How to (re)diversify agri-food systems: the case of field crops in Europe

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Since the 1960s, in parallel with the sharp fall in the number of farms, a dual specialisation of agricultural systems has taken place during the agricultural modernisation phase: regional specialisation, with a reduction in livestock and mixed farming, and specialisation within plant and animal production systems. Agriculture has thus gradually specialised in terms of production systems and of number of species grown, with the aim of increasing the economic efficiency of agrifood systems. This modernisation phase made it possible to achieve the production targets set for agriculture at the time, but it also had negative impacts on the environment and of human health. The transition of European agriculture towards systems based on biodiversity and relying on ecosystem services is a major way to meet the challenges of balancing production and environmental protection. Crop diversification increases biodiversity within fields, provides numerous ecosystem services and helps close nutrient cycles, while replacing chemical inputs. However, despite these benefits and stated political objectives, specialisation is still at work.

The reason for this is the existence of numerous interconnected barriers, not only technical but also organisational and institutional (agricultural policies, regulation, research, education, etc.), resulting from the alignment and high degree of coherence of the sociotechnical regime put in place during the modernisation phase. This 'lock-in' must be overcome by a deep transformation of the sociotechnical system that governs today's agrifood systems. Unlocking strategies include (i) supporting stakeholders in managing transformation rather than providing ready-to-use solutions, (ii) reorienting research priorities and the way research is managed and organized to support diversification, (iii) revising exclusive commodity chain logics and aligning strategies within agrifood commodity chains, as well as (iv) radically revising public policies and regulations to encourage the transformation of agrifood systems.

Keywords : crop diversification, sociotechnical lock-in, design, sustainability

Introduction

Over the last few decades, European agriculture has gradually become specialised at farm level and around a small number of cultivated species (dominant crops), with the aim of increasing the economic efficiency of agri-food systems. This specialisation of production systems, which began during the agricultural modernisation phase in the 1960s, can be seen in particular in the greater Paris basin: regional specialisation with the disappearance of mixed farming and livestock resulting in a sharp reduction in grassland in favour of arable crops on the one hand, and the simplification of cropping systems and a shortening of rotations, illustrated by the sharp increase in rapeseed/wheat/barley rotations (Schott *et al.*, 2010), on the other hand. This trend can also be seen at European level, with little diversification in cropping systems (monocultures and short rotations) and the associated - often globalised - value chains dominating European agri-food systems.

This modernisation phase has undoubtedly made it possible to achieve the ambitious production targets set for agriculture at the time, but it has also had negative impacts on the environment, ecosystems and human health (IPBES, 2019), even though Europe is self-sufficient overall. Agricultural production systems are not very diversified and are largely dependent on the use of external inputs (synthetic fertilisers and pesticides), which contributes to soil degradation, air and water pollution, greenhouse gas emissions and the erosion of biodiversity.

A transition in European agriculture from current cropping systems dependent on external inputs to systems based on biodiversity and relying more on ecosystem services, consistent with the development of local and short value chains, is a major way of meeting the challenges of balancing production and preservation of the environment (Tibi *et al.*, 2022).

In this context, crop diversification is a major lever for increasing biodiversity in fields, promoting ecosystem services, reducing greenhouse gas emissions, helping to close nutrient cycles, and reducing the use of chemical inputs, which is the objective of the European Commission's Green Pact (European Commission, 2019). However, despite the expected benefits of diversifying cropping systems, specialisation is still at work and ongoing. This is due to a number of interconnected technical, organisational and institutional barriers, which need to be analysed and overcome by radically transforming the socio-technical system that governs current agri-food systems.

After outlining the various obstacles to diversification, the article stresses the need for a systemic approach and puts forward a number of proposals for transforming the socio-technical system, which need to be tackled simultaneously and in a coordinated manner.

1. Crop diversification is a major lever for delivering ecosystem services.

Numerous studies have been conducted worldwide on the impact of different forms of diversification. Recent meta-analyses (Beillouin *et al*., 2019; Tamburini *et al*., 2020; Beillouin *et al.*, 2021a) report the effects of agricultural diversification on a range of ecosystem services such as production, soil fertility, carbon storage, adaptation to climate change and pollination (Figure 1). The vast majority of the effects reported are positive, including on overall food production on a given area. The combination of several diversification levers leads to greater effects. However, the results obtained are highly variable and difficult to interpret in the context of these meta-analyses, given the diversity of soil and climate conditions, crops and cropping systems considered on this global scale.

