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Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 01 July 2024
DOI 10.3389/fsufs.2024.1412281

OPEN ACCESS

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RECEIVED 04 April 2024
ACCEPTED 20 June 2024
PUBLISHED 01 July 2024

CITATION
André M, Pujos L and Martin G (2024) Potential for and impacts of mainstreaming diversification crops through institutional catering.
Front. Sustain. Food Syst. 8:1412281.
doi: 10.3389/fsufs.2024.1412281

Potential for and impacts of mainstreaming diversification crops through institutional catering

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Introduction: In France, land use is dominated by a narrow range of crops. As crop diversification is increasingly promoted to transform the food system, outlets for diversification crops need to be identified. We assess the scope for introducing diversification crops from farmers' fields to canteen plates, and the agroecological, environmental, work-related and nutritional impacts of their introduction.

Methods: We focus on three diversification crops: chickpea, squash, and millet, to partly replace soft wheat, potato, and durum wheat, respectively. For each crop, we define three scenarios of low (1), medium (2) and high (3) integration into institutional catering on a national scale. We assess the scenarios against the amount of diversification cropland area needed and their expected impacts.

Results: Diversification crops can be developed through institutional catering. Taking the case of chickpea, in Scenario 1, chickpea flour is introduced in a cake served once every 20 days, replacing 30% of the soft wheat flour used. This amounts to 874 ha cropped. In Scenario 2, chickpea flour partly replaces wheat flour in all preparations, and 4,048 ha are required. In Scenario 3, raw chickpeas are also introduced into new recipes and 20,958 ha are needed. All three diversification crops support the establishment of agroecological cropping systems, with enhanced nutrient cycling in particular, and reduce their environmental footprint, notably by avoiding pesticide use. Diversification crops do not generate work constraints for farmers and cooks. However, they have a lower productivity per unit area than the reference crops, although they do improve several nutrition parameters such as fiber intake.

Discussion: We show for the first time that institutional catering provides a tangible outlet for developing diversification crops and improving the sustainability of agriculture. Our scenarios can support concerted actions between farmers, supply-chain actors, cooks and policy makers, as well as communication to eaters surrounding their impacts on agriculture.

KEYWORDS

canteen, catering, minor crops, crop diversification, sustainable agriculture

1 Introduction

In France, 48% of the 26.8 million ha of arable land is covered with annual grain and tuber crops (Agreste, 2022). This land use is dominated by a very small number of crops: wheat (5.1 million ha), barley (1.8 million ha), corn (1.5 million ha), rapeseed (1.2 million ha), and sunflower (0.6 million ha). This specialized and input-intensive agricultural model has been criticized for contributing to exceeding several planetary boundaries, particularly in relation to climate change, biodiversity loss, and interference with nitrogen cycling (Rockström et al., 2023). The ability of the current food system to provide healthy diets for all people is another major concern. A number of related chronic diseases, such as obesity and diabetes (Blüher and Stumvoll, 2020), have emerged on every continent. There is therefore growing recognition that the current food system is at the core of a nexus of environmental, economic and social issues (Godfray et al., 2010; iPES FOOD, 2015).

To transform the food system and make it sustainable, the development of diversified farming systems has become increasingly popular, as illustrated by the content of the European "Farm to Fork" strategy (European Commission, 2020). These diversified systems "intentionally include functional biodiversity at multiple spatial and/or temporal scales in order to maintain ecosystem services that provide critical inputs to agriculture, such as soil fertility, pest and disease control, water use efficiency, and pollination" (Kremen et al., 2012). Thus, diversified farming systems require crop diversification in time and space. In France, achieving this diversification is a real challenge given the country's current land use. Moreover, the lack of agronomic knowledge on diversification-crop cultivation, along with technological and socio-economic lock-ins such as low diversification-crop consumption habits, have been identified as obstacles to the development of diversification crops (Magrini et al., 2016; Meynard et al., 2018).

Within the food systems of advanced economies, institutional catering has a major impact on production and consumption practices. In France, it represents about 3.562 billion meals served every year (MASA, 2023) to a diverse range of eaters: young children in kindergartens, children at primary school and high school, patients or the elderly in the health and social sector, workers in the public and private sectors, prison inmates, and so on. Research has shown that sustainability transitions in institutional catering are feasible (Martin et al., 2022), with cases of organic and often local procurement by canteens that vary in size and have different organizational models (deferred vs. cook-serve meals, i.e., central units sending out meals to satellite canteens vs. meals cooked and served on site at canteens). Institutional catering can thus be used as a lever to facilitate the consumption of diversification crop products by eaters and, indirectly, the spread of diversification crop production in farmers' fields (Figure 1).

We assessed the scope for introducing diversification crops from farmers' fields to canteen plates and the multiple ways in which this influences the establishment of agroecological principles in cropping systems, the prevention of environmental impacts, work constraints for farmers and cooks, and the nutritional features of the food produced. We performed this assessment for three diversification crops: chickpea, millet, and squash, to partly replace soft wheat, durum wheat, and potato respectively, based on the outcomes of a crop selection process with cooks (Section 3.2).

