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RESEARCH ARTICLE

Identification and description of relationships between actors involved in crop diversification experiences across Europe

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Abstract
Agriculture can benefit from crop diversification to facilitate its transition to more sustainable agrifood systems. However, these practices remain rare in Europe. One major barrier is the existence of sociotechnical lock-ins. To clarify the dynamics at work, we analyzed the relationships between actors involved in 23 crop diversification experiences across 11 European countries. The novelty of this paper lies in the systemic analysis of the network of actors involved in crop diversification experiences. Using data from qualitative interviews and cognitive mapping approaches, we identify and describe the role of actors and the key relationships in crop diversification and detect relationships that are currently missing. Our study shows that in the different European countries, similar relationships act as levers or barriers to crop diversification, with farmers and researchers playing a crucial role. The most important cognitive factors that influence the choice of farmers to diversify are environmental and health concerns and the desire to make profit and innovate. We relate the cognitive factors to organizational, technical, economic, and political factors and suggest levers for crop diversification based on successful crop diversification experiences.

Keywords Agroecological transition · Cognitive mapping · Social-ecological systems · Qualitative approaches · Dynamics of agri-food systems

1 Introduction

As cropping systems have undergone greater simplification and specialization, food production has soared, largely thanks to the heavy usage of agrochemicals and mechanical interventions (Nerlich et al. 2013). The unfortunate side effects have been negative environmental, socioeconomic, and health outcomes (Frison 2016). This agricultural shift is manifest throughout the agrifood landscape: the number of mixed crop-livestock farms is declining, value chains are optimizing logistics and exploiting economies of scale, and most European countries are witnessing a loss of farms and people in rural areas (Meynard et al. 2018). Current cropping systems are less resilient to climate changes and are strongly linked to lower levels of farmland biodiversity, agroecosystem functioning, food quality, and human health (Duru and Therond 2015; Meynard et al. 2018). To tackle these problems, the European Union (EU) recently adopted the Farm to Fork strategy, a pillar of the European Green Deal. This approach seeks to make agrifood systems fairer, healthier, and more environmentally friendly (European Comission 2020). One means of reaching these objectives is to develop and adopt more diversified agrifood systems (Tamburini et al. 2020; Beillouin et al. 2021).

Crop diversification boosts diversity in agricultural systems by exploiting space (e.g., intercropping), time (e.g., multicropping and extending crop rotations), and genetic diversity (e.g., cultivar mixtures) (Messéan et al. 2021a). This strategy can positively affect crop yield, biodiversity, and ecosystem services (e.g., soil quality, water quality, and pest/disease regulation) while also increasing environmental and economic resilience (Beillouin et al. 2021). Despite its numerous potential benefits, crop diversification is not widely used in Europe. Previous studies have indicated a

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range of sociotechnical lock-ins that hamper the transition to more diversified cropping systems (Meynard et al. 2018; Morel et al. 2020; Messéan et al. 2021a).

Long and highly organized value chains have been established around major crops such as wheat and oilseed rape, which has led to actor interdependence and has thus limited crop diversification opportunities (Frison 2016; Magrini et al. 2016; Morel et al. 2020). Upstream, farmers often lack the resources required for crop diversification, namely suitable equipment and locally adapted varieties for crops such as grain legumes and hemp (Morel et al. 2020). Downstream, logistics are complicated for small volumes of minor crops (e.g., lentils, peas) because costs are high, facilities are lacking, and actors must confront new and/or challenging management systems. At the market level, local minor crops do not compete well with similar crops or other crop types (e.g., soybeans) that can be produced more cheaply elsewhere in the world. They therefore cannot become established within existing stable markets. Additionally, consumers often have little knowledge about crop diversification and its benefits, making effective communication difficult. Moreover, while the EU's Common Agricultural Policy (CAP) during the 2014–2020 programming period contained a number of instruments promoting crop diversification, incentives remained sparse, limiting the scope of implementation (Baccar et al. 2020). Past work has underscored the need for all types of actors, including researchers, to better coordinate efforts aimed at overcoming barriers to crop diversification (Montrone et al. 2015; Meynard et al. 2018; Morel et al. 2020; Antier et al. 2021; Marette 2021; Rodriguez et al. 2021).

The processes involved in the transition to more sustainable European agrifood systems are complex and non-linear, requiring constant adaptation (Messéan et al. 2021a). Farmers frequently lack the technical knowledge needed to diversify their cropping systems (Morel et al. 2020), a process that requires redesigning crop and commercialization regimes alike. Knowledge is not acquired via a simple transfer of information among actors. Instead, there is dynamic learning, internalization, and integration (Röling 1988) that involves multiple actors (Macken-Walsh et al. 2022). Various studies have highlighted how important it is for farmers to acquire various kinds of knowledge from various stakeholders, including experience-based knowledge and informal knowledge through peer-to-peer learning and mutual support (Šūmane et al. 2018; Blom and Rossing 2022).

Multiactor networks benefit from a diversity of perspectives, interests, and ideals. Members share "formal" and "informal" knowledge, which fosters more sustainable practices and policies (Sol, 2012 in Meynard et al. (2018)). In such networks, farmers are active partners who co-produce knowledge and practices (Šūmane et al. 2018; Lamprinopoulou et al. 2014). To develop better strategies for encouraging crop diversification, it is essential to identify key relationships, successful approaches, and remaining gaps to develop a culture of knowledge sharing and innovation.

