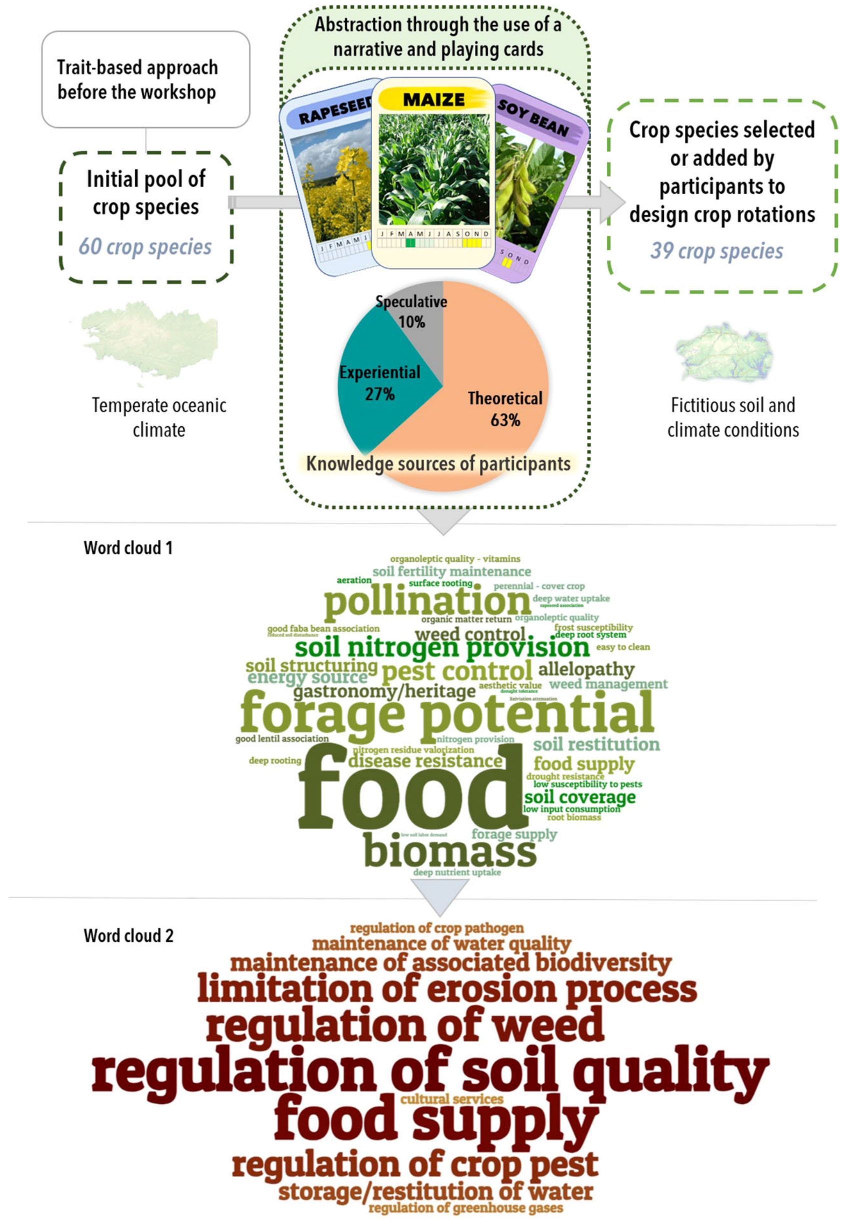


FIGURE 6
The five participants of the participatory workshop selected 37 out of 60 crop species (previously identified as relevant for Brittany, France) and added 2 species to design crop rotations that would provide both provisioning and regulation and maintenance ecosystem services over time on the fictitious island. The pie chart illustrates the sources of the participants' knowledge (theoretical, experiential, or speculative) expressed as a percentage of the all justifications. Word cloud 1 illustrates the main characteristics that explained why the participants selected the species, while word cloud 2 illustrates which ecosystem services, influenced by these characteristics, influenced selection of the species the most.

perceived that nitrogen could be a limiting nutrient on the island, they considered that sowing white clover as a relay crop a few months before buckwheat and rapeseed (Figure 7a) would be a good nitrogen source for the rotation, due to its high nitrogen-fixation capacity, according to a farmer. The same idea, related to the regulation of soil quality, led the participants to include different cereal-legume intercrops (e.g., wheat – pea) (Figure 7a): "intercropping cereal and faba bean could improve the yield and grain quality", "faba bean will fix nitrogen from the air and transfer it to the soil, providing a potential benefit for cereals".