2 Literature review

Diversification crops have remained understudied by the research and development community over the past decades (Meynard et al., 2018). Their national yield trends have either stagnated or declined and farmers have been growing them less and less as reported by Peltonen-Sainio et al. (2016) for Finland. This has strengthened the status of major crops. Yet the recent agroecological turn observed in several countries [e.g., France (MAAF, 2016) and the United Kingdom (Cusworth et al., 2021)] has shed light on features of diversification crops that have not received sufficient attention, such as the value of the low harvest index of minor cereals to return sufficient crop residues to the soil, and that of nitrogen fixation by pulses to avoid or reduce synthetic fertilizer use. Owing to these traits, minor crops provide supporting and regulating services, with effects on provisioning services (Stokes et al., 2023). Hence the current momentum to reconsider the use of diversification crops in agriculture. However, encouraging diversification-crop production

FIGURE 1
Diversification crops such as chickpea (left, photo credit: Guillaume Martin) can be served in canteen plates (right, photo credit: Romain Marion).

requires addressing the technological and socio-economic lock-ins to their use (Magrini et al., 2016; Meynard et al., 2018), especially low consumption habits.

Multiple agronomic studies (Ladha et al., 2016; Liang et al., 2023) have experimented the diversification of crop rotations, sometimes with minor crops, but they do not link to the necessary changes in food consumption patterns. Few studies (Nette et al., 2016; Saget et al., 2020) have assessed the environmental impacts of substituting major crops (e.g., wheat) foodstuffs with diversification-crop equivalents but they do not address the area needed if this substitution and the related consumption of diversification-crop foodstuffs are being upscaled. Model-based scenario analyses (Ibarrola-Rivas et al., 2022; Kaufmann et al., 2022) are very useful to assess this balance between production and consumption at a large scale, according to hypotheses regarding among other things land use and human diets. However, by focusing on rather broad product categories (e.g., cropland products, monogastric livestock products), such studies do not take into account the role or potential role of diversification crops in more sustainable food systems. Moreover, such studies are focused on society's consumption as a whole and do not focus on the potential leverages offered by sectors that institutions can influence most via public procurement such as institutional catering.

In order to spread in farmers' fields and in canteen plates, we posit that diversification crops must meet the requirements of sustainable food systems, i.e., delivering food in "a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised" (FAO, 2018). This entails economic profitability for farmers, social benefits for farmers, cooks and society at large and a positive or neutral impact on the natural environment. As economic variables are extremely sensitive to value chain formation factors, we excluded profitability issues from this study. We conserved four main conditions to the spread of diversification crops: (i) fostering the establishment of agroecological principles in cropping systems to promote supporting and regulating ecosystem services and (ii) limit the environmental footprint of cropping systems; (iii) limiting work constraints for farmers and cooks; and (iv) providing eaters with sufficient, nutritious and healthy food.

3 Materials and methods

3.1 Definition of an indicator system

A host of evaluation methods can be applied to agricultural systems (Soulé et al., 2021). However, none of them jointly consider the four above-mentioned goals. This is especially the case for assessing the extent to which a diversification crop limits work constraints for both farmers and head cooks. Thus, none of these existing methods are fully suited to assessing the impacts of introducing diversification crops from farmers' fields to canteen plates. We therefore selected indicators from available methods and complemented them with *ad hoc* ones to develop an indicator system that matched our four evaluation goals. Indicators of foods' nutritional value are standard indicators used to describe nutritional composition, as are food productivity indicators based on energy and protein content (Table 1). Indicators capturing the achievement of agroecological and environmental objectives and the work constraints induced for farmers were borrowed from the MASC (Sadok et al., 2009) and IDEA (Zahm et al., 2019) methods. They aligned with the criteria assessed and were clear indicators, easy to gather data for or to estimate—i.e. the necessary data were easily available—, and focused on the crops themselves, not crop rotations or cropping systems. *Ad hoc* indicators of work constraints for cooks had to be established; we defined and discussed them with a group of head cooks and came up with three scores reflecting their priorities when selecting foodstuffs: versatility of use, ease of cooking and conservation.

3.2 Selection of diversification crops and reference crops

The list of possible diversification crops is extensive. To establish a list of candidate crops, we considered the crops grown as part of niche initiatives such as short supply chains (e.g., cooperatives collecting, sorting and packing crop harvests just before their sale by another entity) and direct sales by farmers, assuming they are manageable. Earlier work focused on pioneering institutional catering initiatives (Martin et al., 2022) had already shed light on a number of innovative uses of diversification crops and corresponding foodstuffs, which enabled us to further narrow down the list of crops. Based on this shortlist, we organized a workshop with three head cooks previously surveyed (Martin et al., 2022), who managed three different types of kitchens (cook-serve with a few hundred meals per day, deferred with 1,500 meals per day, and deferred with several thousand meals per day) and who we knew experimented with new cooking practices in their kitchen, particularly using diversification crops and related foodstuffs. We asked them to select the most promising crops and to identify the reference crops and foodstuffs that they would substitute. We also asked them to consider the maximum level of substitution – as it might not be possible to fully substitute reference foodstuffs –, and to provide the current levels of consumption of the reference and diversification foodstuffs in their kitchens.

