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RESEARCH ARTICLE

Introducing intermediate wheatgrass as a perennial grain crop into farming systems: insights into the decision-making process of pioneer farmers

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Abstract

The perennial grain intermediate wheatgrass (*Thinopyrum intermedium*, commercial name Kernza™) has been proposed as a diversification crop for producing forage and grain and providing ecosystem services to farmers. Although a few studies have addressed farmers' interests in the crop, information is lacking about the links between farmers' goals and crop management, i.e., how farmers aim at integrating this crop in their systems. Closing this gap, this paper analyzes for the first time the introduction of intermediate wheatgrass (IWG) from a farmer perspective, as a set of decision plans and goals. The overarching orientations of the farm and organization of the production system, referred as strategic decisions, interact with short-term crop management (i.e., tactical decisions) and farmers' goals for IWG. In total, 17 individual semi-structured interviews and 2 collective crop management prototyping workshops in France were used to analyze farmers' rationales as a function of their farm systems, agronomic constraints, and know-how. The study demonstrates that farmers' interests in IWG revolved around multiple ecosystem services and financial returns. Three ideal-types of farms testing IWG emerged from the relationships between existing farming systems and goals for IWG. The strategic and tactical decisions regarding the integration and management of IWG were contingent on the farming systems, the goals for IWG, the farmers' know-how, and their ability to mitigate risks. Implications for the future development of intermediate wheatgrass as a niche innovation are considered based on farmers' points of view. This study provides insights into the ideas and concerns of French farmers regarding IWG and proposes a framework for discussing the introduction of a new crop in a farm system.

Keywords *Thinopyrum intermedium* · Diversification · Prototyping · Participatory research · Crop management · Strategic and tactical decisions

1 Introduction

In a context of climate change, agricultural systems have to cope with highly variable weather conditions, elevated temperatures, and water scarcity. Moreover, industrialized cultivation of annual cereals is challenged because of its role in soil erosion, soil organic matter depletion, loss of biodiversity, nutrient leaching, and sensitivity to water stress (Pimentel et al. 2012; FAO 2021). Therefore, both grain and forage producers are looking for options to adapt their management to drought events, increase their resilience (Amigues et al. 2006), and minimize the environmental impact of their practices.

Agricultural diversification is proposed as a promising strategy to enhance ecosystem services and reduce dependency on agronomic inputs (Tamburini et al. 2020). Within this logic, the introduction of perennial grains has received considerable attention in the last decade as a means of diversifying crops and improving of soil fertility. In Europe where annual wheat is the main small grain crop (European Commission 2023), the domestication of intermediate wheatgrass (hereinafter "IWG", *Thinopyrum intermedium*) developed by the Land Institute in Kansas (USA) and commercialized under the name Kernza™ is the most advanced initiative toward the introduction of an

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alternative perennial grain crop with the objective of producing both forage and grain (Fig. 1). In France, research on IWG for grain production has been initiated in 2017 through on-farm experiments. Research on IWG originally had the intention to improve crop agronomic performance to foster successful and profitable use on farms. Breeding efforts mostly focused on enhancing grain yield–related traits and ease of harvesting (DeHaan et al. 2020), which are believed to be major barriers to IWG adoption. Literature results show that grain yields range from 300 to 1200 kg.ha^{-1} depending on the year and on management options, with a decrease from the first to fourth year (Hunter et al. 2020). To maintain profitability despite low grain yields, scientists have proposed to use IWG as a dual-purpose crop for forage and grain, providing a dual income to farmers (Bell et al. 2008; Hunter et al. 2020; Law et al. 2021). In addition to multiple uses of IWG products, IWG is believed to provide several ecosystem services to farmers (Pimentel et al. 2012), notably thanks to its year-round soil cover and extensive rooting system (Duchene et al. 2020). For example, recent findings showed IWG's tolerance toward temporary drought events (de Oliveira et al. 2018; Clement et al. 2022) and, in comparison with annuals, a greater carbon sink in the long term (de Oliveira et al. 2018), greater carbon accumulation in soils as particulate organic matter (Audu et al. 2022; van der Pol et al. 2022), and more effective prevention of nutrient leaching (Huddell et al. 2023).

Surveys and interviews among IWG-interested farmers revealed that ecosystem services, especially regarding soil structure and fertility, were driving motivations for uptake (Adebiyi et al. 2016; Marquardt et al. 2016; Wayman et al. 2019). Interviews with IWG growers in the USA highlighted the ecological and economic benefits that motivated IWG cropping, and the agronomic and economic issues faced by growers (Lanker et al. 2020). However, information is lacking

Fig. 1 Intermediate wheatgrass harvest on a farmer experimental plot in 2021. Source: C. Bathellier.

about the relationships between farm systems, targeted ecosystem services, and IWG management by farmers. This would assist in a more comprehensive understanding of farmers' decisions regarding the integration of IWG. In the literature, farmer decision-making process is frequently described as a hierarchy of strategic and tactical decisions respectively pertaining to the long term and the farm level, and to the daily, mid-term, and field level (Cowan et al. 2013; Robert et al. 2016).

The implementation of IWG on farms necessitates the development of crop management in accordance with farmers' strategies and goals. This is of particular importance because the performance of perennial grasses is influenced by the dynamic balance between vegetative and reproductive growth, which may be favored by particular management practices or pedo-climatic conditions. The testing and introduction of such a novel crop into farming systems therefore necessitate considerations that are often context-specific and that can only be identified by farmers. Their involvement in the process of innovation is essential to ensure the coherence between research frameworks and on-field decision-making processes by farmers (Prost et al. 2012; Ravier et al. 2016). Given the diversity of potential socio-technical scenarios on farms, there is no single, universally applicable solution and farmers are central stakeholders to determine the extent to which the proposed IWG management can be regarded as generic.

A farm network has been set up in France in 2020 in which small-plot experiments with IWG are carried out by farmers under various pedo-climatic conditions and farming systems (e.g., grain growers and livestock farmers, organic and conventional farms). Leveraging the diversity of farms involved in this network, the aim of this study was to understand the arguments that farmers use to test IWG in their farming systems based on their early observations of the crop. Thus, three main questions were investigated: (1) how are the IWG ecosystem services expected by farmers contingent on their farm systems?; (2) how do farmers' strategic objectives affect IWG management on the farm?; and (3) based on farmers' experiences, what crop management can be proposed for IWG cultivation? We used individual interviews and collective farmer workshops to investigate the introduction of IWG in the farming systems from the strategic to the tactical level of decisions.

2 Material and methods

2.1 Conceptual framework

The conceptual framework used in this study is presented in Fig. 2. A farm system can be understood as an interaction between a biophysical and a decision subsystem (Damour et al. 2018), where final marketable products are produced by ecosystem services and anthropogenic inputs (Dardonville et al. 2022). In our framework, the term "ecosystem services" refers to all biophysical processes in agroecosystems that provide benefits to farmers for agricultural production.