The participants had high expectations for the cover crops. For example, Chinese radish as well as fodder radish (*Raphanus sativus*) and white mustard were identified as "potential allelopathic producers" that could control pathogens and pests, "particularly soil nematodes" (ecosystem services: regulation of plant pathogens and regulation of pests). White clover was selected in part for its potential to support pollinators due to its nectar-production property. In addition, the participants included two multispecies cover crops, mainly to regulate soil quality (Figure 7a). First, the intervals of bare soil during the winter were short, justified by

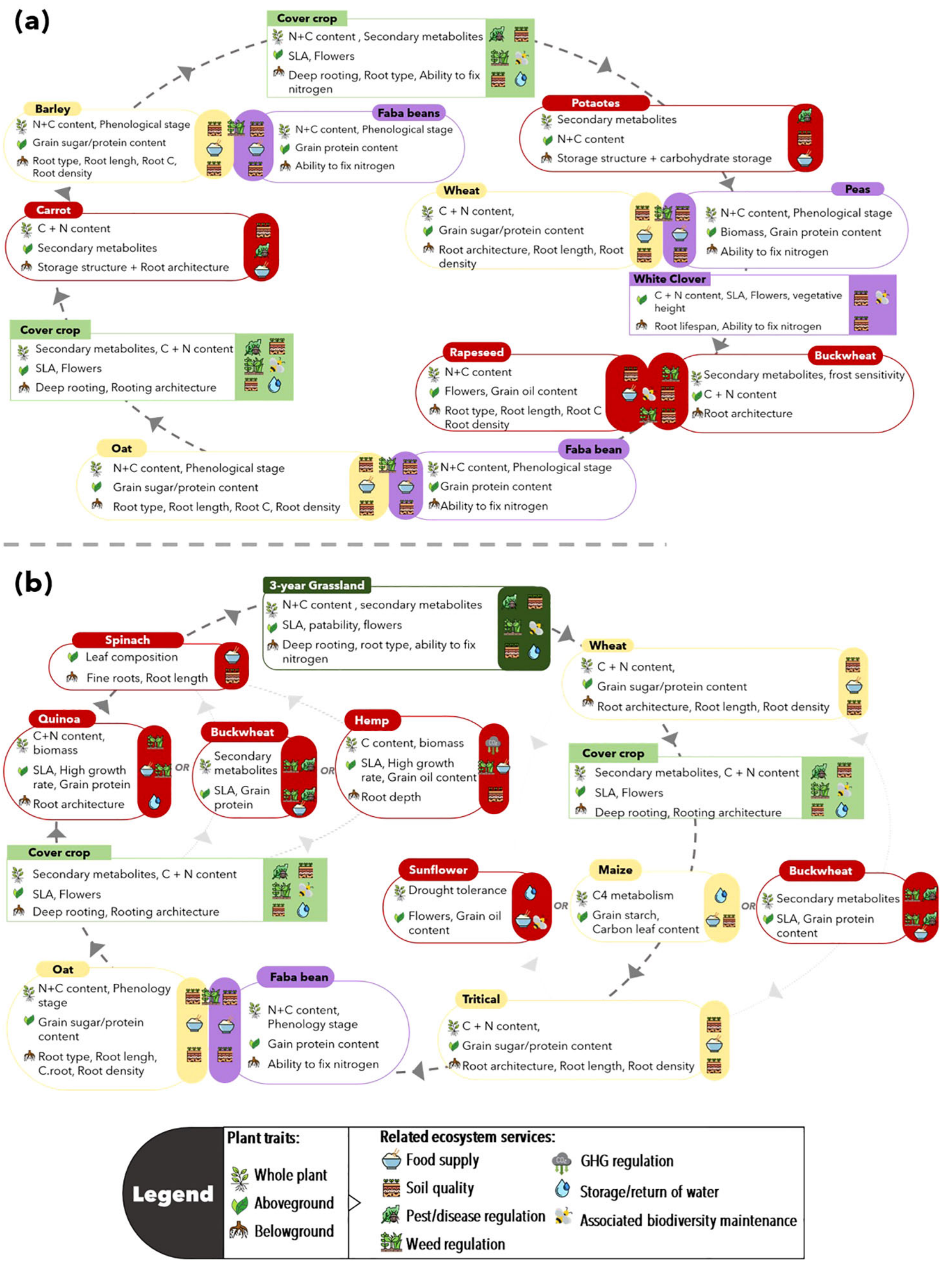


FIGURE 7
The plant traits and related ecosystem services of the crops included in the co-designed crop rotations **(a)** R1and **(b)** R2. N, nitrogen; C, carbon; SLA, specific leaf area; GHG, greenhouse gas.