The head cooks produced three proposals:

- organic chickpea flour to substitute conventional soft wheat flour. The maximum substitution level was deemed to be 30%, as the head cooks pointed out difficulties with eaters accepting meals beyond this level of substitution due to bitterness;
- organic millet to substitute durum wheat semolina. The maximum substitution level was deemed to be 30%, as the head cooks mentioned that they mixed semolina and millet to make it easily acceptable by eaters; and
- squash to substitute potato. The maximum substitution level was deemed to be 30%, as the head cooks mentioned that preparations become too watery beyond this level.

3.3 Data collection

We extracted data on reference crops and related foodstuffs from the scientific literature, French public databases on agricultural practices (Agreste, 2020), and food composition databases (USDA, 2023). The public data on agricultural practices applied to reference crops was provided by 1,866 field surveys on soft wheat, 999 on durum wheat, and 1,060 on potato (Agreste, 2020). Data (e.g., fertilization rates) is provided as average from the entire set of fields surveyed without accounting for the variability related to factors such as soils and climate conditions.

Due to the lack of investment in research and development surrounding diversification crops, we drew from different sources to gather the elementary data necessary to calculate the indicators in Table 1: scientific literature; gray literature; public databases; and interviews with farmers and cooks. Nitrogen fixation and harvest index data were found in scientific articles. The composition of foodstuffs and the current land use they represent were extracted from public databases (Agreste, 2022; USDA, 2023). For each diversification crop, we conducted interviews with 10 farmers all across France. They were randomly selected from a national database (owned by Ecocert France®) of organic farmers, filtering for farmers growing such crops. We conducted the interviews over the phone, using a questionnaire that covered all the stages of crop management (crop establishment, tillage, sowing, fertilization, weeding, irrigation, pesticide application, harvesting, storage, and processing), the complexity of crop management, crop yield, and direct production costs. The interview data were used to create a typical crop management pattern for each crop. We also noted specific feedback on crop problems that the farmers faced. These typical patterns and associated direct costs were triangulated with technical factsheets developed by advisory services (e.g., Marguerie, 2017; Chambre d'Agriculture Centre-Val de Loire, 2019; Mansion-Vaquié et al., 2022), to ensure the consistency of the data used and to fill any gaps in the data. Using these patterns, we estimated average values for the considered indicators namely the cumulative sum of soil perturbations through tillage, freshwater consumption, the number of field interventions, synthetic nitrogen fertilizer use, the number of pesticide applications, and the N balance of crop cycles. As with the farmers, the three head cooks accustomed to preparing foodstuffs using diversification crops were also asked to answer a questionnaire in order to gather data on foodstuffs' versatility of use, cooking complexity, and shelf life.

3.4 Scenario design and assessment

The scenarios are based on the 3.562 billion meals served every year by institutional catering in France. We defined three scenarios for each diversification crop, following a gradient of integration into institutional catering meals and aligning with the guidelines on amounts and frequencies of reference foodstuffs set by the Groupement d'Etude des Marchés en Restauration Collective et de Nutrition [a public-led initiative that provides nutritional

TABLE 1 Indicator system developed to assess the introduction of diversification crops in food systems against reference crops.

Goal	Criterion	Indicator	Unit	Data source
Fostering the establishment of agroecological principles in cropping systems	Nutrient provision	N fixation	kg N/ha/yr	Barbieri et al. (2023)
	Nutrient cycling	Harvest index	No unit	Ayaz et al. (2004); Tailleur and Dauguet (2020)
	Structural stability of the soil	Sum of soil perturbations through tillage	cm	Interviews with farmers and Agreste (2020)
	Crop diversification	Presence in the landscape	%	Agreste (2022)
Limiting the environmental footprint of cropping systems	Water consumption	Freshwater consumption	m^3/ha/yr	Interviews with farmers and Agreste (2020)
	Energy consumption	Number of field interventions	No unit	Interviews with farmers and Agreste (2020)
	Synthetic fertilizer use	Synthetic N fertilizer use	kg N/ha/yr	Interviews with farmers and Agreste (2020)
	Pesticide use	Number of pesticide applications	Units/ha	Interviews with farmers and Agreste (2020)
	Water pollution	N balance of the crop cycle	kg N/ha/yr	Interviews with farmers and Agreste (2020)
Limiting work constraints for farmers and head cooks	Crop management	Crop management complexity	1–3 range	Interviews with farmers
	Economic viability of the crop	Production costs	1–3 range	Interviews with farmers
	Versatility of use of the foodstuff	Range of meal components	1–3 range	Interviews with cooks
	Ease of cooking the foodstuff	Cooking complexity	1–3 range	Interviews with cooks
	Foodstuff conservation	Shelf life	1–3 range	Interviews with cooks
Providing sufficient and nutritious food	Fiber provision	Fiber content	%	USDA (2023)
	Protein provision	Protein content	%	USDA (2023)
	Energetic productivity	Net energy yield	Mcal/ha/yr	Interviews with farmers and Agreste (2020)
	Protein productivity	Net protein yield	Kg protein/ha/yr	Interviews with farmers and Agreste (2020)

recommendations for institutional catering over 20-day periods (Groupe d'étude des marchés de restauration collective et nutrition, 2015)] and the Programme national nutrition santé [a public-led initiative that sets nutritional standards (Ministère de la Santé et de la Prévention, 2023)]:

- Scenario 1 corresponds to low integration: diversification foodstuffs are introduced at the above-mentioned substitution rate and on an occasional basis, that is, in a single recipe of a single component of a meal (i.e., a starter, main dish or dessert) served once every 20 days.
- Scenario 2 corresponds to medium integration: diversification foodstuffs are introduced at the above-mentioned substitution rate and every time the reference foodstuff is used, that is, in several components of a same meal and several times in a 20-day cycle. Data on the amounts of reference products used were provided by the pioneering head cooks interviewed.
- Scenario 3 corresponds to strong integration: this scenario adds to Scenario 2 by integrating diversification foodstuffs into other components of the meal, that is, without substitution and in more innovative, often unusual preparations. Data on the amounts of diversification products used were provided by the pioneering head cooks interviewed.