The structure (i.e., the components of the system and their interconnections) and functionality (i.e., the functions emerging from the components and their interactions) of the system are both a consequence of and a constraint for farmer's decisions. In their conceptual framework, Cowan et al. (2013) propose hierarchy of decision "plans" described as follows:

> This hierarchy of plans begins at the highest level with the farm business strategy, which is the fundamental decision of what the business is going to produce and for whom. This farm business strategy leads to decisions regarding how the farm production system is going to be organized to produce outputs. (…) Once a farm has been organized to produce a set of outputs identified by strategy, tactics are used to translate inputs from the task environment through production processes to produce these outputs. Tactics are chosen from alternatives, all of which can serve the strategy under certain circumstances.

Strategic decisions usually pertain to the long term and impact the whole farm: the farm business strategy relates to decisions on, e.g., marketable products, marketing strategy, and certification, while production system plans define the spatial and temporal land allocation. Tactical decisions (sometimes referred as operational decisions) are rather short-term and made at the field level (Robert et al. 2016), adapting to the farm environment. We define crop management as a farm tactic involving the set of cropping practices carried out by the farmer throughout the crop life cycle. Within this farm-scale framework, each crop has its own set of decisions: IWG strategic decisions entail IWG business strategy, e.g., the marketable products, and the IWG cropping plan, understood as the place of IWG on the farm area and in the rotation.

A hierarchy of goals defines the objectives followed by the farmer and interacts with strategic and tactical decision plans. The highest-order goal is the financial survival of the farm business, while lower-order goals refer to the needs of the farm (Cowan et al. 2013). For each specific crop, we propose that goals include a variety of ecosystem services and financial returns that are based on farmer's environmental and social values, observations, and knowledge. These included improving soil structure, reducing inputs, lowering the impact of agriculture, building a relationship with consumers, and reducing workload. At the crop level, we do not prioritize goals. Plans and goals at the farm level and at the crop level are intertwined.

2.2 A methodology based on participatory approaches

Following the steps proposed by Richard et al. (2020) for farmer-oriented co-design, the methodology combined individual semi-structured interviews with collective farmer

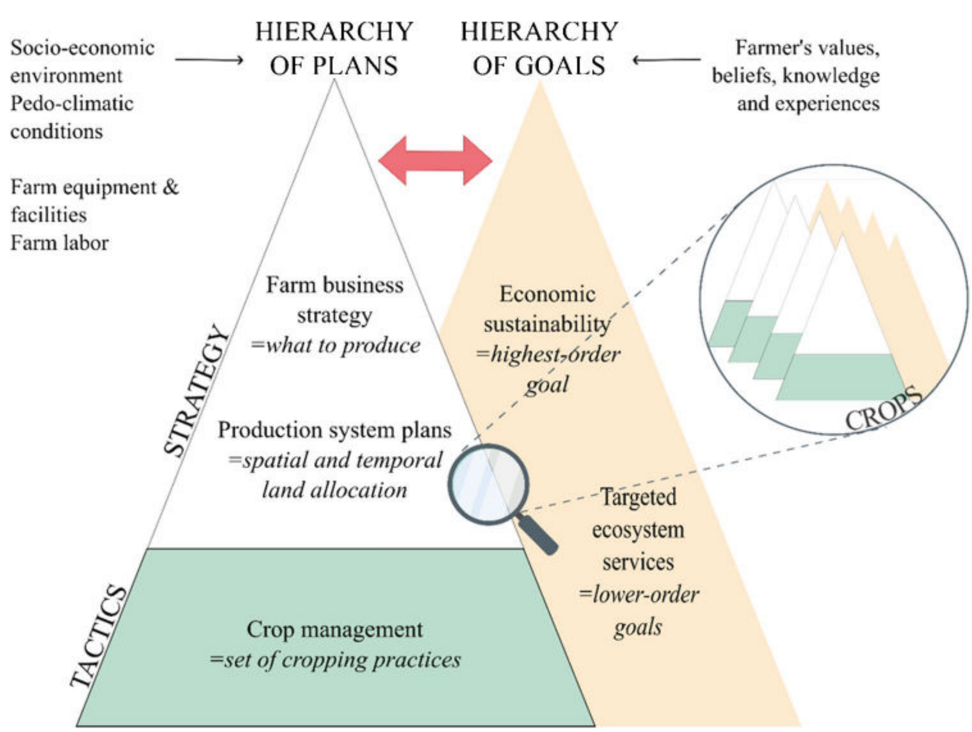

Fig. 2 Conceptual framework used in this study, based on the hierarchy of plans and hierarchy of goals proposed by Cowan et al. (2013). The different levels of decision plans are described in the hierarchy of plans, from the strategic to the tactical level. Farmer's goals for the farm interact with decisions and have two levels of importance. Within this farm-level framework, each crop of the system has a set of similarly ordered decision plans and goals, represented in the zoom. Factors influencing plans and goals are represented by the black arrows.

workshops (Fig. 3). There were two objectives for meeting farmers individually first: (1) to gather primary information on their knowledge and expectations regarding IWG to feed into the workshop preparation and (2) to gather information on their farm systems and how they see the place of IWG on their farms.

The workshop methodology was based on two co-design approaches in agricultural research, namely prototyping and Knowledge-Concept-Practice (KCP) methods. Prototyping helps farmers and scientists to produce novel crop management that can be tested on farms subsequently (Vereijken 1997; Reau et al. 2009). Prototyping is anchored in a real situation and results in site-specific solutions. In our case, previous experiments with IWG by the participants provided concrete situations with locally developed knowledge. As there is no system of references to build on in Europe for designing IWG cropping practices, creativity and innovative ideas are critical. A recent evolution of participative methods has led to the adaptation of the Concept-Knowledge theory to agricultural research, aiming at encouraging participants to be creative and think "out-of-the-box" (Le Masson et al. 2009; Berthet et al. 2016). The KCP method is the application of the C-K theory. It defines objectives toward which the group works but that are on purpose out of reach. The KCP method is conceived to overcome cognitive bias, also known as fixation effects, that block individuals from innovative ideas (Le Masson et al. 2009).

Therefore, the workshops built on the guidelines proposed by Reau et al. (2018) and Berthet et al. (2020) for prototyping and KCP workshops, respectively, and were designed to encourage the emergence of both generic concepts and applicable solutions.