participants by the need to “decrease leaching risk to maintain both soil and water quality”. Second, root complementarity among the species helped “maintain soil structure while avoiding competition [for resources between crop species] in the same soil horizon”. One farmer explained that “rye (*Secale cereale*) has a very deep rooting system that explores a different soil horizon than radish, which has a shallow taproot”.

The participants then collectively determined that a second crop rotation (R2, Figure 7b) should be established to complement R1 (Figure 7a). They proposed implementing R1 and R2 simultaneously on two different fields: “since we have no limit on the number of fields, we can produce and manage a second rotation in parallel that complements the first one”. Rotation R2 differed from R1 in several ways: a longer duration (nine years), more species (19), and less intercropping. However, the main difference was the inclusion of temporary grassland to facilitate livestock production: “since we’re focusing on the human food supply, I think it’s a good idea to put some forage in the second [rotation] to ensure livestock production to provide some useful organic inputs”. This complex multispecies temporary grassland included three legume species selected for their ability to fix nitrogen: alfalfa, bird’s-foot trefoil, and red clover. In addition, four grassland grasses were included to provide a large amount of forage: bristle oat (*Avena strigosa*), cocksfoot, English ryegrass, and timothy. The grassland mixture was also based on the same decision rules that had been applied to cover crops: an emphasis on nitrogen supply by legumes and root complementarity (Figure 7b). Grassland plants were selected for their forage potential: "timothy is a very rich grass that is ideal for forage" and their drought tolerance, as one farmer highlighted: "cocksfoot is more tolerant to drought and heat than timothy or ryegrass and could replace them, ensuring continuity in the grassland".

3.5 Analysis of the collective design process

The collective-design process used plant traits and spatio-temporal arrangements to yield two diversified crop rotations that could provide a bundle of ecosystem services over time. During the workshop, contributions of participants were ranked by their occurrence of interventions as 1) farmers, 2) advisors, and 3) scientists. Throughout the workshop, roles derived into distinct patterns. Farmer 1 primarily acted as the main source of proposals and was a technical decision-maker. Farmer 2 provided ideas but challenged all suggestions, particularly those of Farmer 1. Both farmers played a pivotal role in the decision-making process, taking the lead in formulating ideas during the second phase of the workshop. Advisor 1 acted as a mediator, helping to arbitrate between the farmers' proposals. She also suggested ideas based on her experience of field trials, thereby enabling a more structured consensus to emerge. Advisor 2 focused on synthesizing decision rules and validating crop choices to ensure the internal coherence of the crop rotation under construction. The scientist took on a facilitating role, asking probing questions to the decision-making actors to refine the rationale behind the solutions and to deepen the collective discussion. Participants' feedback at the end of the "TomorRot" workshop demonstrated that they understood the workshop's objective and methods well (mean grade = 5.0 out of 5.0) (Figure 8). They perceived it as a genuinely collective activity (mean grade = 4.0), agreed with the decisions made (mean grade 4.5), and felt strongly involved in the decision-making process (Figure 8). They believed that the "TomorRot" workshop successfully met the objective of designing a rotation that included at least six crop species over at least six years (mean grade = 4.8) and agreed that the co-designed rotations were distinct from existing ones, yet remained feasible for implementation (Figure 8). They considered the use of intermediate elements (cards, "island theme") to abstract from legal and socio-economic constraints as useful and appropriate for achieving the workshop's objective: "the cards were a good idea to speed up crop selection and refocus the discussion". During the crop selection phase, we noticed that Farmer 1 stated: "I haven't tried quinoa yet, but I know it's an interesting crop – it provides food and also summer ground cover". Later, during the second phase, Farmer 2 remarked: "I've never grown carrots before, but I imagine a strip-cropped system with an autumn harvest". Notably, neither farmer included vegetable crops in their actual farming systems.