Taken together, the different actors involved in a crop diversification experience can be perceived as a social organization. These actors include farmers, researchers, extension officers, enterprises, processors, retailers, consumers, infrastructures, and institutions determining public policies and social norms affecting the interactions between the actors. The joint actions of these actors can contribute to enhance or limit the development of innovations in the agrifood system. In line with transition approaches and system analysis of sociotechnical regimes (Geels 2002; Macken-Walsh et al. 2022), this work aimed to study crop diversification from a systems perspective. We sought to look beyond technological innovation to consider structural features such as ideals, practices, knowledge, policies, infrastructure, and market mechanisms. Mapping and understanding the relevance and the nature of relationships among actors of these social organizations is crucial to explore the dynamic and the context of agricultural innovation. This study is therefore also grounded in social network theory (Liu et al. 2017), where model-based approaches describe the proximity of actors within networks and the dynamics of innovations diffusion. This theory takes a non-linear perspective when examining actor interactions in the context of different relationship groups. Social relationships are strongly affected by human factors such as preferences, perceptions, cognitive processes, and their related behavioral responses. As opposed to data-driven approaches, knowledge-driven modeling techniques such as cognitive mapping are promising approaches for taking into account these human factors in a social network analysis (Stakias et al. 2013; Vanwindekens et al. 2014). To understand the cognitive mechanisms in operation, this study looks at the self-determination theory (Deci et al. 1994), which considers the degree of autonomy behind human actions (internal desires vs. external pressures). Actions following more autonomous choices (identified regulation and intrinsic) increase the probability and sustainability of change (Moller et al. 2006; Garini et al. 2017).

Crop diversification initiatives are highly variable because they are strongly context dependent and customized by specific combinations of actors, agronomic innovations, local markets, and value chain organization. We must better understand the influence of different actors, socioeconomic interactions, and cognitive processes if we wish to facilitate the transition toward crop diversification and, as a consequence, more sustainable agrifood systems (Meynard et al. 2018; Weituschat et al. 2022). During the H2020 project DiverIMPACTS (http://www.diverimpacts.net/), an online survey was administered to assess crop diversification experiences (CDEs) across Europe. It collected data on the innovative systems being used, which helped to identify the main contributors and hurdles in CDEs (Drexler et al. 2018).

Drawing on information for 128 CDEs, the findings underscored that communication and relationships among actors were key elements in the dynamic of the CDEs.

Based on these propositions, this study thus delved deeper into the social networks associated with CDEs across 11 European countries. The goal was to arrive at broader lessons about the dynamics in operation and to identify the main relationships between actors in European crop diversification. Two specific objectives were pursued: (i) mapping main relationships between actors using knowledge-driven modeling approaches to identify and understand which one significantly contributed to CDE dynamic by taking into account actors' worldviews and (ii) achieving a comprehensive view on actor relationships and responsibilities which lead to agricultural change and innovation in the contexts of CDEs.

The novelty of this paper lies in the comprehensive view of the system which was obtained through the systemic analysis of the network of actors who are involved in crop diversification experiences. This allows us to highlight the key relationships in crop diversification and the key relationships that are currently missing among actors in the value chain. We also study the roles of actors in the different dynamics of crop diversification experiences. We highlight the cognitive factors influencing the choice of farmers to diversify and link them to organisational, technical, economic, and political factors. We suggest levers for crop diversification based on successful crop diversification experiences.

2 Materials and methods

The data underpinning the research were collected in 2019 during qualitative interviews of actors involved in 23 CDEs across 11 European partner countries (Fig. 1) and three simplified climatic zones: (i) Atlantic, (ii) Mediterranean and Alpine South, and (iii) Continental, Pannonian, and Nemoral (Metzger et al. 2005). The collection of these qualitative data followed an exhaustive quantitative survey of 128 CDEs carried out in 2018 (Drexler et al. 2018). This preliminary quantitative survey aimed to have a first overview of the diversity of CDEs in fifteen European countries, highlighting main success and failure factors, enablers, and drawbacks of innovative practices linked to crop diversification. The results of the quantitative survey influenced the present study in two ways: (i) in the selection of the main topic, as relationships between actors were highlighted in the survey as a major factor in CDEs development, and (ii) in the selection of the crop diversification experiences for being qualitatively interviewed. In this section, we detailed how the CDEs to be further analyzed were selected and how the data were collected and analyzed.

2.1 Selection of crop diversification experiences (CDEs)

We selected a subset of 23 CDEs (Table 1) from the broader collection of 128 CDEs that were documented during the previous quantitative survey. Strongly constrained by the research project structure, the selection consisted of a multi-stage purposive sampling formalized in a systematic procedure including quantitative and qualitative approaches (Fig. 2).

The first step was a two-fold clustering of the 128 CDEs, based (i) on the structure and overall level of success perceived by the respondent (clustering 1) and (ii) on the detailed success factors linked to each CDE (clustering 2). The input

Fig. 1 Experimental fields visit in Belgium. Map of partner countries (orange) and location of crop diversification experiences (blue) whose actors were interviewed. *Nota Bene* - Location of experiences were fuzzified. Simplified climatic zones are based on Metzger et al. (2005): Atlantic = Atlantic Central, Atlantic North and Lusitanian, Continental = Continental, Panonian and Nemoral, and Mediterranean = Mediterranean and Alpine South.

Table 1 Description of the 23 CDEs that were selected for being qualitatively analyzed. Abbreviations for new diversification practices: *I* intercropping, *M* multicropping, *R* rotation. Abbreviations for initiators: *A* advisor(s), *At* authorities, *CC* commercial company(-ies), *F* farmer(s), *Rs* researcher(s), *PP* partner(s) of the program. Zones are aggregated climatic zones based on Metzger et al. (2005): *Atl.*, Atlantic Central, Atlantic North, and Lusitanian; *Cont.*, Continental, Panonian, and Nemoral; and *Med.*, Mediterranean and Alpine South; see map of Fig. 1). Farmers (*n*) is the number of involved farmers. Initiators are the initiators of the CDE.