We calculated the gross amounts of diversification foodstuffs used based on the net amounts, factoring in the data on storage and processing waste provided by the farmers and head cooks. Based on this gross value and the diversification crops' yield, we estimated the agricultural land needed to produce each diversification crop. We organized two workshops to present the scenario outputs to researchers in agronomy and head cooks, respectively. Discussions helped to validate or slightly refine the scenarios to improve their consistency. We assessed the agroecological, environmental, work-related, and nutritional impacts of the introduction of diversification crops by comparing the reference and diversification crop indicators presented in Table 1.

4 Results and discussion

4.1 Main features of the diversification crops and reference crops

Soft wheat is the main winter crop grown in France (4.808 million ha). In conventional cropping systems, it generally follows an oilseed crop and precedes another cereal (Figure 2). The dominant practice remains deep tillage followed by shallow operations to prepare for sowing. Fertilization rates are quite high, with an average of 174 kg N/ha, and pesticides are used seven times over the course of the crop cycle. Irrigation remains a marginal practice. The mean yield is 7.1 t/ha, and farmers and cooperatives master storage well. Likewise, the processing by millers is efficient, with 26% loss as bran.

Chickpea is a spring crop (sown in mid-March in most cases) seldom found in France (about 20,000 ha). Under organic conditions, in most cases it follows a cereal. The soil remains bare without a cover crop until sowing, as farmers consider cover crop termination during winter to be too complex. Chickpea tends to be followed by another cereal. While the soil preparation is similar to that of wheat, far less input is used: it consists of seeds only, as the plant can fix atmospheric nitrogen and is as of yet not subject to significant pest pressure. Weeding is crucial and consists of mechanical interventions with a weed harrow or a cultivator. Yields are limited to 1.1 t/ha. Storage is not problematic. Milling leads to 20% loss.

Durum wheat (303,000 ha in France) under conventional farming is managed in a very similar way to soft wheat, with the exception that fertilization rates are higher by 17 kg N/ha and pesticide use is limited to five applications. Irrigation is also necessary in the Southern part of France, resulting in an average irrigation rate as high as 83 m³/ha on a national scale. Furthermore, harvests are smaller than for soft wheat, with 5.4 t/ha, and milling losses to prepare semolina are higher, amounting to 33%.

Millet is not common in France. Public data indicate about 70,000 ha of "other cereals," including millet, buckwheat, quinoa and so on. It is a summer crop sown in mid-May, usually grown following

	Previous crop	Soil preparation	Sowing/ Planting	Fertilization	Irrigation	Weeding	Pesticide applications	Harvest	Storage	Processing	Next crop
Chickpea	Cereal	Plough Vibrocultor Rot. harrow	Cereal seeder 190 kg/ha Feb.-Mar.	-	-	Weed harrow Cultivator	-	Mechanized 1.1 t/ha Jul.-Aug.	On-farm grain bins	Milling losses: 20%	Cereal
Millet	Cereal	Plough Vibrocultor Rot. harrow	Cereal seeder 32 kg/ha May	-	-	-	-	Mechanized 1.9 t/ha	On-farm grain bins	Shelling losses: 60%	Cereal
Squash	Cereal + green manure	Plough Rot. Harrow Weed harrow	By hand or mechanized 10,000 plants/ha	16 t/ha of manure	1,167 m³/ha	Weed harrow Cultivator	-	Manual 13 t/ha Sept.-Oct.	12°C in palox Losses: 12%	-	Cereal
Soft wheat	Oilseeds	Plough Vibrocultor Rot. harrow	Cereal seeder 120 kg/ha Oct.-Nov.	174 kg N/ha incl. 164 kg synthetic N	15 m³/ha	Weed harrow Herbicide application	6.9	Mechanized 7.1 t/ha Jul.	On-farm grain bins	Milling losses: 26%	Cereal
Durum wheat	Oilseeds	Plough Vibrocultor Rot. harrow	Cereal seeder 120 kg/ha Oct.-Nov.	191 kg N/ha incl. 188 kg synthetic N	83 m³/ha	Weed harrow Herbicide application	4.9	Mechanized 5.4/ha Jul.	On-farm grain bins	Milling losses: 33%	Cereal
Potato	Cereal + green manure	Plough Rot. Harrow	Mechanized 40,000 plants/ha Mar.-Apr.	189 kg N/ha incl. 136 kg synthetic N	516 m³/ha	Cultivator Herbicide application	18.8	Mechanized 43 t/ha Jul.-Aug..	7°C in palox or in pile Losses: 20%	-	Cereal

FIGURE 2
Main features of the crop management patterns for the diversification crops (dark gray, data from interviews with farmers) and reference crops [black, data from Agreste, 2022].

and preceding many different crops (cereals, pulses, oilseeds). It is not preceded by a cover crop, with the soil left bare during winter in most cases. Under organic conditions, the dominant practice for soil preparation is limited to shallow operations, for instance using cover crops and cultivators. Like chickpea, organic millet requires very few inputs – only seeds. Owing to the crop's intrinsic competitive ability, farmers do not control weeds. They just sow and harvest the crop at maturity with a combined harvester. Yields are as high as 1.9 t/ha. Shelling losses lead to 60% loss as bran.