However, they found the workshop relatively complex, particularly given the lack of a predefined farming system and the need to work toward a broad objective that was less tangible: "it's difficult to know for certain whether the rotation will be truly adapted to the context and objectives; we really tried to design in this way, but it's a little complicated to plan for difficult years or rare events;" […] even if we try to avoid them, some crop failure are still possible". One participant (from the scientist category) also noted a desire "for more detailed information about crops and their traits", believing that it would "have improved [their] ability to engage more effectively with the other participants". They also highlighted that they were not used to attempting to provide eight ecosystem services, which was therefore more complex than expected: "it's not easy to consider all of these services, especially since some of them, like greenhouse gas emissions, concern more technical issues and a larger scale, and it's hard to address them only through the design of the crop rotation".

4 Discussion

The objective of the present study was to analyze whether the developed framework, which was based on two hypotheses (i) the transfer of functional ecology information to non-specialists, and (ii) the utilization of a fictional narrative to reduce fixation effects, contributed to increasing diversity in co-designed cropping systems that can provide a variety of ecosystem services at different timescales.

4.1 Functional ecology information supports the diversity in co-design rotations

The increased biodiversity generated by co-design during the "TomorRot" workshop was due mainly to the inclusion of complex, multi-species cover crops and associations of cash crops and service plants. While considered as a diversified rotation, the "low pesticide" rotation had lower CRD and functional richness than the R1 and R2 rotations. We hypothesized that using cards promoted functional biodiversity. In turn, more ecosystem services, including cultural ecosystem services were noticed. Our results are consistent with the conclusions of European projects DiverIMPACTS and ReMIX, which revealed that crop rotations extending to at least six years with high functional diversity are potentially effective strategies for enhancing the resilience and sustainability of agroecosystems (Antier et al. (2021); Bedoussac et al., 2022). The participants demonstrated the ability to readily apply their understanding of trait-based ecology to select crop species using provided species cards. Participants also showed no hesitation in explicitly relating this knowledge to ecosystem services, which resulted in their ability to easily adopt the theoretical framework. Interestingly, participants mentioned both above- and below-ground plant traits, with the latter being mentioned more frequently to decrease competition and promote complementarity between crops. Additionally, below-ground plant

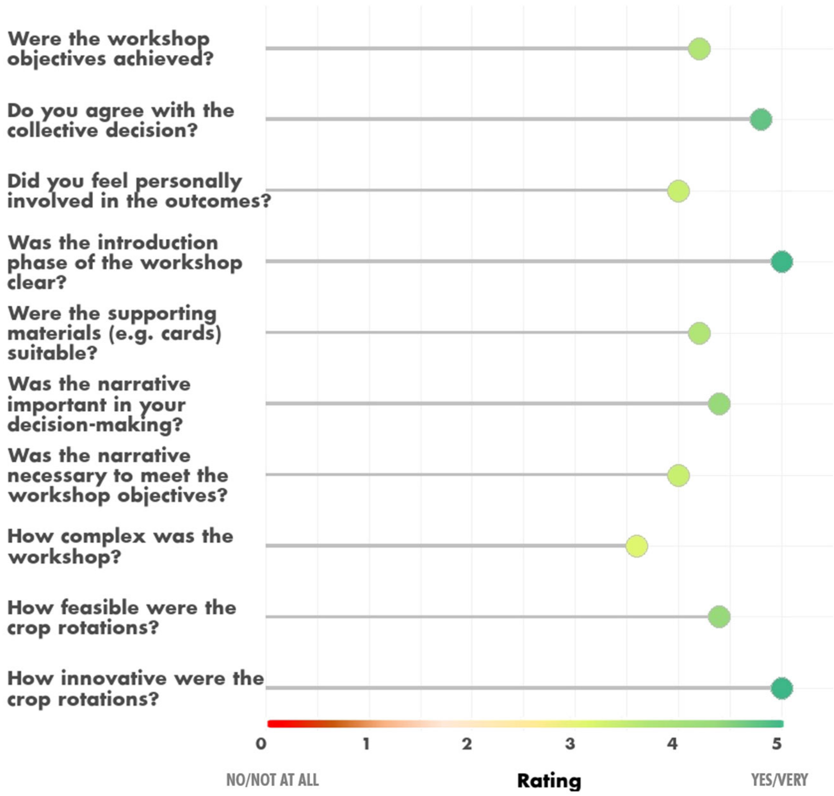


FIGURE 8
Mean grades (from 0 (no/not at all) to 5 (yes/very)) given by the five participants for 10 most representative questions from the thirty proposed. These grades were collected at the conclusion of the workshop, in which the participants evaluated the benefits of the crop rotation design, the workshop itself, and the co-design process.