Crop diversification experience	Zone	Starting date	Size (ha)	Farmers (n)	New practices	Initiator(s)
Cover crops in a water protection area	Cont	1993	200	45	M	F
Development of early maize variety	Atl	2008	1500	75	M	CC
Intercropping by organic farmers	Atl	2015	>2000	>200	I	A
Intercropping with grain legumes	Med	2008	500	70	I	Rs
Zucchini and grass/clover intercropping	Atl	2008	65	1	I	Rs
Minor crops cultivation	Atl	2014	400	30	R, M	A, CC
Promotion of sugar beet as a biogas substrate	Atl	2011	1500	20	R	At, CC
Cultivation of foreign mustard	Med	2010	7	5	R	F
Rotation, cover- and companion cropping	Atl	NA	NA	NA	R, I	F
Hemp in crop rotations	Atl	2010	150	20	R	F, Rs
Catch crops to reduce nutrient leaching	Cont	2001	480	1	R	A, At
Conservation agriculture and cover crops	Med	2013	6	20	R, M	At
Four-year rotation of potato crops	Med	2000	500	100	R	A
Minor crops cultivation	Cont	2016	165	3	R	F
Seeds for minor crops, processing, and trading	Cont	2013	100	3	R	Rs
Cooperative for local and diversified products	Cont	2014	20	4	I	CC
Culture of soybean	Atl	2013	30	10	R	PP
Value chain for old varieties of cereals	Cont	1986	48	2	R, M, I	F
Processing of organic fruit and vegetables	Cont	1990	60	4	R, M, I	F
Intercropping sunflower with lucerne	Cont	2017	80	1	I	F
Production of lentils	Atl	2015	3600	300	R	A, CC
Use of heritage cereals for nutrient density	Atl	NA	NA	1	R	F
Rape seed-wheat-barley system	Atl	2005	6000	17	I	F

variables of the quantitative survey used in this step are detailed in Fig. 2. The results of these clustering and additional input variables were used to qualitatively select the 23 CDEs by the two researchers leading this study.

We aimed to target approximately 2 CDEs for each of the 12 partner institutions while covering the wide diversity of CDEs revealed by the quantitative survey. The CDEs were classed as either (A) a value chain innovation, subdivided in (A.1) food-main crops, (A.2) food-minor crops, and (A.3) non-food crops or as an (B) agronomic innovation, subdivided in (B.1) cover crops and (B.2) intercropping. When it was feasible, we selected one value chain innovation (class A) and one agronomic innovation (class B) in each region, avoiding as much as possible (i) experiences described as less successful by promoters, (ii) marginal ones in terms of size (low farm area and/or low number of farmers involved), and (iii) most recent ones. Even if this set of constraints was taken into account, some selected CDEs only involved a small number of farmers or applied only on a reduced area. Before the final selection, we included a discussion and validation step with local partners to ensure the relevance of the identified CDEs. One partner did not have the opportunity to conduct interviews related to one of its two selected CDEs.

The selection procedure and the internal constraints lead to a list of CDEs highlighting the diversity of ongoing dynamics aiming to valorize the potential benefit of cropping systems diversification. While heavy heterogeneity can be considered an issue in comparative studies including statistical analyses, it is an added value in the descriptive approach used in this study (Allmark 2004).

The CDEs were carried out on farmed surface areas ranging from 6 to 6,000 hectares (ha). Diversification mainly involved introducing new cash or cover crops. Intercropping and multicropping were utilized to a lesser extent. The CDEs were initiated by different actors, including farmers, government authorities, researchers, agricultural advisors, and commercial companies. Most (n = 17) were paid for by the farmers themselves, although sometimes national and/or European funding was available. A smaller number of CDEs (n = 6) were supported by public- and/or private-

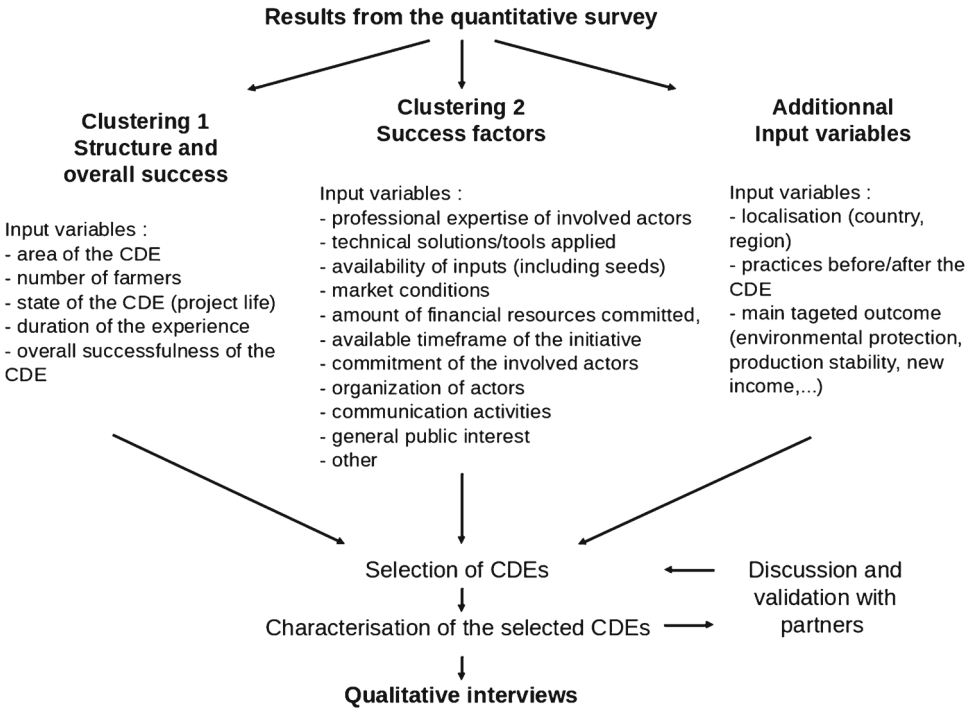

Fig. 2 The 23 crop diversification experiences that were interviewed were selected using a systematic multi-stage purposive sampling.