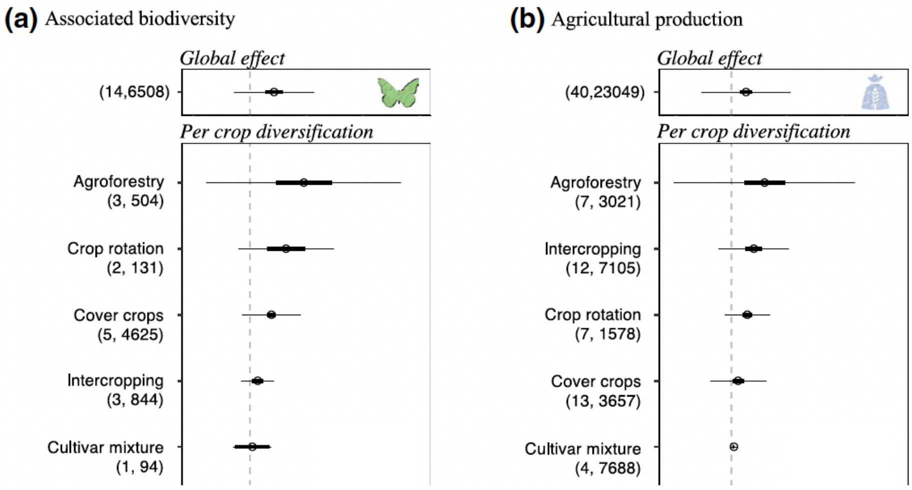


Figure 1: Summary of studies analysed by Makowski *et al* (2021) on the impacts of crop diversification strategies on biodiversity (Fig. 1a) and production (Fig 1b). The results represent the ratio between diversified systems and reference systems (the dotted vertical line corresponds to a ratio of 1 - no difference). The dots, thick lines and thin lines represent the estimated median effect, 95% confidence intervals (CI) and 95% prediction intervals (PI). They are reported for all diversification strategies and for each of them separately. The number of meta-analyses and experiments used are indicated in brackets under each category.

As a consequence, despite the benefits of diversification and the political objectives set out several years ago, specialisation is still highly dominant in France and Europe. Wheat, barley, maize and rapeseed still occupy around 60% of arable land in France, and the percentage of wheat planted after wheat is increasing despite the negative impact on yield (wheat after wheat yields 0.6 to 0.8 tons less than after rapeseed or after pea, Schneider *et al*., 2010; Bennett *et al*., 2012) but also the risks of leaching, the efficiency of nitrogen fertiliser use and greenhouse gas emissions (Beillouin *et al.*, 2021b).

2. Why has diversification still not been adopted?

2.1. Not all diversification strategies are good

Numerous experiments have been carried out in recent years to assess the impact of different forms of diversification on a multi-criteria basis (Alletto *et al.*, 2022; Viguier *et al.*, 2022; Pelzer *et al.*, 2012a). In the experimental network set up by the European DiverIMPACTS project (https://www.diverimpacts.net/field-experiments.html), the conventional reference system at local level was compared with one or several diversified systems (longer rotations, intercropping, sowing under cover, introduction of grain legumes) over three or four years.

As with the meta-analyses cited above, on average, there has been an improvement in environmental indicators such as greenhouse gas emissions linked to nitrogen fertilisation and pesticide use, while economic variables linked to production tend to have deteriorated (Figure 2a). There is considerable variability in the results, and many trade-off. There exist diversified systems whose performance, including environmental performance, is poorer than the one of reference systems. There are many reasons for this. From an agronomic point of view, replacing or introducing a new crop does not in itself necessarily guarantee an improvement in performance, not all diversification strategies are suited to all local conditions (soil and climate and market outlets) and input levels and crop management in general are not always adjusted at the cropping system level. Indeed, conventional crop management is rarely adapted to the introduction of new species into the rotation: for example, the dose of nitrogen applied to a cereal crop after a legume crop is often not adjusted. In terms of technical knowledge, farmers and advisers are less familiar with diversification crops and strategies. Furthermore, diversification crops lack competitiveness due to lower investment, while, in contrast, current simplified cropping systems have benefited from decades of R&D efforts, and research priorities (particularly in plant breeding) are still generally crop-specific , though major gains are possible by taking into account the characteristics that make them suitable for diversification (e.g. suitability for combining cereals and legumes).