2.3 Description of the participants

Participants of this study were part of the French national observation network for IWG, created in 2020. In this network, 25 farmers received IWG seeds after having contacted the research team to start small-scale experiments (< 0.3ha). In total, 17 farmers of this network were interviewed, out of which 9 participated in the workshops (Fig. 4). All participants had prior experience with the

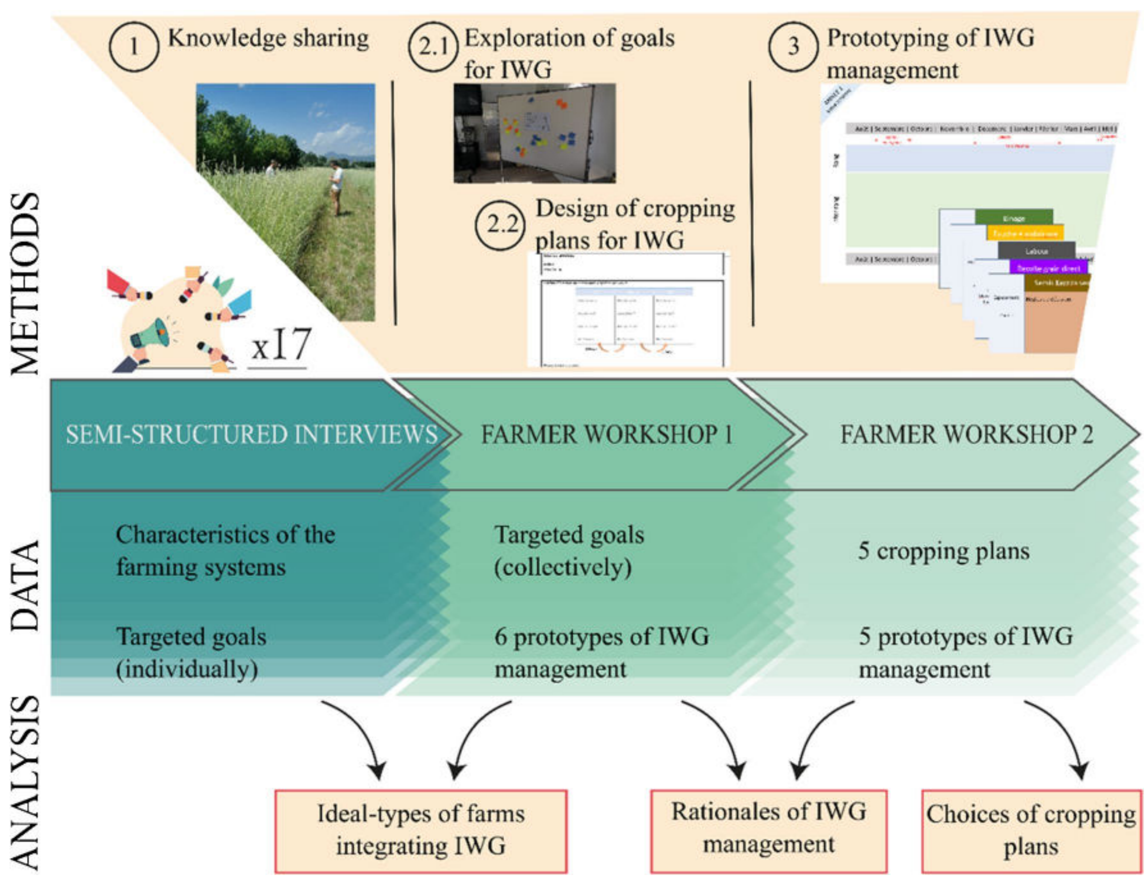

Fig. 3 Methodology of the study. The 17 semi-structured interviews were followed by 2 collective farmer workshops. The three phases of the workshops are represented in the yellow box at the top of the figure: (1) knowledge sharing; (2) exploration of goals for IWG (workshop 1) or design of cropping systems individually (workshop 2); (3) prototyping of crop management. Outputs and analysis derived from interviews and workshops are described at the bottom side of the picture.

crop for at least one cropping season. One additional farmer with no IWG experience took part in the first workshop. The farming systems represented were grain growers (10 farms), livestock farmers (3 farms), and mixed systems (2 farms) and 2 farms were producing a variety of crops but having fodder as a main product. There were 9 organic farms, for both grain and livestock production, and one farm had both organic and non-organic products. The agricultural utilized area ranged from 35 to 387 ha, with a median size of 177 ha. The distribution of farms across various regions of France reflected the influence of different climatic conditions and local economic dynamics. Information on the farms is presented in Supplementary material 1.

2.4 Individual interviews

2.4.1 Conducting of the interviews

During farm visits, 17 semi-structured interviews were conducted (Fig. 3). The interviews were designed to last around 1 h, although they were eventually shorter for two farmers due their time constraints. Two of the 17 interviews were conducted by phone, before the farm visit. During the interviews, information was collected on (i) the farm system (characteristics, activities); (ii) farmer's goals for growing IWG; (iii) practices applied and farmer observations on the IWG trial; (iv) suggestions about practices and crop management; and (v) perceptions about the future development of IWG in France. The first two themes were used to describe farming systems and interests in IWG. Themes 3 and 4 were used for preparing the workshops and theme 5 brought elements for opening the discussion beyond farm boundaries.

2.4.2 Description of the farm systems and interests in IWG

To analyze the interviews, a framework was developed with criteria describing the farm systems and the ecosystem services expected from IWG. The farm system was described in terms of history of the farm, land area, soil type, type of crop and livestock, equipment and farm buildings, farm products, processing and direct selling activities, non-farming activities and activities outside the farm, market labels, workforce, involvement in farmer organizations, common pests, weeds and diseases, and crop fertilization. From the interviews, the expected services expected from IWG were compiled, to enable comparison among farmers.

Based on this framework, we identified key characteristics that distinguished farms from each other. They were the