sector funding. Farmers were always among the participants, mostly in an individual capacity but sometimes as part of informal groups or farmers' associations. Testing mainly took place on farms and was led by farmers and/or farmers' associations; sometimes, it took place on research plots made available by commercial firms or public scientific institutions. Thirteen CDEs were carried out using organic farming practices. Fourteen CDEs included upstream activities such as seed production, organizational preparation, and input development with a view to promoting production, effective equipment usage, and breeding. Fifteen CDEs included downstream activities such as product processing, quality assurance, logistics, transportation, marketing, and sales.

A general description of the 23 selected CDEs is provided in Table 1 and is provided with more details in Appendix of Supplementary Materials S1.

2.2 Data collection, coding, and data processing

We used a cognitive mapping approach for analyzing systems of practices (CMASOP) (Vanwindekens et al. 2013, 2014) to describe the social networks and their role in CDE development and implementation. This approach centers on (1) open-ended interviews, (2) inductive coding, (3) individual cognitive mapping, (4) social cognitive mapping, and, in some cases, (5) comparative analyses.

2.2.1 Step 1—data collection

Data were collected in accordance with grounded theory (Glaser and Strauss 1967). This inductive approach makes it possible to identify the range of factors that boost or impede innovation without using predefined concepts, which can cause important elements to be missed.

Apart from introductive and conclusive phases, the core of the interview grid is structured around three main open-ended questions, each of them subdivided into questions either mentioned by the interviewed actor in answers or used by the interviewer to ask for details (Table 2). The complete interview grid is proposed in Appendix of Supplementary Materials S1.

Within each CDEs, local partners were asked to identify and select actors from different levels of the value chain (farmers, manufacturers,…) to be qualitatively interviewed. At the end, each CDEs involved one to six interviewed actors. In total, 53 interviews were conducted, translated, and transcribed by the 12 partners. These transcriptions are the corpus of our study.

2.2.2 Step 2—coding

The study's corpus was coded by identifying the relationships between two actors of the food systems and their influence on the dynamic of the CDE, as described by the interviewees. Coding took place at the quote level. A single

Table 2 Main part of the qualitative interview grid.

1. Can you describe the evolution of the project since the very beginning and how you were involved?
- Who was involved?
- When did it start?
- Which diversification strategies were implemented?
- What was new?
- Why did you start/join this project? What were your initial motivations, the triggering factors?
2. What contributed to the success of the project, or, on the contrary, made its implementation complicated?
- How is the project a success? What is a successful project according to you?
- What problems did/do you encounter? How did you get around problem(s)?
- How was your relationship with other actors?
- How is the knowledge you gained on the subject shared, inside/outside the project?
- How was your project funded?
- Concerning what is working or not, can you point out evolution since the beginning of the project: new constraints or resolution of old constraints?
3. In general, how do you feel about the project?
- If you were to do it again, what would you do?
- How do you see the project in the future?

quote can be coded by multiple relationships if various actors were involved. We identified 5 actor categories containing 17 actors (Table 3).

Based on what they provided, relationships were classified into five main groups:

1. Knowledge: knowledge, information, or lack thereof, encompassing activities such as knowledge creation, diffusion, advice, monitoring, farmer experience sharing, and actor coordination
2. Materials: labor, animals, and resources such as equipment, seeds, feed, and farm products
3. Administration: formalities related to agreements between people, quality criteria, certification, incentives, policies, and legislation
4. Funding: funds, processes that result in profits, subsidies, and market-related processes that influence financial investments
5. Ideals: mindsets or worldviews, encompassing people's own ideals, specific objectives, or expectations imposed by external parties (e.g., market demand, interest, or concern) as well as the influence exerted via trust

Actor relationships were also characterized based on their directionality, which was determined by the causes, influences, and flows at play. Additionally, they were designated as positive or negative when they promoted or hindered the CDE, respectively.

Using this systematic coding approach, we reduced the subjectivity that arises when dealing with qualitative data (i.e., interviews) and that can affect the results (ElSawah et al. 2013; Jones et al. 2011; Vanwindekens et al. 2013; Vanermen et al. 2020).

2.2.3 Step 3—individual cognitive mapping

We generated a list of relationships identified at the CDE level, which was independent of relationship occurrence in the interviews and the number of interviews for each CDE. The lists were used to build 23 individual cognitive maps

Table 3 Categories of agrifood actors involved in crop diversification experiences. (*) Local authorities = national, regional, and municipal government officials.

Actor category	Actors
Farmer	Farmers, fellow farmers, farmers' unions
Upstream value chain actor	Suppliers
Downstream value chain actor	Processors, retailers, collectors, traders
Institution	Researchers, advisors, European institutions, local authorities(*), federations, banks, insurance companies
Society	Consumers, citizens, media

(ICMs), where the nodes were the CDE's actors and the lines were the relationships between them.