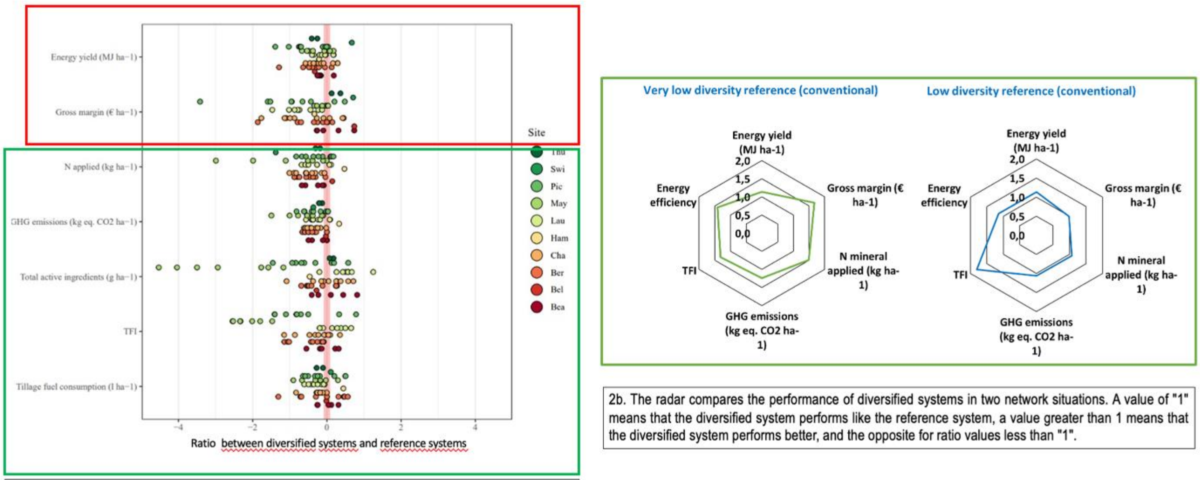


Figure 2a. The vertical line '0' indicates no difference, a positive value indicates a higher value for the diversified system than the reference system, a negative value the opposite.

2b. The radar compares the performance of diversified systems in two network situations. A value of "1" means that the diversified system performs like the reference system, a value greater than 1 means that the diversified system performs better, and the opposite for ratio values less than "1".

Figure 2. Variability in the performance of diversified systems compared with reference systems in the DiverIMPACTS experimental network.

However, in most of the situations studied in the DiverIMPACTS project (Figure 2b), some diversification strategies that improve both economic and environmental indicators have been identified, revealing the possibility of reducing the use of inputs and limiting greenhouse gas emissions, while maintaining or even improving economic performance. This is difficult and requires the diversification strategy to be adapted to the local context, but seems possiblein many situations.

2.2. There are many socio-technical obstacles to diversification

Diversification is constrained by a range of interconnected technical, organisational and institutional barriers along value chains (Meynard *et al*., 2013, 2018) including:

- There has an accumulated under-investment in research for diversification crops,e.g., plant breeding and crop protection, due to their limited market.Genetic improvement is slow and there are few, if any, protection solutions, making them less competitive than dominant crops. In addition, the various forms of diversification (intercropping, sowing under cover) are not taken into account in current genetic improvement strategies, which are still often based on the "one pure crop per year" approach;
- Farmers and their advisers lack knowledge, expertise and feedback on less developed crops or crop combinations;
- The beneficial effects of minor crops in the rotation are generally not taken into account by farmers: for example, the yield gain from wheat following peas is “allocated” to wheat in gross margin calculations, and the possibility of reducing nitrogen fertilisation is not always exploited (Sodjahin *et al*., 2022). Indeed, in farm accounting systems, gross margins are calculated on a crop-by-crop basis (sometimes with input costs distributed evenly between crops), which does not allow to highlight the economic benefits of diversification crops (which often have lower gross income but also lower costs);
- Logistics to handle crop diversification are often more complex with the increase in the number of crops to be collected, and in smaller volumes than the dominant crops. Sorting at harvest is still necessary for mixtures of species, as current supply chains are still monospecific;
- Outlets remain underdeveloped due to a lack of investment in the processing sector.