traits, particularly those of cover crops, were frequently associated with the concept of soil quality, and recent studies have confirmed these observations (Freschet et al., 2021; Griffiths et al., 2022). However, one should note that one of the two farmer participants implemented soil-conservation guidelines on his farm, so his presence likely increased the group's concerns regarding soil quality. In agreement with Isaac et al. (2018), we considered the farmers' knowledge of plant traits as part of their implicit traditional agroecological knowledge because they were more willing to use this information compared to the scientist representative. In line with the traditional knowledge, participants selected buckwheat in rotation R1, a crop closely tied to Brittany's biocultural heritage testified since the XVth Century (Chaussat, 2017). This crop was selected to ensure food security given its tolerance of low soil quality, resistance to pathogens, high seed-to-yield ratio, and flexibility in mixed farming due to its short development cycle (Small, 2017; Zhang et al., 2012). Along with this biocultural heritage, the co-designed crop rotations included the ideas of rurality and well-being (Isaac et al., 2024). In particular, the aesthetic value of the flowers of species such as common sainfoin (*Onobrychis viciifolia*), selected by one participant, and phacelia (included in R1 and R2) was spontaneously mentioned, which resonates with farmers' general pride in beautifying the landscape (Junge et al., 2015) and aligns with their personal and spiritual connection to nature (Utter et al., 2021).

4.2 Importance of the narrative trigger to expand creativity of participants

Designing biodiversity-based cropping systems that have multiple objectives presents complex and uncertain challenges (Debaeke et al., 2009). Because the design process needs to be changed radically to overcome fixation effects, we hypothesized that abstracting through the medium of a narrative would contribute greatly to unleashing participants' creativity in a co-design workshop. Accordingly, the "TomorRot" workshop employs a format centered around collective oral dialogue among participants, which is crucial for enabling agricultural stakeholders to articulate and share their knowledge effectively (Thomas et al., 2020).

We highlighted that imagination allowed participants to transcend their immediate experiences and create transformative responses while remaining anchored in reality. For example, participants selected species without constraining themselves with common commercial considerations, such as the lack of a supply chain or market outlets. However, they continued to regard food production as essential, maintaining the primary food-producing role of agriculture. The inclusion of potatoes and carrots in the co-designed rotation reflected a willingness to engage in system innovation beyond individual constraints. This approach allowed them to transcend their daily constraints to ensure a transformed yet still relevant cropping system regarding the workshop objectives. As Vervoot and co-authors (Vervoort et al., 2024) observed, the most transformative creative practices combine two key elements: (i) situated imagination (facilitated in the present study through the narrative) and (ii) many ways to change and adapt responses (captured in the present study by rotations R1 and R2). Results of this study agreed with those of Sutherland et al. (2012), who concluded that an effective method for promoting change in farming practices is to face a "trigger event" (in the present study, being stranded on a deserted island). Finally, one pivotal value of creative methods in sustainability transformations for complex systems is their ability to generate unexpected outcomes (Patton, 2019). In our study, the identified cultural services (magnifying landscape, gastronomy…) and their importance in the discussion among participants, act as the unexpected outcomes and show the importance of the connection between agricultural stakeholders, especially farmers, and the natural environment underlying the importance to take this consideration in account in co-design exercises.

4.3 Limits of the study

It is important to note that the purpose of our framework is to design diversified crop rotations based on the different types of expertise involved. These rotations are not intended to be directly tested in the field, especially when studying the long-term evolution of the ecosystem services offered by biodiversity-based cropping systems. Such an objective requires modelling tools (Martin et al., 2016) and, as such, is beyond the scope of this article.