2.2.4 Step 4—social cognitive mapping

The ICMs were then compiled into social cognitive maps (SCMs) expressing the basic structure of CDE actor networks, which were described using two graph theory indicators—relationship weight and actor centrality. In the SCMs, a relationship's weight was the sum of the CDEs that mentioned the relationship. Actor centrality was the cumulative weight of the relationships an actor entered into and departed from Özesmi and Özesmi (2004).

2.3 Data analysis and data interpretation

After being coded and processed, the content of the interviews was explored and analyzed to reach our two goals.

First, we highlighted the relationships among actors that significantly contributed to CDE dynamic using (i) synthetic tables of graph theory indicators (e.g. weights of relationships, centrality of actors) and (ii) graphs, like SCMs, complete or filtered according to categories of actors or groups of relationships.

Secondly, we achieved a comprehensive view on actor relationships and responsibilities in initiating CDE using (iii) tools allowing researchers to retrieve quotes that are behind the relationships of these SCMs, complete or filtered ones.

3 Results and discussion

3.1 Overall social network

The overall SCM displays the full network of actors that were involved in the CDEs (Fig. 3). Near the top are the actors that largely initiated or drove the relationships; near the bottom are those who were mainly impacted by the relationships. Farmers were the most central actors (centrality = 240). They were often mentioned in interviews because they were linked to all the other actors. Their activities could extend beyond agricultural production to supplying seeds, processing food products, participating in trade, and acting as retailers. Researchers were the second-most central actors (centrality = 67). They were mostly linked to institutional actors, farmers, farmers' unions, and processors. The actors' relationships were characterized using the graph theory indicators (Fig. 4).

3.2 Key relationships influencing the crop diversification experience

We observed eight key relationships (weight $\geq$ 12) that differed in their patterns of relationship type (Fig. 5). The relationships involved actors in three categories: farmers, institutions, and society. They were all directed toward farmers, except for the relationship between farmers and fellow farmers, which was bidirectional. A farmer's relationship to themselves was also described as a way to express their own motivations. The eight relationships led to different outcomes, including the strengthening of existing CDEs, or their long-term establishment, and either fostered or hampered crop diversification depending on the context. Fellow farmers, researchers, and advisors played a major role in boosting knowledge and information exchanges. European institutions and local authorities had an administrative influence on farmers' choices via policies and regulations. Finally, both farmers and consumers tended to act based on their ideals. We describe the relationships and provide main quotes in the text in the Appendix S1 (which are sorted by relationship type: 1–7).

3.2.1 The self relationship farmers–farmers

Farmers were self-motivated to adopt crop diversification as a result of ideals and/or funding. Eight of the 24 farmers interviewed in this study undertook crop diversification to produce healthy food and protect their families, the environment, animals, and plants. Using, for example, "the least possible spray tank. . . the least possible use of carcinogens for me, my environment, my family. And first me" (Farmer, Atlantic).

Three interviewed farmers were curious and excited to experiment with new agricultural practices and/or value chains, pointing out that "We like to innovate and keep up with new processes. We are very open for learning new things" (Farmer, Atlantic).

For example, Dutch farmers included grass clover in their crop rotations and row cropping while Italians extended their potato rotation to four years, cultivating potatoes, carrots, tomatoes, maize, and vegetables. A German farmer tried out sugar beet for biogas substrate. They were willing to take the risk when they had diverse agricultural activities or when they received financial support from other actors. Of the 23 CDEs, 12 were completely self-funded, and 5 were funded by combining the farmers' own resources with research money from local authorities (national level) and/or European institutions.