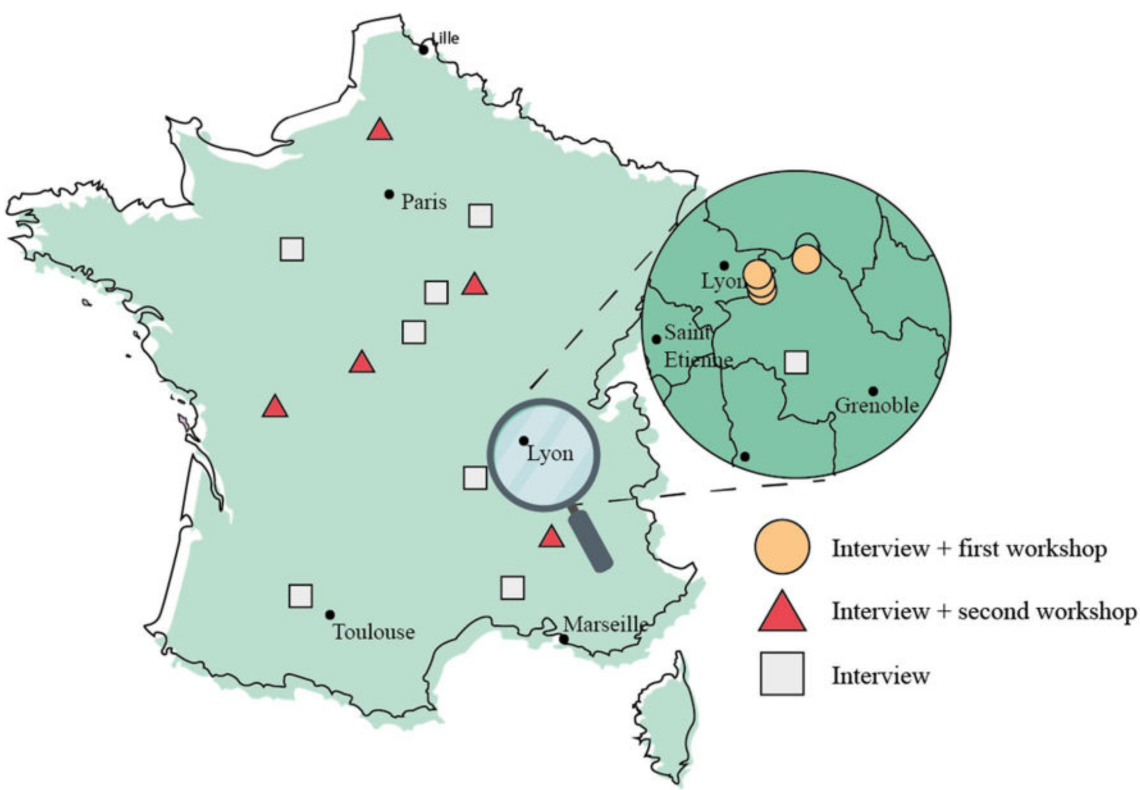

Fig. 4 Map. Seventeen farmers participated in the semi-structured interviews, out of which 9 participated in the workshops. All farmers had experienced the crop for at least one season.

ones most often used as arguments by farmers for justifying their goals and cropping practices. These characteristics were used to create three farm ideal-types. The word "ideal-type" is understood as a conceptual tool for understanding the farm systems, but by no means refers to the ideas of "desirable" or "perfect." It is a simplification of reality and does not pretend that all characteristics are always found perfectly in observed reality. An example of its use in agricultural sciences can be found in Nguyen and Purseigle (2012). The ideal-types reflected a particular combination of (i) type of existing farming system, (ii) main marketable IWG products, and (iii) main targeted goals.

2.5 Collective workshops

2.5.1 Workshops organization

Two farmer workshops were organized on April 14, 2022, and June 16, 2022, with 9 of the 17 farms interviewed. The first objective was to open up reflection on crop management by discussing the direct and indirect financial returns that would make the crop profitable. A second objective was to design cropping systems (i.e., land use allocations and rotations) that included IWG. The last objective to which most time was devoted was to co-design IWG crop management. The first workshop, lasting half a day, took place in the Rhône-Alp region (45.64N, 5.29E) with 6 participants from 5 different farms of the area (Fig. 4). All the farms were in organic production. One farm was a mixed farm and 4 were arable. The second workshop lasted a full day and was organized in the Burgundy region (47.67N, 3.88E), with 7 participants representing 5 farms from 5 regions (Fig. 4). There was one organic hay farm, one organic crop farm, 2 conventional crop farms, and 1 conventional crop farm with a no-till system. Only farmers were invited (and not technicians or researchers) in order to avoid bias and "self-censoring," and to put farmers at the central position.

Both workshops were structured in three phases, derived from the KCP method framework and the prototyping methodology (Fig. 3). The first phase was dedicated to knowledge sharing. The aim was to share actionable knowledge that farmers could later use in the design (Leclere et al. 2021), while avoiding fixation effects (Della Rossa 2020). Therefore, farmers were invited to share their own experiences and observations while the researchers' presentation on IWG phenology and yields was kept short and basic. This phase was supported by a testimony of a seed producer of forage grasses sharing his practices for the first workshop, and a field visit during the second workshop.

Phase 2 differed between both workshops. Farmers of the first workshop were presented with the target "Integrating Kernza in the rotation for three years in a profitable way" and were invited to mention all the elements that could help reaching this target, without any restrictions on the types or the scale of the ideas. In the second workshop, it was decided to focus this phase on cropping plans so as to investigate further the farmers' rationale regarding their choices about spatial allocation of IWG on the farm and its place in the rotation, following the method proposed by Leclere et al. (2021). At the end of this phase, participants defined objectives for guiding the design of crop management in the next phase.

The last phase of the two workshops concerned the collective design of crop management prototypes. Each prototype served a specific objective that was based on the outcomes from the previous phase. A board similar to the one developed by Meunier (2019) was used as an artifact in this phase. The board represented IWG rows and inter-rows and a time frame, and "cropping practices" cards with different options for soil preparation, seeding, weed management, fertilization, irrigation, harvest, and post-harvest management (Fig. 3). In the first workshop, two main objectives were discussed by farmers: maximization of grain production over 3 years (objective 1), and minimizing workload and maximizing soil functions (objective 2). In the second workshop, farmers designed the crop management tactics for three of the cropping systems they had proposed in phase 2. Implements, decision rules, fertilizer and seeding doses, and timing of interventions were discussed and added to the prototypes when possible. At both workshops, discussions were recorded and subsequently transcribed.

2.5.2 Description of cropping plans and crop management

The cropping plans proposed by participants during the second workshop entailed temporal and spatial arrangements at field and farm scale. They were described following 4 components: (i) where to place the crop on the farm (land allocation); (ii) to intercrop IWG or not (sowing architecture); (iii) where to include IWG in the rotation and for how long (temporal decision); and (iv) when to sow IWG, i.e., in autumn or spring (sowing period).

Prototypes of crop management were formalized as timelines describing the sequences of tactical decisions. The different options and knowledge gaps discussed by farmers were specified. Because prototypes differed greatly in their complexity, underlying rationales of crop management were analyzed based on (i) the type of fertilization and weed management proposed and (ii) the workload associated with the cropping practices over the course of the crop cycle.

3 Results and discussion

3.1 IWG as a strategic choice for a farm

3.1.1 Farmers saw a variety of ecosystem services from growing IWG

During the interviews and workshops, farmers mentioned several uses of IWG products: grain for human consumption, forage used as hay or for grazing, seeds, straw, and biomass for energy or cellulose extraction. Out of the 17 farmers, 5 were highly interested in the dual production of grain and forage. Many farmers explained that they could not valorize forage because of a lack of local market. All farmers were interested in producing grain, although forage (and in one case biomass) was the primary target for 5 of them. Structuring a market and obtaining authorization for selling grain for human consumption in Europe was brought up as a prerequisite for any development of IWG cropping.

Although marketable products were necessary for ensuring direct economic profitability, farmers emphasized ecosystem services as primary goals in relation with their farm strategy. First, farmers were interested in enhancing the biophysical functioning of their fields. They were looking to improve soil structure (8/17 of respondents), increase soil organic matter and carbon storage (4/17), have a new crop to increase rotation length (5/17), and manage weeds with a perennial crop (4/17). Interest for a service was dependent on the farm's soils and cropping systems. For instance, Farmer_12 explained: "I have no real issue with soil structure because I have light soils, but as everybody else, I will have an organic matter issue." He was the only one stating having no interest in soil structure. Lengthening crop rotation was associated with the idea of introducing perenniality in systems to benefit from denser and deeper rooting, limiting soil tillage, diversifying the crop rotations, and managing weeds. Yet, farmers were unsure about the capacity of IWG to suppress weeds, and some were even afraid to worsen weed pressure during crop establishment or for succeeding crops. These ecosystem services are consistent with previous results for perennial wheat (hybridization of *Triticum aestivum* L. and *Thinopyrum* spp.) in the USA (Adebiyi et al. 2016), for intermediate wheatgrass in the USA and France (Wayman et al. 2019; Lanker et al. 2020), and for perennial grains in Sweden (Marquardt et al. 2016). Farmers aimed at replacing certain anthropogenic inputs (fertilization, pesticides, plowing, etc.) by ecosystem services (N fixation, crop diversification in time and space, soil structuring) for the production of marketable goods. IWG was perceived as a crop that may improve the field productivity, i.e., as a crop providing "input services" (Tibi and Therond 2017).