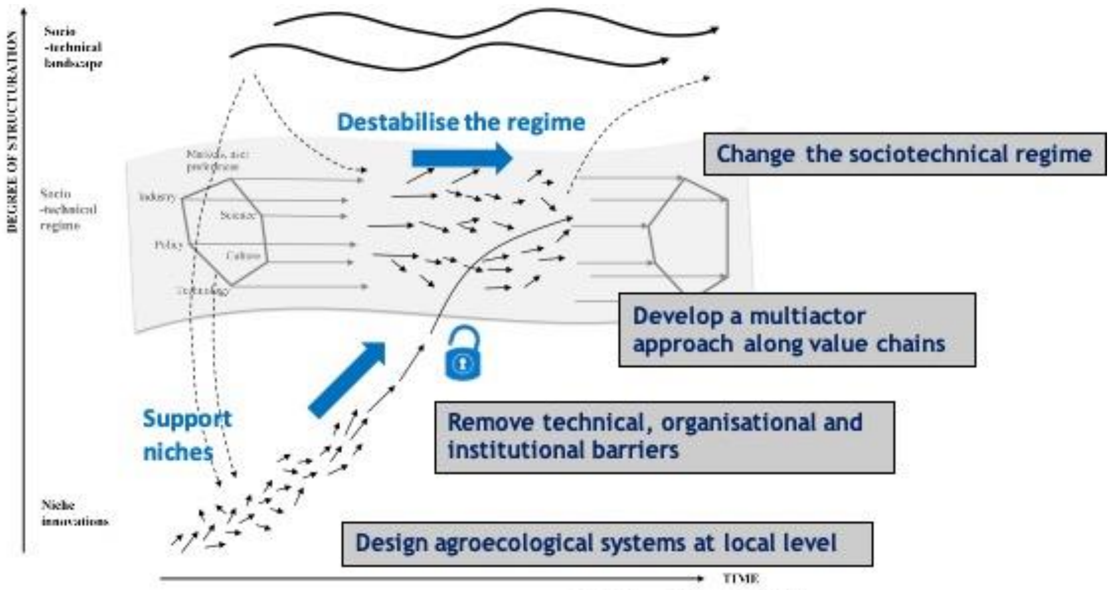
In addition to these technical and organisational barriers, there existnstitutional barriers within the socio-technical system (Meynard *et al*., 2013, 2018), i.e. the institutional arrangements that govern agri-food systems:

- Agricultural policies remain highly sectoral and the Common Agricultural Policy has long favoured the dominant crops;
- Most regulations were built around models that established the "single-variety pure annual crop" as the standard for field crops and used criteria for registering varieties that were adapted to the dominant models;
- Research, both private and public, works mainly on those dominant crops, which are well mastered and already well studied, making it easier to acquire new scientific knowledge and develop innovations;
- Diversification implies moving away from the "one crop, one problem, one solution" model, which represents a paradigm shift that advisory bodies and technical training programmes did not take into account until recently and are only slowly integrating.

In this way, the socio-technical system has gradually become organised around the dominant systems, reinforcing their economic efficiency and coherence according to the logic of increasing returns to adoption. This has led to an unintended socio-technical lock-in in which all the players are jointlyresponsible, but from which it is now difficult to escape.

2.3. Only a systems approach can bring about transformation

Transforming agri-food systems therefore requires both adapting systems to local conditions (soil and climate, markets, farmers' preferences) and changing the 'rules of the game' (the socio-technical regime), i.e. the set of institutional arrangements that have been put in place to support current production models. As illustrated in Figure 3, adapted from Geels (2002), the development of innovative alternative systems, or 'niches', needs to be supported by research and public authorities, and this has developed significantly in recent years in certain disciplines. However, while this is necessary, it is not sufficient, as the development of these alternatives is hampered not only by the agronomic and genetic aspects associated with the new species introduced, but also by the socio-technical system. This has been built up in a context where priority has been given to increasing production and productivity per hectare, within the framework of specialised sectors, and has gradually been optimised around systems that are not very diversified. One also needs to ensure that this socio-technical regime - the rules of the game (policy, regulation, research, education) - adapts to the new challenges of the agro-ecological transition, or at least no longer favours the production systems that currently dominate.