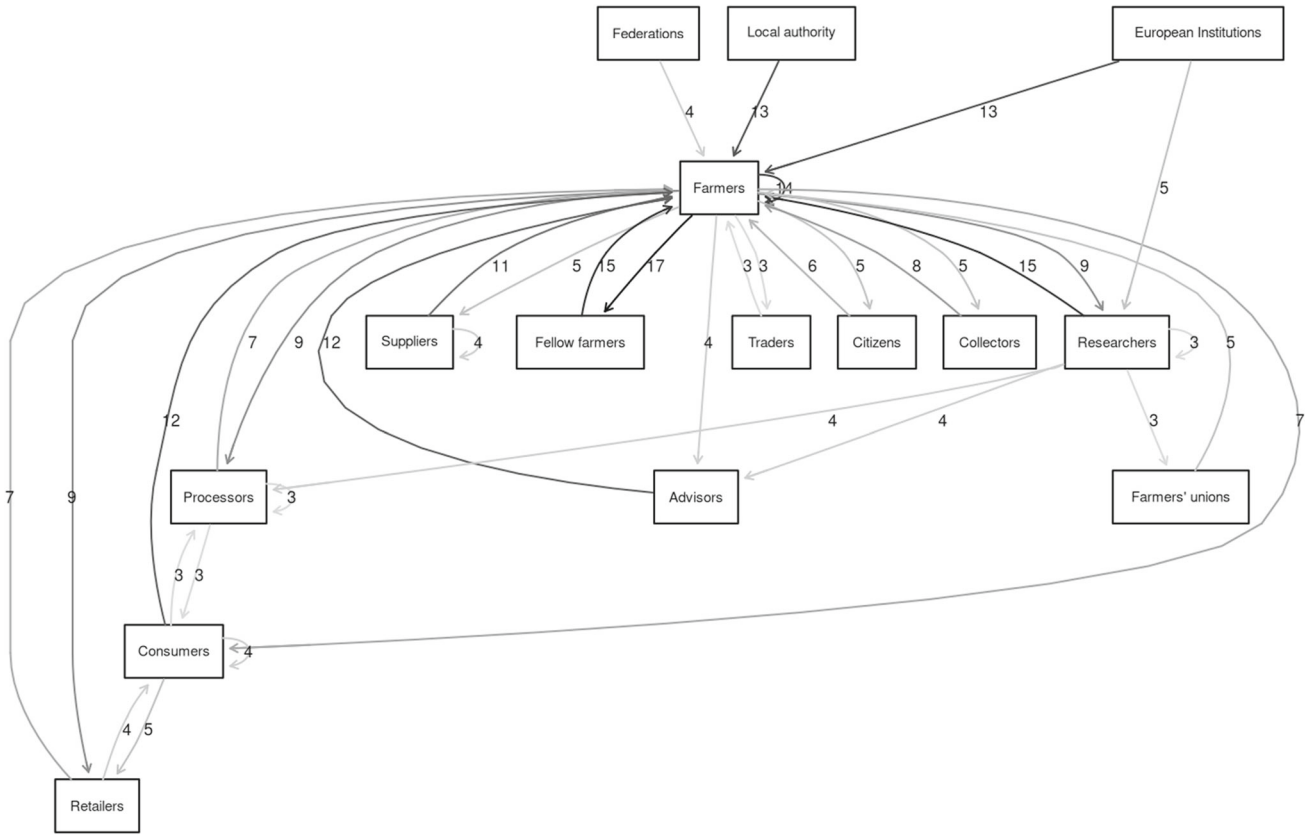

Fig. 3 Overall social cognitive map. Farmers occupied a central position and were directly linked to all the other actors. Only relationships with a minimum weight of three are shown ($w \geq 3$). Farmers were distinguished from fellow farmers: the former is the farmer who was interviewed or specifically mentioned by another actor, whereas the latter is any other farmers who influenced the crop diversification experiment but who were not necessarily directly involved.

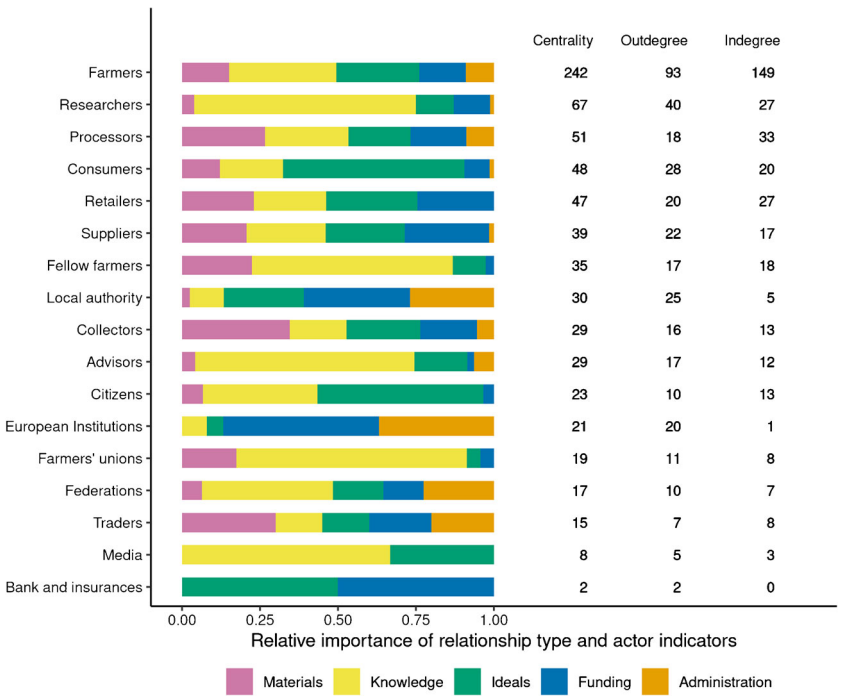

Fig. 4 Main relationship types and actor centrality in crop diversification networks. Centrality was the summed weights of all of an actor's relationships. Some actors served as initiators, as seen in their higher outdegree values (i.e., weights of all their outgoing relationships). Indegree is the weight of all their incoming relationships. The relative importance of different relationship types (colored bars) also varied among actors: researchers, advisors, and farmers' unions had a high proportion of knowledge-based relationships; consumers and citizens tended to have ideals-based relationships; processors, collectors, and traders largely had materials-based relationships; and local authorities and European institutions mainly had relationships based on administration and funding.