Second, ecosystem services were targeted by farmers in order to anticipate future constraints originating from climate change inducing regular water stress, but also from evolving fertilizer and pesticide regulations. Farmers were looking for a new drought-resistant crop (9/17, especially forage producers) and low-input crop (6/17, all conventional). Conventional farmers were willing to try mechanical weed management to avoid herbicides. Farmer_4 stated: "I think that this crop, provided that it is really zero-pesticide, can be a solution for the drinking water catchment area where I am. I see how the horizon is coming, there are pressures from the ecologists and the administration: today we have grass strips of 5m, and I think we will be asked to increase them to 30m (…). Could the Kernza be interesting for these strips and try not to lose out financially?"

Finally, IWG was seen as a way to improve the overarching farm strategy by optimizing land use. This was especially true for the use of marginal lands, i.e., of fields with major biophysical constraints where main cash crops did not achieve their yield potential. In those fields, IWG could maintain production with less work and input needs. According to the farmers, IWG might have an advantage compared to highly productive small grain cereals for low-productive or damaged fields (4/17 of respondents), no-treatment zones near water courses, housing, or protected areas (5/17), or fields that are remote and not easily accessible with machinery (2/17). Farmer_7 concluded: "The Kernza, it should be kept for low-productive fields," in line with the proposal of Duchene et al. (2019). This idea was shared during the first workshop, but further discussions also revealed that more water and fertilizers would be needed in low-productive fields to maintain yields. These fields may also have greater weed seedbanks and weed pressure. This is contrary to the idea of a low-input, low-workload, and non-irrigated crop, and may compromise the profitability of the crop if yields, already low, are further reduced. However, farmers have highlighted that IWG would perform more effectively and with fewer inputs than another main crop on such fields. The literature indicates that the profitability of perennial grain crops is relatively enhanced when the profitability of other crops is lowest (Bell et al. 2008) because the difference of financial return between the two is reduced (Bell 2013). Growing IWG in order to value marginal lands was therefore tightly linked to the overarching farm strategy.

The responses of farmers demonstrate the impact of goals, driven by values and external constraints, on the decision to introduce a new crop. Economic profitability was more a constraint or necessary requirement for ensuring the financial survival of the farm than a real first-order goal for the crop. Research on ecological intensification also revealed that profit is an insufficient motivation for adopting an innovation but that the innovation needs to be compatible with farmers' values and beliefs (Kernecker et al. 2021). As discussed by Adebiyi et al. (2016) for perennial wheat, "[farmers] proposed perennial wheat as a mean of solving a problem for which no other crop provided an adequate solution." The selling price of IWG grain was more important than yields per se, which contrasts with the idea that yields would be the first characteristic driving adoption. This balance between yield and market prices for ensuring profitability of perennial wheat is well illustrated in Bell et al. (2008). The first collective workshop revealed that profitability was considered a combination of direct and indirect benefits that resulted from IWG growing and was considered at the farm system level rather than for the individual crop. In addition, farmers did not consider profitability in comparison to conventional systems and they did not see IWG as a substitute for other cash crops. These findings are in line with previous studies on perennial grains (Adebiyi et al. 2016) and give another perspective to Wayman et al. (2019)'s observation that French and American farmers consistently ranked "increase or maintain profitability" among their top interests in perennial grains: what farmers defined as their farm profitability may differ from economists' views.

3.1.2 Farmers' goals were related to their farming systems

Comparing farmers' answers about interests in IWG and the characteristics of their systems reveals that the goals mentioned by individual farmers were dependent on the farm business strategy, reflecting the requirement for an innovation to have a relative advantage and to be compatible with the current system (Kernecker et al. 2021). Introduction of a new crop leads to a change in the farm structure and therefore in the business strategy (Cowan et al. 2013). Three ideal-types emerged from the 17 interviews, based on 3 components of farming systems, 5 goals for IWG, and 2 marketable products. Regarding the farm business strategy, the criteria were (i) the market label: organic or not; (ii) a recent (less than 5 years ago) change in production system, label, or practices; and (iii) the possibility to use or sell hay. Among goals for IWG, 5 were cited most frequently: (i) crop and food diversification, (ii) soil structure, (iii) allocating the crop to non-treatment zones, (iv) reduction of pesticides, and (v) drought resistance. The two marketable products most often targeted by farmers were grain and forage.

A first ideal-type, designated as "grain organic," represented organic grain farms that had undergone substantial changes in their systems in the last 5 years, and were only interested in IWG grain production. This type looked for diversification of crops and foodstuffs, and had a major interest in improving their soil structure and/or organic matter. For instance, Farmer_13 had a grain farm and started converting to organic farming in 2019. He was interested in reducing soil tillage and improving soil structure, and producing IWG grains. Also related to this ideal-type, Farmer_5 was not organic but aimed at conducting the system organically, had obtained a no-till label, and had switched from livestock to grain production recently. The "grain conventional" ideal-type represented conventional grain farms that were interested in IWG for grain production and for putting the crop on non-treatment zones or protected areas. Farms of this type aimed to reduce inputs, especially pesticides, and to a lesser extent workload. They preferably concentrated their cash crops on easily workable and productive fields, while they wished their marginal lands could be "self-sufficient" with less demanding crops. Farmer_15 was related to this ideal-type because he had a conventional arable farm and aimed to reduce inputs but, unlike this ideal-typical farm, he wanted to produce biomass for biogas and grain production was rather secondary. This was explained by the larger size of the farm (387 ha) and the presence of 2 biogas digesters on the farm. The third ideal-type represented organic or conventional farms that were firstly interested in producing forage, with grain as a possible secondary product, and that typically already had a hay outlet. These farms were notably concerned by climatic change adaptation and drought resistance was a major service expected from IWG. We called this type "forage." All mixed farms were found to be close to this ideal-type, plus three crop farms that had hay production as a major activity.

3.2 IWG cropping plans and tactical decisions

3.2.1 Farmers proposed several options for sowing date, rotations, and intercropping

At field scale, IWG cropping plans reflected farmers' concerns in terms of spatial and temporal characteristics of crop establishment. Farmers' answers regarding date of IWG sowing and its place in rotations were variable and site-specific. The choice between autumn and spring seeding was mainly dependent on weather conditions and especially water availability. Most farmers were more inclined to sow in autumn in order to harvest grains the first summer, but also mentioned the option of a spring seeding as a potential adaptation to drier autumns. Rotations differed greatly in length and species composition. For instance, Farmer_2 did not want to apply synthetic or organic fertilizers, so he designed a rotation of around 15 years permitting to maximize nitrogen fixation and nutrient recycling by a combination of N fixing crops and perennials, and incorporation of straw. On the contrary, Farmer_5 proposed a 6-year rotation with continuous IWG for 3 years. Crops proposed by farmers to precede IWG were legumes (alfalfa, peas) for fixing N, winter cereals (wheat, barley, meslin; i.e., mix of grain crops for animal feed) because their cycle is compatible with early sowing in autumn and are major cash crops, or spring oil crops (sunflower, flax, rapeseed) because they are broadleaf crops so that it should be easier to control regrowth with herbicides (Fig. 5).