It would have been interesting to replicate the workshop with a greater number of participants and diversify the selection of farmers profile who are in our case study relatively similar. For example, both farmers were male, a fact that has been demonstrated to influence farmers' perception of soil quality (Zhang et al., 2021) and their involvement in sustainable agricultural practices (Tourtelier et al., 2023). Furthermore, one farmer implemented soil-conservation guidelines on his farm, which likely increased the group's concerns about soil quality. However, we argue that our objective of experimenting an original co-design framework is not adapted for statistical replications. Indeed, we would need as many case studies as possible combination of participant categories and background to statistically consider it as a "human factor". However, our framework is very promising according to the ecological indices (section 4.1), the two different rotations obtained (R1, R2), and the satisfaction of participants. Indeed, the "low pesticide" rotation is considered as a very good example of biodiversity-based rotation, and the co-designed crop rotations were much more diverse. We noticed that the most diversified co-designed crop rotation (R2) retained traditional crop patterns such as maize – temporary grassland – wheat. Imagination is both cognitive and emotional, including deep-rooted beliefs, personal social values, and inner visions of the surrounding environment that are constructed through personal experiences (Pereira et al., 2019). In addition, local norms and social groups to which individuals identify or belong also influence the characteristics of their imagination (Mische, 2009). It is challenging to bypass these inherent biases while remaining realistic (i.e. crops adapted to the agronomic context), since the legitimacy of the process also requires respecting and acknowledging participants' personal values throughout the design process (Pereira et al., 2019). One way to limit "default" selection of well-known crops would be to send participants details about the plant traits to be discussed one week before the workshop, so that the participants could familiarize themselves with the information. Including this preparatory phase would have helped dispel preconceived notions about crops by allowing participants to acquire new knowledge that they could have applied during the workshop, thus increasing the potential to select lesser-known crops. Inspired by the importance of oral transmission (Nimmo et al., 2020), we used an narrative to envision the long term. While the participants successfully co-designed diversified rotations, they failed to consider events associated with the long term, such as the frequency of extreme climate events or carbon sequestration/mitigation. The lack of consideration of long-term processes may have been due, in part, to certain narrative elements. The participants considered the soil carbon content, which they learned about when they arrived on the island, to be "high and sufficient … over long term", which may explain why they did not prioritize it. In addition, setting the narrative on a deserted island led them to prioritize food production for survival, such as potatoes in rotation R1 to rapidly provide calories. This phenomenon can be mitigated by using complementary tools such as visual aids derived from modeling or long-term experiments. Nonetheless, we believe that human societies will always have difficulty grasping the long term, mainly due to human psychology (Joireman and King, 2016), given that when pressing short-term concerns are present, hypothetical future events are often sidelined, even if they are acknowledged (Wheeler and Lobley, 2021). Altogether, even considering its limitations, this framework is considered as a positive, pioneering approach that could be supplemented by other approaches such as modeling to cope with the complexity of the long-term consideration by farmers and stakeholders.

5 Conclusion

Nature-based solutions have gained popularity as an integrated approach than can address several issues such as climate change, biodiversity loss, and food security. However, there are serious concerns that the development of biodiversity-based cropping systems may require more than technical developments. This article addresses specifically the need of fostering creativity for researchers studying biodiversity-based cropping systems, and not a co-design of rotation to be directly implemented on fields. Ecology and landscape sciences increasingly use design processes based on imagination to envision desirable futures. Such activities fostering creativity seem promising for the design of these cropping systems. The framework proposed herein, centered around a fictional narrative, demonstrated the significance of plant functional ecology concepts and the relevance of using imagination for biodiversity-based cropping system co-design. First, we demonstrated that the material objects, crop species cards, were adapted to transfer the knowledge on functional ecology to fuel the rotation design. Second, the co-designed rotation improved, in terms of diversity index, the local reference considered by experts as a diversified cropping system. Third, farmers acknowledged the benefits of the framework. This study has several limits, particularly regarding the profile of participants, and would benefit to be reproduced with a larger diversity of people. The description of plant functional traits could also be improved for participants. For these reasons, we reasonably speculate that such a framework, in conjunction with crop models, could be used by agronomists to design diversification scenarios that provide a better balance between different ecosystem services expected from society over the long term. Finally, this framework could be useful for various applications regarding biodiversity-based cropping systems, ranging from co-design to education.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The participants [OR participants legal guardian/next of kin] provided their written informed consent to participate in this study.

Author contributions

AD: Writing – original draft, Investigation, Formal Analysis, Writing – review & editing, Methodology, Data curation, Conceptualization, Visualization. MC: Project administration, Validation, Data curation, Supervision, Methodology, Visualization, Funding acquisition, Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Resources. OG: Writing – review & editing, Funding acquisition, Supervision, Conceptualization, Methodology. ELC: Funding acquisition, Methodology, Supervision, Writing – review & editing, Visualization, Conceptualization, Project administration, Writing – original draft, Validation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. The authors used Generative AI to create the images used in Figure 2a.

Publisher’s note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2025.1601337/full#supplementary-material

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