Potato is the second most grown tuber crop in France (19,000 ha) after sugar beets. When grown in a conventional way, it requires a lot of inputs, from seedlings (40,000 seedlings/ha) to water (516 m^3/ha), fertilizers (189 kg N/ha), and pesticides (18.8 applications). However, it is a highly productive spring crop with an average yield of 43 t/ha, and harvesting is facilitated by widespread mechanic harvesters. Storage is complex and requires low temperatures. Losses at this stage are as high as 20%.

Squash is another uncommon summer crop in France (about 9,000 ha). Farmers either sow it with a seeder, generally in early May, or they transplant seedlings (10,000 seedlings/ha) in late May, an operation that can be time consuming. The approach chosen depends on the area grown. Under organic conditions, deep tillage and manure application (16 t/ha) prior to sowing the crop are preferred. While most farmers consider irrigation necessary (1,167 m^3/ha on average), some do not, especially those who sow the crop. Weeds can be controlled using a weed harrow and/or a cultivator. The harvesting involves manual work and is costly but the yield is high, with 13 t/ha. While storage does not necessarily require cooling, losses are unavoidable, at around 12%.

4.2 Scope for introducing diversification crops

In Scenario 1, chickpea flour is introduced in a cake preparation served once every 20 days to replace 30% of soft wheat flour. One portion of cake is considered to contain 15 g of wheat flour. Across the 3.562 billion meals served annually on a national scale, this amounts to 2,671.5 tons of flour, 3,366.0 tons of soft wheat when including milling losses, and 474 ha cropped. A total of 961.7 tons of chickpea flour could therefore be introduced, requiring 874 ha (Figure 3). In Scenario 2, chickpea flour replaces 30% of all the wheat flour in all preparations. According to the head cooks interviewed, 34.7 kg of wheat flour are used for every 10,000 meals, in cakes, sauce binders, and béchamel sauce. On a national scale, this amounts to 12,368.1 tons of flour, 15,583.8 tons of soft wheat, and 2,195 ha when including milling losses. Chickpea could therefore be cropped over 4,048 ha to produce the necessary 4,452.5 tons of chickpea flour. In Scenario 3, chickpea flour is used in the same way as in Scenario 2, but chickpea flour and raw chickpeas are also used in new recipes such as salads, socca and panisses. The head cooks interviewed reported that this high level of integration involves 25 kg of chickpea flour and 34.7 kg of raw chickpea for every 10,000 meals. When including milling losses, this adds up to a total of 23,054.0 tons of raw chickpea, which corresponds to 20,958 ha.

In Scenario 1, millet replaces 30% of durum wheat semolina, which is served once every 20 days at a rate of 30 g/eater. Annual semolina needs on a national scale amount to 5,343.0 tons, which corresponds to 7,079.5 tons of durum wheat. Shelled millet could be introduced at an annual rate of 1,602.9 tons, which represents 2,564.6 tons of raw millet and 1,350 ha. In Scenario 2, millet replaces 30% of durum wheat semolina every time it is served. Semolina consumption is similar to wheat flour consumption – 34.7 kg of wheat flour is used for every 10,000 meals. Thus, 3,710.4 tons of shelled millet would be required on a national scale, or 3,125 ha of millet crop when taking shelling losses into account. In Scenario 3, as for chickpea, millet is used to partially replace semolina but it is also introduced through a new recipe: a cake containing 8 g of millet per portion, served twice in every 20-day cycle. This increases the amount of raw millet needed to 10,496.0 tons and the crop area to 5,524 ha.

In Scenario 1, squash is used in a soup served twice in every 20-day cycle, replacing 30% of the potato used so as to sufficiently

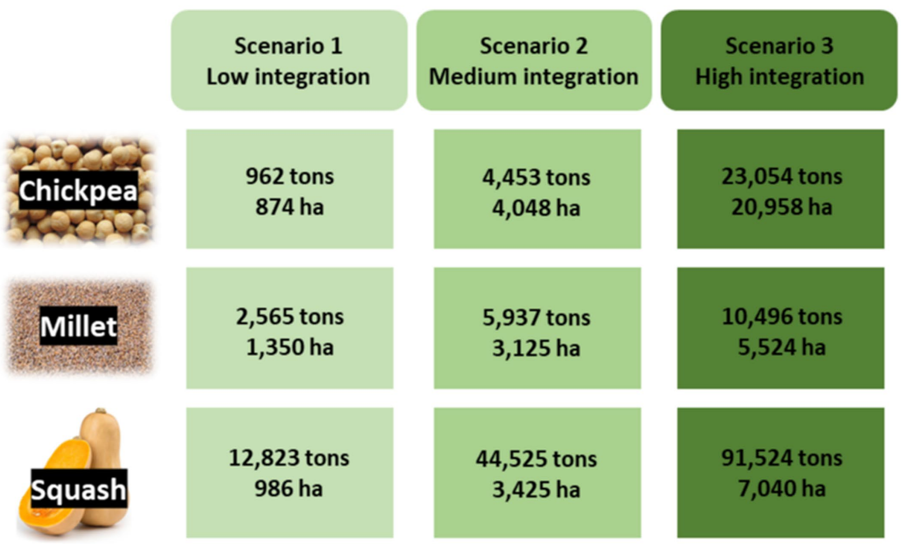

FIGURE 3
Overview of the raw amounts and area needed for each diversification crop based on its level of integration into the meals.