Decisions regarding intercropping IWG with another grain or forage crop were more straightforward in farmers' answers, possibly because they were highly dependent on farmer know-how. Legume crops were usually preferred for enriching the system with nitrogen, while undersowing in a winter cereal or a summer crop (e.g., peas, flax) was discussed as a way to avoid weed pressure during IWG establishment (Fig. 5). Cover crops were selected based on their ability to compete with weeds and their competition with IWG, their allelopathic effects, and their harvest periods. Grain farmers who were not used to cover cropping were reluctant to adopt them on their farms because they considered themselves to lack knowledge and experience for a successful implementation. Further, they were sometimes afraid to jeopardize their other cash crops. For instance, for undersowing IWG in barley, reducing the density of barley appeared necessary so Farmer_10 concluded: "So we want to do Kernza grain but we jeopardize the barley we do before! That's the problem with intercropping: do we favour the second crop at the expense of the first?"

3.2.2 IWG crop management reflected farmers' goals

In total, 11 crop management prototypes were proposed by the participants, for 5 different objectives:

- Maximizing grain production over 3 years in organic farming
- Maximizing grain production over 3 years in conventional farming
- Producing grain over 3 years and minimizing economic risks in organic farming.
- Dual production of grain and forage over 5 years in organic farming
- Minimizing workload and maximizing soil functioning

Although crop management entails cropping practices from soil preparation to post-harvest treatments, prototyping of IWG crop management by the farmers focused mainly on sowing methods, fertilization, and weed management. Soil preparation and pest and disease management were barely mentioned and harvest and post-harvest treatments were only little discussed, probably due to the lack of experience of many growers and the few pest and disease issues encountered on their fields. Sowing was seen as the most critical operation for IWG success: "the year of sowing is where everything is determined. The challenge is to succeed crop planting" (Farmer_13). To our understanding, the fact that IWG is perennial (hence sowing determined the management and yields for multiple years) made this operation even more critical. Sowing was very dependent on the approach to weed management, which made Farmer_10 conclude the discussions about row spacing by stating that "the row spacing is what allows, if you will, to hoe, and I think the answer is individual."

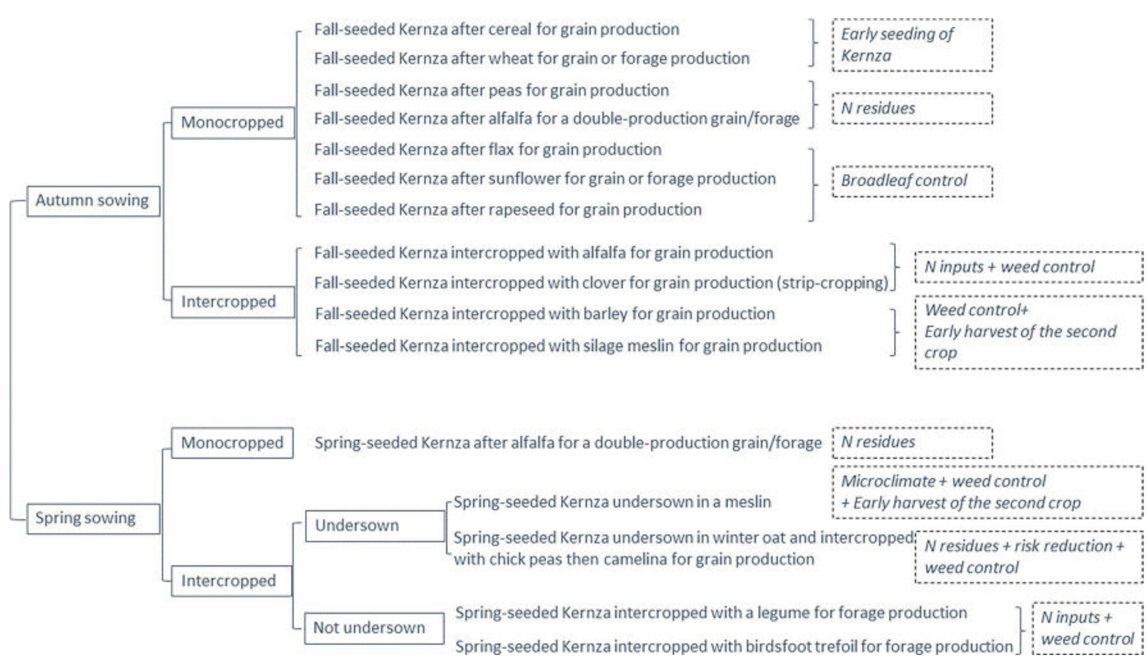

Fig. 5 Examples of cropping plans proposed by farmers for IWG. Benefits from preceding crop or intercrop are provided in the dotted boxes on the right.

In the prototypes, we could distinguish between chemical fertilization, organic fertilization, based on bovine or chicken manure, and "biological" fertilization based on the use of legumes as preceding crops and/or intercrops. Similarly, there were 3 types of weed management: chemical, mechanical, and biological (using an intercrop or a cover crop to compete with weeds). Based on these observations, prototypes designed by farmers can be separated in 3 rationales guiding crop management

- *Grain cropping based on external inputs*: these prototypes were based on the use of fertilizers (chemical or organic) and chemical or mechanical post-emergence weed removal. They essentially adopted and adapted cropping practices commonly used for managing winter cereal in conventional or organic systems. Most participants proposed this type of operational strategies: they were either conventional crop farmers or had turned organic less than 5 years ago and had farms of all sizes.
- *Grain cropping based on ecosystem services*: this type of management was based on the use of ecological processes and functions for crop nutrition and for preventing weed emergence. Thus, legumes were proposed as preceding crops or intercrops to bring N into the system, and IWG was grown together with another crop that competed with weeds and prevented their appearance. Intercropping covered part or the whole duration of IWG life cycle, and if there was weed pressure after the removal of the secondary crop, mechanical weeding was used. This rationale was illustrated by a prototype from the second workshop (Supplementary material 2) and close to Famer_14's ideas during the interview. Farmer_7 is an organic farmer that has been through a long-term development of complex practices to cope with economic and environmental risks, based on the introduction of new species and the understanding of ecological processes.
- *Low-workload crop management*: this type of crop management used biological fertilization and only mechanical weed control (crushing, mowing) when necessary. The number of cropping practices was reduced to its minimum resulting in a low-input system with no fertilizers or herbicides, minimal fuel use, and minimal labor input. This rationale was illustrated by a prototype in workshop 2 (Supplementary material 2), and close to the comments of Farmer_1 and Farmer_3 during the interviews. In this rationale, minimizing inputs was a strategy for coping with economic risks by low financial investments in the system, while minimizing working time to benefit from more leisure time (Farmers_2 and 3 were retired) or to maintain another economic activity (Farmer_1 had a full-time job beside the farm). It is noteworthy that forage was the initial production objective, with IWG grains representing a further advantageous product during the initial 2 years.