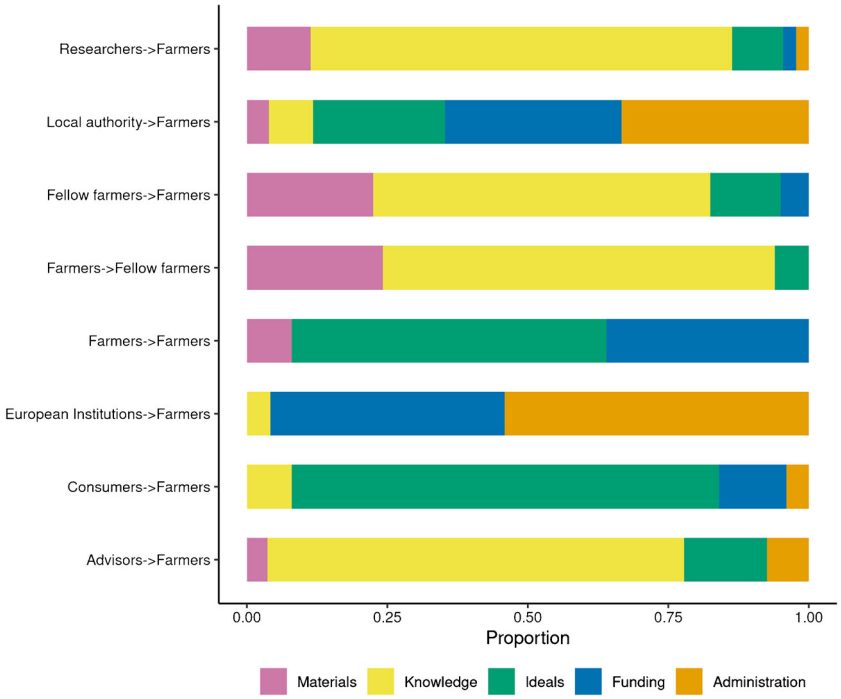

Fig. 5 Proportion of relationship types within the eight key actor relationships observed.

Some farmers also considered the financial implications of crop diversification. The potential for better returns was an incentive for change. A desire to become more self-sufficient was another motivation. For example, a Belgian farmer looked for more lucrative crops than wheat and tried to grow peas and lupins that he gave as feed to his cows. He is closing the cycles on his farm and noted that "in other words, we are becoming more self-sufficient, this means that we will buy less from suppliers" (Farmer, Atlantic).

From these results, we uncovered three of the main factors motivating farmers to diversify: (i) a desire to protect the environment, (ii) a hedonic curiosity and need to innovate, and/or (iii) an aspiration to boost earnings via the policies and financial incentives offered up by local authorities. This concurs with the findings of Weituschat et al. (2022) as well as Bonke and Musshoff (2020). Implementing CDEs based on the two first motivation factors requires a higher willingness by farmers to take risks. In our study, we found that farmers were more willing to take such risks when they had diverse agricultural activities or when they received financial support from others.

3.2.2 Consumers–farmers

This relationship highlights the direct influence exerted by consumers on farmers. Consumption patterns reflect choices, and the interview quotes associated with this relationship were mainly associated with ideals.

For eight CDEs, consumer-driven market demand had a crucial positive influence on the dynamic. One strategy was for farmers to adapt their production patterns to respond to consumers. There were niche markets in which consumers were concerned about environmental issues and were ready to pay a fair price for vegetables, potatoes, old varieties of cereals for all kinds of products, sarrasin, lentils, quinoa, little spelt, and tan products. For example, they cared about a product's origin or production system. Another strategy is for farmers to sell directly to consumers on the farm or on farmers' markets. It is a way to skip intermediaries and to achieve better prices for farmers. With the help of direct marketing, farmers and consumers can build a closer relationship. It allows farmers to better inform consumers about production methods and the role of diversification. Farmers and consumers consider that this aspect will become even more important in the future. Interviewees acknowledge, however, that direct marketing requires higher efforts in marketing and building up a network of reliable customers.

In contrast, for five CDEs, market demand was either saturated or non-existent in the target area. Interviewees mentioned that consumers lacked awareness about nutrition and agrifood systems. For example, they do not recognize the difference between organic and integrated production. In some countries, consumers were unfamiliar with the product (sweet corn was uncommon for Belgian or Hungarian consumers while it was sold in Germany, Sweden, Switzerland, and England), or they were consuming it in small quantities (mustard).

At the global scale, market prices fluctuated with supply, and it was difficult for farmers to predict whether there would be demand for their products: "Basically the difficulties come

from the fact that the market has such a great influence. When they can offer good prices the territories dedicated to these varieties grow significantly, if the prices go down the territories shrink. [. . .] The market price is key in these decisions unfortunately" (Institution, Continental).

Situating themselves on local markets reduced this uncertainty. British farmers mentioned that they would not be affected by Brexit for the wheat sold on the local market, while Hungarian farmers were affected because England stopped buying organic sweet corn from them. Additionally, potential profits drove farmers toward crop diversification.

Our study highlighted that crop diversification relies on consumers with a high degree of awareness of the benefits afforded by crop diversification. We have already highlighted the role of direct relationships between farmers and consumers as it is the case for direct marketing. But retailers could also serve the role of raising consumer awareness because they market to and communicate with consumers. Because they involve consumers in product choices, cooperative supermarkets are a good first step in the right direction. However, they remain relatively rare.

3.2.3 Fellow farmers–farmers

We noted the crucial importance of relationships among farmers, namely between the farmer who was interviewed or occupied a central role in the CDE and fellow farmers within their family and social environment. These relationships were often bidirectional and provided ideals, knowledge and materials.

In the interviews, there were several references to how farmers' ideals are shaped by other farmers. For example, a Dutch farmer said that his motivation to experiment with mixed cropping was "To show my son that there are other ways of farming. We are not a farm with 300 milk cows, and we do not want to be that big anymore."

Knowledge and information flowed between farmers and fellow farmers at various scales. For example, exchanges occurred within families, among neighbors in the same village or region, among farmers within the same country, or even among farmers in different countries. One farmer specified that "[The knowledge is] shared through [a farmer's association] and Whatsapp groups and between friends and farmers that visit our farm" (Farmer, Continental) and another one that "Through years of experience, knowledge exchange with colleagues, farmers came from all over the country" (Farmer, Continental).

One British farmer talked to organic spelt farmers in Norway. Most transfers happened on-site: "The key element is that we were able to meet regularly, to observe in the fields, and to be connected to concrete cases. We also managed to get some farmers with different profiles to work together. By telling them: faced with this problem, what would you do? Sometimes the exchanges between them have been rather fruitful" (Institution,Atlantic).