(adapted from Olivier et al., 2018 who adapted it from Geels, 2002)

Figure 3: Objectives of the H2020 DiverIMPACTS project in the context of transition theory and socio-technical lock-in. *Alternative ('niche') innovations need to be supported by research and appropriate policies, but their adoption is also limited by the 'rules of the game' (strategies, industrial investment, agricultural policies, education, advice, research) put in place during the agricultural modernisation phase, which favoured the 'dominant' model. It is therefore necessary to change these rules of the game (destabilise the current system) to allow a genuine agro-ecological transition.*

A systems approach is essential if the actions to be taken at these different levels are to be coordinated and simultaneous: co-design of cropping systems at field level, coordination/coupling of innovations within value chains, mobilisation, involvement and coordination of all stakeholders, and gradual transformation of the socio-technical system.

Its practicalimplementation requires a profound transformation of our activities, organisations and existing institutions.

3. How to initiate this systemic transformation

The systemic transformation that is required is necessarily dynamic. The rules of the game must evolve from the existing system to produce a new socio-technical system adapted to the challenges of the agro-ecological transition, which is a considerable challenge that requires long-term thinking. The step-by-step design approach described for cropping systems (Meynard *et al.*, 2023) could and should be adapted to transform the socio-technical system. Based on the DiverIMPACTS case studies, we can suggest several recommendations.

3.1. Acknowledge that there is not one, but many ways of driving diversification

As emphasised above, there are no ready-to-use solutions anymore and cropdiversification is good in itself. Diversification paths must therefore be differentiated according to local contexts, markets and farmers' preferences, as observed in existing diversification situations (Revoyron *et al.*, 2022). It is also essential to adapt support measures and public policies to this diversity, while policies are still too uniform, particularly at European and national level.

3.2. Moving away from a crop-specific approach towards a systems approach

On the basis of DiverIMPACTS experiments, we have been able to draw some general conclusions about the rules for managing diversification at farmer level, which still need to be adapted to suit different contexts:

- Maintain dominant crops that perform well and are well managed byfarmer,s while adapting their management to the other crops present in the rotation; indeed, these dominant crops have been the focus of major efforts over the last few decades and will remain competitive in the short term;
- Introduce diversification crops that provide ecosystem services:
    - Legumes to introduce nitrogen into the cropping system as a substitute for synthetic fertilisers and thus reduce greenhouse gas emissions;
    - “Cleaning" species (such as hemp) to reduce weed pressure;
    - More generally, cover crops or service plants.
- Implement "compensation strategies", insofar as diversification species are still often less profitable than major crops (mainly because they have received less investment in research):
    - Introduce intercropping that increase overall productivity: cereal-legume associations produce more than separate crops with a "Land-Equivalent Ratio" greater than 1 (Bedoussac *et al.*, 2015);
    - Sowing a second cash crop under cover to improve the economic balance of the rotation (Pitchers *et al.*, 2023).

These rules need to be adapted to the pedoclimatic context, but they also need to evolve over time to cope with the greater uncertainties that farmers face (climate change, volatile markets, high variability linked to external inputs reduction). In this context, it is vital to capitalise on learning over time to improve diversified systems step by step (Meynard *et al.*, 2023).
Given the need for cropping systems to be locally adaptable, their greater dependence on local soil and climate conditions, and the increased uncertainty linked to climate change and market instability, there is no longer an optimal system that meets all challenges, no "turnkey" solutions or prescriptive cropping systems to be deployed in the same way as technical innovations at crop level have been in the past. Diversification is a non-linear process that is driven dynamically, with no a priori definition of alternative target systems (Figure 4).

3.3. Renewing knowledge production systems

Current research is still marked by a process of designing and disseminating innovations that is strongly driven by a fairly top-down vision of Research and Development. These approaches that were valid in a context where cropping systems were less dependent on local environmental conditions, due to the high use of external inputs, and a socio-economic and soil-climate context that was relatively stable over time, are now falling apart.
It is no longer possible to develop solutions, even if they are systemic, in a given place and at a given time,and to deploy them everywhere. The notion of “technical references” is being challenged by this paradigm shift. Designing more robust systems, supporting farmers who are constantly innovating and adapting their practices to speed up this transition, understanding why innovations are successful in one place and learning from them to design fit-for-purpose solutions, opens up new avenues that have yet to be explored: tracking down innovations (Salembier *et al* 2021), supporting on-farm experimentation (Catalogna *et al.*, 2018, 2022), formalising and structuring generative knowledge (Quinio *et al.*, 2022a, 2022b).