These rationales of crop management illustrated how existing farming systems and farmers' goals, driven by environmental and social values, directly affected the selected production activities. Farmers did not stress the need for developing technical expertise straight away: discussions on crop management showed that many questions remained open but farmers were not concerned about them. They rather underlined that for weeding, fertilization, harvest, regrowth, and pest (voles) management, they would make a decision when the question would arise rather than plan for it in advance.

3.3 From farm strategy to crop management

3.3.1 Links between strategic and tactical levels were not deterministic

Figure 6 summarizes the IWG goals and decision plans of farmers from the strategic to the tactical level. Results show that tactical decisions were very dependent on the farm system before the introduction of IWG and the practices that were used by the farmer on the other crops (intercropping, mechanical or chemical weeding, fertilization, etc.). However, it should be noted that the choices made for IWG at the strategic level did not strictly determine the choices made at the tactical level.

For instance, the crop management prototypes were strongly associated with IWG cropping plans, especially regarding the sowing date and seeding architecture that constrained weed management and harvest methods. However, one cropping system could have multiple management options because tactics were also influenced by the label (organic, no-till), the equipment available, and the pedo-climatic conditions on the farm. For this reason, tactical decisions were farm-specific.

Similar farm types could be related to different crop management alternatives. Comparing farming system ideal-types and crop management rationales, we observed that each ideal-type tended to favor different management rationales, but not all. For instance, farmers close to the grain-organic model were also the ones close to the first two rationales of IWG crop management, i.e., management based on external inputs or ecosystem services. Farmers related to the forage ideal-type proposed management that was associated with the low-workload or ecosystem services–based management rationale, as for managing pastures. Although this may not apply perfectly to other IWG growers (adding more participants to the study might have changed the ideal-types and management rationales), these observations suggest that farm system limited the type of crop management rationale that can be applied, but did not strictly determine it. Farm ideal-types and crop management were neither totally disconnected nor strictly related. This opened a variety of possibilities for each farmer to integrate IWG in his/her existing cropping system.

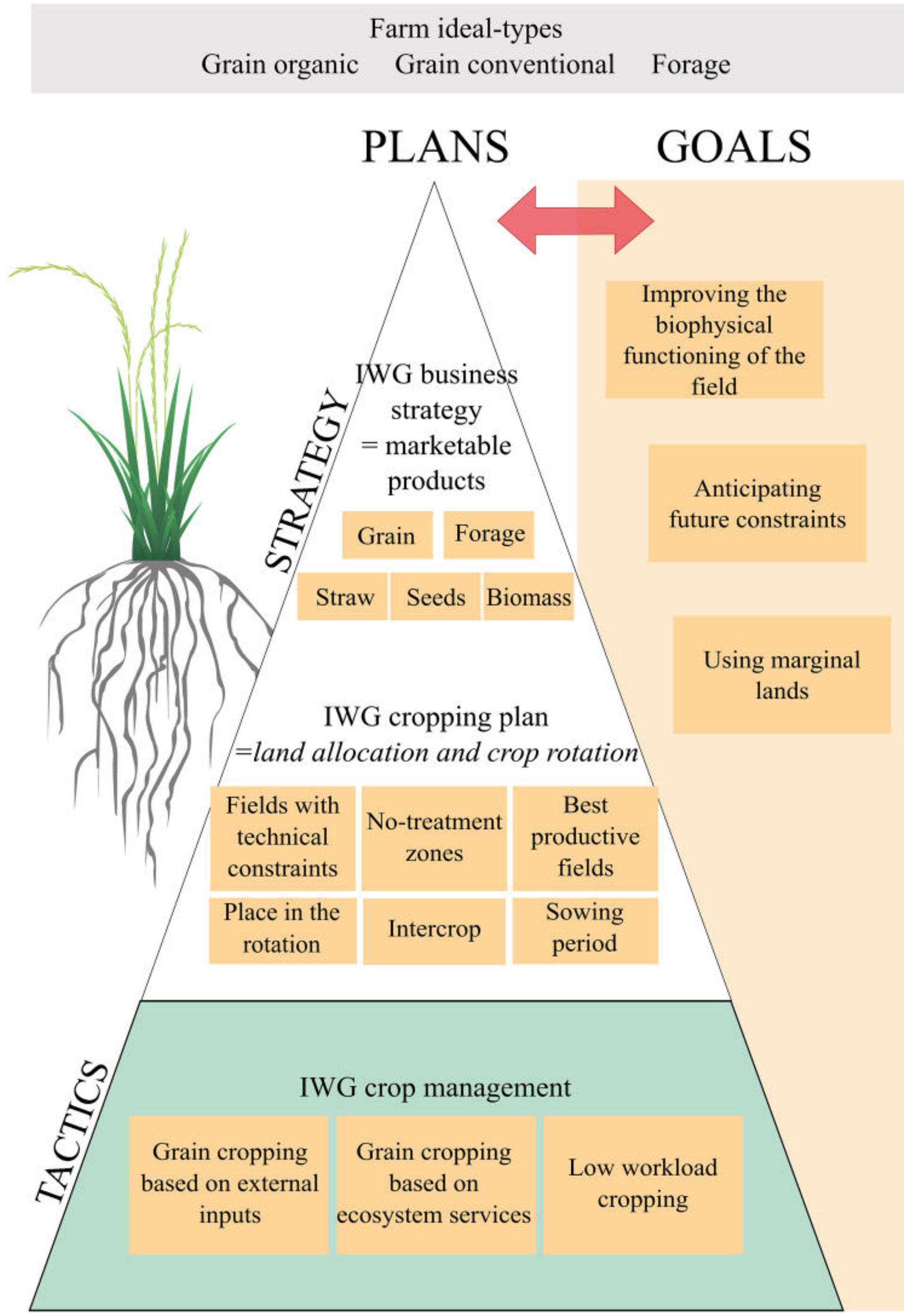

Fig. 6 Farmer decision-making process for integrating IWG on farms in France. The 3 ideal-types of farms are represented at the top. The various options for strategic and tactical decisions and goals for IWG are represented in the boxes

3.3.2 Farmers integrated risks and uncertainties in their decisions

Although a longer-term study would be necessary to analyze the evolution in farmers' decisions, our results suggest the existence of feedback loops that reflected the loose control between strategic and tactical decisions. Farmers mentioned various options of IWG cropping plans and crop management during interviews, or even raised different ideas in the individual interviews or during the workshops, showing constant adaptations. The uncertain context in which they tested IWG, both from the production side (lack of information about the crop physiology, optimal development conditions and services provided) and the marketing side (no recognition of the crop in Europe and therefore no processing and supply chains), and the fact that decisions depended on the goals targeted, explained that introducing this crop from the strategic to the tactical level is a long-term process driven by trial-and-error and exchanges between practitioners. As Leeuwis (2004) explained, “farmers’ decisions may involve perceptions about the consequences of [particular] practices in a large number of distinct domains, and are linked with an even higher number of perceptions regarding (un)certainty, likelihood and risk.” These perceptions are shaped by their knowledge and perceived capabilities (Leeuwis 2004). Other studies show the complex and dynamic nature of farmer decision-making both for adopting a disruptive technology such as perennial grains (Adebiyi et al. 2016) or designing a cropping plan (Dury et al. 2013). When considering that farm behavior is not deterministic, uncertainty becomes a core element of the dynamics, and resilience a criteria for assessing system performance (Prost et al. 2023).