preserve the texture of the soup and ensure a balanced nutritional content. This soup uses 100 g of potato per eater, which corresponds to 35,620.0 tons of potato on a national scale. Thus, 10,686.0 tons of squash are needed, which requires producing 12,823.2 tons over a surface area of 986 ha when taking losses from storage into account. In Scenario 2, squash is used to replace 30% of all the potatoes used. The head cooks use 100 kg of potatoes for every 10,000 meals, that is, 123,680.6 tons over a year on a national scale. This translates into a total of 3,425 ha of squash to produce the necessary 44,525.0 tons before storage loss. In Scenario 3, squash is further integrated, with its introduction through new recipes for starters, main dishes, and desserts, leading to the consumption of 110 kg for every 10,000 meals. The necessary amount of squash, factoring in storage loss, is 91,523.6 tons, representing 7,040 ha.

4.3 Impacts of the introduction of diversification crops

The three diversification crops considered foster the establishment of agroecological principles in cropping systems (Figure 4). As a pulse, chickpea provides nitrogen for the next crop (29 kg/ha). Chickpea and millet have slightly lower harvest indexes compared to soft wheat and durum wheat respectively, which results in higher shares of crop residue returning to the soil and enhanced nutrient cycling with proportionally less outflows. All three diversification crops require fewer tillage interventions compared to the reference crops, leading to lower cumulated sums of soil perturbations, especially in the case of squash (30 cm vs. 75 cm for potato), and better preservation of the soil structure. Overall, these three crops are minor crops in France's landscape, covering less than 0.1% of farmland. Extending their area can thus contribute to landscape heterogeneity, a key factor for biological pest control.

All three diversification crops reduce the environmental footprint of cropping systems. They all require fewer field interventions (6 to 8 vs. 12.6 to 24 for reference crops) and no synthetic inputs – neither N fertilizers nor pesticides –, while potato, for instance, is sprayed 18.8 times per crop cycle. Still, whereas the N balances of chickpea and millet indicate a drastic reduction of N loss, in the case of squash, since organic N fertilization is high, the N balance of the crop is slightly poorer (+ 11 kg N/ha compared to potato). Millet even has a negative balance, indicating soil mining. The same can be observed with freshwater consumption. While chickpea and millet do not require irrigation, squash receives more than twice the amount of water that potato does (1,167 vs. 516 m3/ha), although some farmers have managed to avoid irrigation and still obtain high yields.

Diversification crops do not generate work constraints for farmers. All three diversification crops are easy to manage—even easier than the reference crop in the case of millet and squash. Such crops do not require additional machinery and can be managed with the same machinery used for major crops. Production costs are lower than those of the reference crops in the case of chickpea and millet, as these crops are rustic and input costs are limited to seeds, whereas the reference crops considered are synthetic N fertilizer- and pesticide-intensive. For squash and potato, these costs are similar. In kitchens, according to the head cooks we interviewed, the diversification products are as easy to store and use as the reference crops. They even afford greater versatility of use in the case of millet and squash, as they can be added to desserts, which is far less the case for durum wheat and potato.

Goal	Criterion	Indicator	Chickpea	Soft wheat	Variation	Millet	Durum wheat	Variation	Squash	Potato	Variation
Favor the establishment of agroecological principles in cropping systems	Nutrient provision	N fixation (kg/ha)	29	0	↗	0	0	→	0	0	→
	Nutrient cycling	Harvest index	0.45	0.49	↘	0.42	0.44	↘	NA	NA	NA
	Structural stability of the soil	Sum of soil perturbations (cm)	23	35	↘	32	35	↘	30	75	↘
	Crop diversification	Presence in the landscape (%)	<0.1	28.0	↘	<0.1	2.1	↘	<0.1	1.1	↘
Limit the environmental footprint of cropping systems	Water consumption	Freshwater consumption (m^3/ha)	0	15	↘	0	83	↘	1167	516	↗
	Energy consumption	Number of field interventions	6	14.4	↘	6	12.6	↘	8	24	↘
	Synthetic fertilizer use	Synthetic N fertilizer use (kg N/ha)	0	164	↘	0	188	↘	0	136	↘
	Pesticide use	Number of pesticide applications	0	6.9	↘	0	4.9	↘	0	18.8	↘
	Water pollution	N balance of the crop cycle (kg N/ha)	+9	+57	↘	-47	+55	↘	+57	+46	↗
Limit work constraints for farmers and head cooks	Crop management	Crop management complexity	Easy	Easy	→	Easy	Mid	↘	Easy	Mid	↘
	Economic viability of the crop	Crop production costs	Low	High	↘	Low	High	↘	High	High	→
	Versatility of use of the foodstuff	Range of meal components	High	High	→	High	Mid	↗	High	Mid	↗
	Ease of cooking the foodstuff	Cooking complexity	Low	Low	→	Low	Low	→	Low	Low	→
	Foodstuff conservation	Duration of conservation	Mid	Mid	→	High	High	→	Mid	Mid	→
Provide sufficient and nutritious food	Fiber provision	Fiber content (%)	10.8	2.7	↗	8.5	3.9	↗	2.0	2.1	↘
	Protein provision	Protein content (%)	22.4	10.3	↗	11.0	12.7	↘	1.0	2.0	↘
	Energetic productivity	Net energy yield (Mcal/ha)	4,020.8	18,494.1	↘	2,857.6	12,684.6	↘	2,963.0	27,692.0	↘
	Protein productivity	Net protein yield (kg protein/ha)	250.9	522.2	↘	76.0	437.4	↘	125.8	743.0	↘