3.4. Propose tools to manage diversification

While the production of references on diversified cropping systems is essential for understanding the processes at work, their implementation on each farm generally results in highly variable performances depending on the specific constraints and preferences of the farmers. The introduction of multi-criteria assessment tools helps to put this into context and to steer diversification paths adapted to each situation. Such tools are already available for use by commodity chains and research and development (Craheix *et al*., 2012; Pelzer *et al*., 2012b), but they need to be expanded to include new criteria, in particular the nutritional dimension of agriculture, the robustness of cropping systems and the autonomy of farms, as well as indirect impacts (rebound effects) on different scales of time and space.

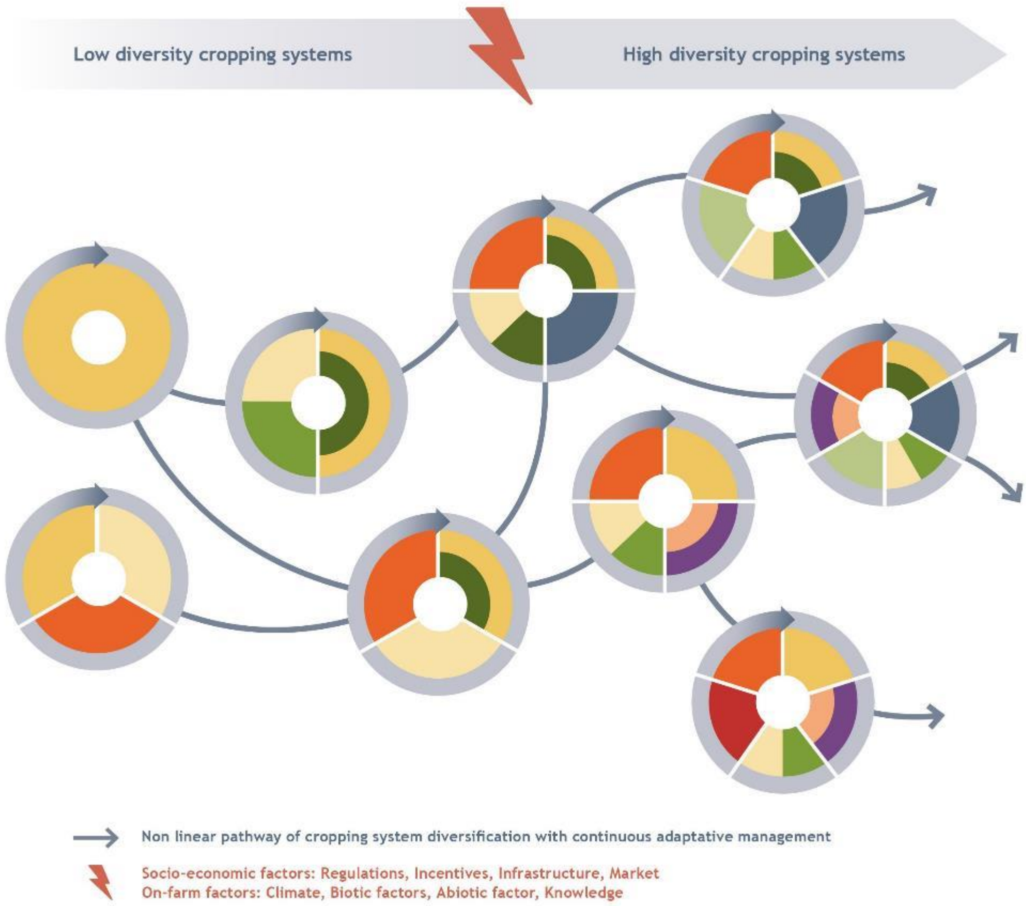


Figure 4: Schematic representation of the agri-food transition dynamic. Each symbol represents a more or less diversified cropping system (new crops, longer rotations, intercropping, etc). In the context of the agro-ecological transition, crop diversification means, starting from reference systems that are little or non-diversified, exploring the extent to which the environmental, social and economic performance of production systems can be improved by combining diversification strategies. This is a dynamic process, with trajectories that constantly adapt to local constraints (soil, preferences) and external constraints (climate, markets).