In this study, farmers who had the clearer link from the strategic to the tactical decisions were the ones that had developed a specific strategy to deal with risks and uncertainties, so that introducing a new crop such as IWG would not differ from what they usually did. For instance, Farmers_2 and 7 had both found a way to deal with economic risks and uncertainties inherent to crop production: thanks to a niche organic hay market and non-agricultural activities, and thanks to crop diversification and intercropping in the other case. Therefore, uncertainties around IWG cropping were less problematic because they believed their systems could handle them, so that they could apply the same logic for IWG as for their other crops. This was not the case for farmers having a small number of cash crops, for whom IWG was very different from what they knew. This suggests that fluctuations in farmers’ answers were not only linked to the uncertainties and lack of information involved with IWG, but also to the way farmers were used to work and handle uncertainties in general. This has previously been described as strategical and tactical flexibility, i.e., the ability to change outputs or the use of input to absorb variability, without changing the whole farm structure (Cowan et al. 2013).

However, it is important to note that “a study conducted as a snapshot of a farmer decision-making process will therefore yield different results across different types of systems and at different points in the adoption trajectory” (Adebiyi et al. 2016). Thus, the differences observed between farming systems, IWG marketable products, and goals and crop management may change as farmer experience with IWG grows over time.

3.4 Perspective for the future development of IWG as a diversification crop

When asked about the future of IWG in France during interviews, farmers’ first consideration was about market development of IWG products. All were optimistic, highlighting that with a specific taste and a low-gluten content, IWG products could be sold easily: “consumers are rather open-minded and are looking for novel things,” explained Farmer_7. Participant farmers did not dissociate the production side from the user side but spontaneously connected both. Producers were aware that if IWG grain production works, they will be in an advantageous niche market: many had contacted local cooperatives, bakers, or brewers to investigate what would be possible to produce and to sell. By targeting small and local partners, farmers bypassed more central actors in the distribution, storage, and processing activities. This illustrates a process of niche structuring that involves actors able to deviate from dominant rules. As explained by Meynard et al. (2018), most cooperatives and brokers are not suited to the development of new crops because their functioning and material infrastructures are based on economies of scale and therefore adapted to large production volumes and reduced logistic costs. However, innovation is also enabled by regime actors: a major point raised by farmers was that certification of IWG for human consumption in Europe is a prerequisite for any further development.

During the workshops, farmers mentioned the necessity to improve cultivars through breeding and to multiply seeds to extend trials, and pointed out knowledge gaps on the ecosystem services provided by the crop, its physiology, and its reaction to some cropping practices. This is in line with the observations of Meynard et al. (2018) that the low breeding investment and the lack of knowledge and agronomic references are impediments to the development of minor crops. In relation to the multiple expected ecosystem services and marketable products, and the various pedo-climatic conditions of the French observation network, this raised the question of selection criteria. Grain yields have been the main focus of the Land Institute breeding program so far (DeHaan et al. 2018) but our results suggest that although farmers were concerned about harvest ease (grain size, threshing, shattering), different cultivars could be developed depending on the targeted marketable products, goals, and the local climatic conditions.

A large body of literature analyzes the transition of an innovation from a niche to the socio-technical regime (Geels 2004) as scaling up/out processes (Wigboldus and Leeuwis 2013), diffusion of innovation (Robertson 1967; Rogers et al. 2009), and theories of change or development. According to the well-known model developed by Rogers (2003), diffusion takes the shape of a S-curve as more and more people adopt the new technology. Although IWG may not replace any current crop, the S-curve of change highlights the two main elements of scaling: adoption and time. Farmers raised the question of scalability of IWG, i.e., “whether the object of scaling can scale at all, and/or whether it still makes sense when it scales” (Wigboldus and Leeuwis 2013): until what point is it desirable to diffuse IWG? If farmers saw the advantages of developing a niche for IWG, they were not necessarily keen to scale out production and marketing. For instance, Farmer_11 was aware to be the only IWG producer on the Atlantic coast and had contacted his small and local cooperative for starting trials to make biscuits. As he explained, his interest was not in IWG going to scale but rather in remaining the only producer in the region: “the co-op[erative] would like to have exclusivity on the sale, and honestly so would I. Exclusivity means good prices and marketing. It's best to keep it a well-controlled niche market.”

4 Conclusion and perspectives

Most of the farmers that participated in this study were characterized by their willingness to experiment with a new crop either because they wanted to try something that is not commonly done and that leads them to think and work “out of the box,” or because they were looking for solutions to agronomic, economic, or climatic issues. Associated with this, satisfaction to work with scientists was mentioned, as well as learning and exchanging knowledge, and limiting the impact of agriculture for the future. The farmers were likely more innovators and risk-takers than most farmers, so the dynamics between farmers’ goals and decisions to introduce IWG may not be generalizable. Nevertheless, these “innovative farmers” provided valuable elements to guide future research on IWG and discuss its potential development pathways in France, thanks to their knowledge, expertise, and field observations. The farmers highlighted several points that were complementary—sometimes opposite—to views of researchers in the literature, for instance regarding marketable products or weed management. This study is based on a small number of participants, which is in part explained by the limited number of farmers having experienced IWG in France. Although semi-structured interviews would have benefited from more participants, having a limited number of people in the workshops was also a choice to favor discussion and collective thinking. To account for this, analysis was made to identify the trends in the farm systems, targeted goals for IWG, and crop management rather than define groups of farmers strictly.

For the first time, introduction of the perennial grain IWG on farms was analyzed as a set of strategic and tactical decisions, in interaction with goals. Goals for IWG mentioned by farmers reflected their farm strategy, with financial profitability considered at the whole rotation (or farm) scale and not just for IWG. Results highlight that the decision process to arrive at the testing and introduction of IWG on a farm is complex because of the diversity of factors influencing farmers’ choices, and because of the uncertain context and lack of agronomic references about IWG in Europe. Thus, tactical decisions were not fixed for the majority of farmers and the discussions surrounding the prototypes reflected the need to build knowledge within the context of farm systems.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethic approval Not applicable.

Consent to participate Verbal informed consent was obtained from all individual participants prior to the interviews and workshops.

Consent for publication The authors affirm that researchers on the picture in Fig. 2 provided informed consent for publication.

Conflict of interest The authors declare no competing interests.

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