FIGURE 4
Comparison between the reference and diversification crops. Data are averages from public data for the reference crops (from 1,866 field surveys on soft wheat, 999 on durum wheat, and 1,060 on potato; Agreste, 2020) and from 10 farmer interviews for each diversification crop (see Section 3.3 for all details). Arrows indicate the direction of change, while their colors—dark green, light green, orange, blue, and red—represent improvement, slight improvement, stability, a slight degradation, and a significant degradation, respectively.

The main drawback of diversification crops is that they produce significantly less food per unit area than the reference crops. Their energetic productivity rate ranges from 2,857.6 Mcal/ha/yr. (in the case of millet) to 4,020.8 Mcal/ha/yr. (in the case of chickpea), which is lower than the values found for the reference crops. The same applies to protein productivity, with productivity reduction factors in the range of 76.0 to 250.9 kg protein/ha/yr. Even chickpea, despite being a pulse, produces less protein per hectare than soft wheat, which has half the protein content but a much higher biomass production rate. As a consequence, the introduction of diversification crops involves severe cuts in the production of the reference crops. For example, producing 23,054.0 tons of chickpea in Scenario 3 requires 20,958 ha and reduces the production of soft wheat by 148,803.4 tons. Moreover, fiber provision is only improved in the case of wheat flour substitution with chickpea flour and durum wheat semolina substitution with millet. As for protein provision, it is only improved in the case of chickpea flour. In the case of squash, the fiber and protein contents are reduced compared to potato, but both crops have overall low fiber and protein contents. Micronutrients (e.g., beta carotene) are the only nutritional parameter that improves in the case of substitution with squash.

4.4 Institutional catering: a lever to support the spread of diversification crops

The use of diversification crops is being reconsidered, both in agriculture and in the food system at large. Crop diversification pathways have been observed (Revoyron et al., 2022), but their sustainability hinges on establishing stable outlets (Mawois et al., 2019). Our scenario analysis based on 3,562 billion meals served every year at national scale shows that there is real potential for creating such outlets by introducing products from diversification crops in institutional catering. While chickpea covers about 20,000 ha in France, we estimated that its introduction in institutional catering could require another 874 to 20,958 ha, depending on the level of integration into meals. Just one portion of cake served once every 20 days with 30% chickpea flour creates an outlet for 874 ha. Similar figures were found for millet and squash in the three scenarios studied. These findings show the multiplier effect of institutional catering on the food demand that needs to be met by farmers and other agricultural supply chain actors. This is the reason why public procurement within institutional catering is often presented as a lever for mass change from farm to fork (Perez-Neira et al., 2021; Swensson et al., 2021; Bizarro and Ferreiro, 2022). While this sector is often depicted as having a highly negative environmental impact (e.g., García-Herrero et al., 2021), sustainability transitions have been shown to be feasible in all types of institutional catering establishments (Martin et al., 2022), and sustainability initiatives have proven efficient for supporting change toward more sustainable consumption behavior (Sullivan et al., 2021). Institutional catering can thus be regarded as a credible solution to create outlets for the spread of diversification crops although that would require investments into value chain formation, which were beyond the scope of that paper.

Earlier findings have shown that farmers are able to implement crop diversification (Revoyron et al., 2022) and that cooks are able to change their practices in order to achieve greater sustainability (Martin et al., 2022). We have also found that the integration of selected diversification crops in fields and of products made from such crops within kitchens appear fully feasible for farmers and cooks in terms of management complexity and workload. Work-related factors are often major barriers to change in agriculture (Malanski et al., 2019) and in the catering sector (Fitzgerald et al., 2016). Agronomic knowledge to manage diversification crops has often been lost (Magrini et al., 2016; Meynard et al., 2018), as has the knowledge needed (e.g., recipes) to cook products made from diversification crops (Magrini et al., 2021). These issues generate uncertainties for farmers surrounding crop management, yield potential, workload, and expected prices (Marra et al., 2003) and, for cooks, around preparation, workload and acceptance by eaters (Magrini et al., 2021). But such hindrances can be preempted, reducing risk aversion by appropriately selecting the crop species that are easiest to adopt and manage, as well as products made from such species that do not entail additional work in the kitchen. These findings illustrate the need to consider crop diversification as a desirable option if and only if the crops introduced and their suitability are taken into account from farm to fork, so as to select crops that can be introduced as easily as possible within the current sociotechnical system. This is already happening with farmers growing chickpea often between a cereal and an oilseed crop, and serving canteens with chickpea flour in the Southwest of France in previously surveyed pioneering initiatives (Martin et al., 2022).