3.5. Encouraging coupled innovations

As emphasised in Meynard *et al* (2017), diversifying agri-food systems means coupling innovations at production and processing levels. This need is well illustrated by the development of the wheat-lentil association by the Qualisol cooperative (Figure 5). From the agronomic innovation linked to the association between a cereal and a legume (the lentil uses the wheat as a support and the wheat benefits from the nitrogen of the legume) to the development of its own commercial brand, via a price guarantee to secure the sector or the revision of accounting rules to take better account of the effects linked to inetrcropping, several types of levers need to be mobilised and coordinated to bring about an agronomic innovation.

Figure 5: Combination of different types of innovation in the development of a lentil supply chain at the **QUALISOL** cooperative (Meynard *et al.*, 2017, based on the LEGITIMES project).

3.6. Redirecting public policy

Generally speaking, the agro-ecological transition and the achievement of the objectives of the European Commission's Green Deal require significant changes to the Common Agricultural Policy (Guyomard *et al.*, 2020). With regard to measures facilitating the diversification of value chains, coordination and collaboration should be supported at the level of the value chain rather than at the level of individual players. This is because coordination and distribution of value between players (farmers, processors, intermediaries, support services) are essential factors in establishing and maintaining crop diversification value chains. In this context, policies could (i) facilitate the implementation of innovative co-design approaches (Meynard *et al.*, 2017; Jeuffroy *et al*, 2022) and new types of contracts by using both incentives and relevant regulations, (ii) contribute to balancing the effort between value chain players by setting up mechanisms for sharing the investment costs and risks associated with innovation, and (iii) facilitate access to support mechanisms for short value chains players.

In addition, it is desirable to support crop diversification value chains in their critical, experimental and innovation phases (i.e. when they are not yet competitive) and ramp-up phases (i.e. when major investments are needed to increase the production, processing and marketing of crop diversification products). This means incorporating financial incentives, such as premiums for the ecosystem services provided by diversification, or encouraging existing labels to include criteria relating to crop diversity and biodiversity (Antier *et al.*, 2022). It is also essential to redefine a regulatory framework that is both favourable to the diversification of practices and guarantees the safety of the resulting products.

Conclusion

The (re-)diversification of agri-food systems is a prerequisite for contributing to food diversity, which is necessary for consumer health, and for guaranteeing food security and sovereignty. It is also a major lever for mitigating the effects of climate change and halting the erosion of biodiversity. However, it remains limited at present due to the existence of a series of technical, organisational and institutional barriers inherited from the agricultural modernisation phase.

Overcoming the barriers to the diversification of agri-food systems is a major challenge, requiring a systems approach, coordination of stakeholder strategies, coupled innovations and a change in socio-technical regimes. Diversified systems need to be adapted to each situation and flexible in order to evolve continuously in the face of accelerating global change. The nature of the knowledge required, the way it is produced through multi-actor distributed design processes, and the urgency to take action all represent a challenge for Research and Development organisations and economic players.

Diversification and the full expression of its potential therefore require (i) an alignment of the strategies of players from upstream to downstream in order to benefit from the added value associated with it and (ii) the orientation of investment in research and development towards crop diversification, which should facilitate the practical implementation of crop diversification strategies in the long term. This presupposes that public policies, which are currently toosector-based and prescriptive, evolve to stimulate a systemic and dynamic approach to the gradual transformation of agri-food systems.

All in all, this is a paradigm shift for all players in value chains and the socio-technical system (policy, regulation, education, extension services and research), and everyone needs to adapt its own strategies in a coordinated fashion. These lessons have been drawn from experience with annual cropping systems, but they also provide a basis for analysing diversification issues in other production systems.

Ethics

The authors declare that the experiments were carried out in compliance with the applicable European and national regulations.

Declaration on the availability of data and models

The data supporting the results presented in this article are available on request from the author of the article.

Declaration on Generative Artificial Intelligence and Artificial Intelligence Assisted Technologies in the Drafting Process.

The authors have used artificial intelligence-assisted technologies to translate from French to English.

Declaration of interest

The authors declare that they have no conflict of interest in the subject matter.

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