In this article, we focused on farmers and cooks, but the diversification crop products considered potentially affect a wider range of operators involved in foodstuff collection, sorting, processing and packing. The spread of diversification crops would clearly challenge their current practices, as collection companies, for instance, have thus far preferred a centralized strategy focused on a few crops, and diversification crops would require more complex logistics (Magrini et al., 2016; Meynard et al., 2018). Only by integrating this whole chain could sustainable food supply chains be achieved (Jordan et al., 2023), linking on-farm crop production to end-use markets with the support of relevant infrastructure, policy, finance, and Research and Development. This calls for interconnected changes or coupled innovations both upstream (e.g., breeding efforts suited to diversification crops) and downstream (e.g., new quality standards for diversification crop products; Meynard et al., 2017), in turn raising the need for participatory design approaches involving such a diverse range of stakeholders.

4.5 Diversification crops for institutional catering: a sustainable option but still requiring further research

As other authors have already suggested, the spread of diversification crops could both strengthen the agroecology of cropping systems and limit their environmental footprint (Zhang et al., 2018; Mawois et al., 2019). The overarching reason for this is that diversification crops require little input. One could argue that we compared diversification crops managed following organic specifications to reference crops managed conventionally. Still, the estimated differences between crops would apply even in the case of conventional management of both the diversification crops and the reference crops: owing to their intrinsic features (N-fixation ability, low harvest index, etc.), diversification crops promote nutrient provision and recycling. Because they are not very present in the French landscape, they are likely to experience lower pest pressure. And because diversification crops have been neglected by Research and Development, recommendations for their fertilization are lacking – as are authorized pesticides, for the number of diversification crops without matching plant protection solutions has increased in recent years (Lamichhane et al., 2015). Thus, input use remains very low even under conventional management, therefore not undermining the potential for the spread of diversification crops. This means that there is value in promoting diversification crops in both the conventional and organic sectors.

The main priority needs to be investment into improving diversification crops' potential productivity, which remains far beneath that of reference crops. This is mainly due to the lack of Research and Development on minor crops that has led their yields to stagnate or even decline over time, as Peltonen-Sainio et al. (2016) have shown in the case of Finland. This particularly applies to breeding efforts. In the 1970s, more than 100 species were bred by INRA, the French National Research Institute for Agriculture, Food and the Environment. Less than 10 species were still studied in the 2000s (Bonneuil and Thomas, 2009). Moreover, farmers lack technical recommendations for the management of diversification crops. This is also why surveyed farmers' answers regarding certain practices, such as soil preparation, revealed a high heterogeneity that could not be attributed to soil-climate conditions. Faced with these issues, participatory breeding (Ceccarelli and Grando, 2020) and on-farm experimentation (Toffolini and Jeuffroy, 2022) with diversification crops offers ways to produce locally relevant genetic material and knowledge and to put innovation into practice *in situ* with a view to inciting more farmers to grow such crops. Such breeding and agronomic efforts could allow for closing the food production gap induced by the substitution of reference crop products with diversification crop products.

Beyond productivity gaps, diversification crops provide partial answers to several nutrition issues currently challenging food systems in Europe. Research has shown that 85% of French adults do not eat enough fiber (at least 25 g/day), which increases risks of inflammatory bowel disease (IARC, 2018). Using chickpea flour and millet as substitutes of soft wheat flour and durum wheat semolina is a way to increase fiber intake. The proposed substitutions also contribute to strengthening dietary diversity, which is key to healthier, more balanced diets (Ruel, 2003). Chickpea flour allows for replacing a source of cereal, one of the main components of European diets. Squash allows for increasing the intake of vegetables that are often lacking in European diets compared to tubers. Specific micronutrients are also found in diversification crops. This is the case of squash, which is high in beta-carotene and vitamin C (USDA, 2023), two key micronutrients for human metabolism and immunity. Thus, the nutritional value of diversification crops ought to be considered across a wider range of parameters than those usually taken into account with reference crops.

5 Conclusion

This is the first article to explore the scope for introducing diversification crops and associated products from farmers' fields to canteen plates. We show the multiplier effect of institutional catering even with very low levels of integration in meals, raising the need for hundreds of additional hectares of minor crops. Expanding diversification crops on farms would strengthen their agroecology and reduce their environmental footprint without entailing additional work for farmers. These findings have implications for several stakeholders. They show policy makers the need to make consistent decisions to incentivize change at both the production and consumption stages, and that institutional catering is a real lever to support on-farm change. They also show cooks their own concrete impacts on agriculture through very basic changes in practices. Finally, they show farmers why they should further target institutional catering procurement to sustain their crop diversification pathways.

Data availability statement

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

Author contributions

MA: Investigation, Writing – review & editing. LP: Conceptualization, Methodology, Supervision, Writing – review & editing. GM: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The authors acknowledge the support of Agropolis Foundation via the Louis Malassis Prize.

Acknowledgments

The authors thank all the farmers, advisors, researchers and head cooks interviewed for their time and for sharing their expertise.

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.

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