Exchanges could also occur in more structured settings—farm visits, demonstrations, workshops, or experimental trials—as well as part of informal occasions, such as during conversations or on social media. Usually, information on positive experiences was more common, though three farmers highlighted the need to talk about mistakes to avoid them. One Swiss farmer had the opportunity to see a failed demo strip of mustard eaten by pollen beetles and other insects and compare it to the crops of his neighbors, working more intensively.

Farmers tended to look locally first in their networking efforts, which they trust more easily. However, they could miss connecting with certain colleagues, which could discourage them from pursuing crop diversification. Effectively transferring information to fellow farmers required good communication skills, which entailed a certain amount of work for the farmers. A Swedish farmer was convinced by conservation agriculture when he was in England. He affirmed that he did not know any farmer in Sweden who did it and was only in contact with someone from Denmark. He made the effort to find colleagues who have the same interest and want to share their knowledge, but at this time in Sweden, he did not find anyone with experience in conservation agriculture.

Farmers also exchanged material resources that facilitated the transition toward crop diversification. These interactions took the form of (i) selling agricultural products to fellow farmers (e.g., soybean and other protein crops used as feed), (ii) selling/exchanging seeds or manure, and (iii) sharing or renting out expensive equipment such as sorting machines or seed sowing machines. The connection between crops and livestock gave many opportunities to farmers. For example, Belgian farmers were asked to cultivate organic vegetables on the land of a pig producer to complete his land rotation. In the other way, an English farmer who had cover crops asked a shepherd if his sheep could graze the cover crops.

Within Europe, different countries have very different production costs, which can generate competition among farmers. Such differences may act as a barrier to crop diversification in some regions. One farmer mentioned that hemp and cereals grown in Eastern countries are much cheaper and Western countries can not compete with it. He nevertheless pointed out that "high prices in our region will probably not be the case, because hemp is also cultivated in neighboring countries. And, in our region, the grounds are too expensive, so hemp is now cultivated abroad where it is much cheaper. We are thus not able to compete with this" (Farmer, Atlantic).

We found that fellow farmers were the most frequent source of information for farmers, as has been observed elsewhere (Caron et al. 2014; Reyes-García et al. 2014). While direct learning can take multiple forms, we noted

that farmers had a clear preference for direct observations. When communicating with peers, farmers acquired practical, experience-based knowledge. When information and advisory services were lacking, peer-to-peer networks allowed farmers to engage in exchanges and demonstrations within their regions, which is an effective way to foster local knowledge (Guerra et al. 2017; Marchand et al. 2021; Blom and Rossing 2022). Nevertheless, if farmers find themselves in areas with competitive markets, fellow farmers may be reluctant to contribute to such networks (Morel et al. 2020).

3.2.4 Researchers–farmers

During the CDEs, researchers were also highly influential actors. Relationships between researchers and farmers generally support knowledge and, to a lesser extent, materials and ideals exchanges.

Three CDEs were initiated by researchers working at research centers and/or universities. As part of research programs, researchers explored crop diversification strategies through the introduction of sugar beet in crop rotations for biogas substrate, the implementation of conservation agriculture practices in a rapeseed-wheat-barley rotation, the inclusion of cover crops within a typical rotation. They mainly carried out field measurements and evaluations regarding fertilization, yields and weed management, and soil analysis regarding, among others, soil biodiversity. The interactions with farmers—the potential system end users—came in during a later step, when knowledge and results were shared.

In this type of CDE, researchers gathered, analyzed, and shared information via a top-down approach: "we may advise farmers on some usual mistakes. We could afford to make mistakes, and by making mistakes we learnt and can help farmers avoid those mistakes" (Institution, Mediterranean).

They took findings from a diversity of specific case studies in order to be able to gain in genericity and highlight general knowledge applicable at broader scales. Outside of monitoring efforts or group exchanges, knowledge transmission to farmers often happened on farms on training days or during open-house events. The advantage was that participants saw experiments being carried out in different regions and at different times of year. Information was also shared in more formal settings, including during seminars or during workshops for students and local farmers at agricultural high schools. One challenge was that farmers often expected more practical knowledge, such as in the form of guidelines. However, guidance was often lacking because much remains of value under too specific conditions. Examples underlined are soybean and hemp crops, plant species in cover crops, or intercropping with perennial crops. There is substantial debate regarding innovative agricultural systems that will benefit from the contribution of new scientific research.

Ten CDEs were launched by the farmers themselves. Upon observing promising results, they sought support with follow-up work, measurement-based monitoring, or indicator usage. In this type of CDE, the interaction was more bottom-up, driven by farmers who were seeking to exchange knowledge. Researchers either contributed formal knowledge that could be experimented under local conditions or collaborated with farmers on field experiments, developing the formal knowledge from specific results. For example, researchers in the Netherlands could advise on companion and strip croppings that they previously studied, while in Belgium, they were discovering the cultivation of soy with the farmer. In both cases, there were some failures. However, some interviewees highlighted that it is important to conduct experimental research projects where there is room for mistakes (thanks to the funds for research). Farmers should then be warned about the mistakes so that they can be avoided and about the "many issues at stake: soil characteristics, the availability of proper machinery, the need to avoid soil compaction, an important problem in our silty soils. Then there are issues with weed management. If farmers are able to deal with all those issues, they may be able to adopt conservation practices, otherwise it may be difficult" (Institution, Mediterranean).

A third way in which knowledge was exchanged between farmers and researchers was within group settings, where farmers and researchers were on equal footing and could both provide their specific input. One group even included consumers. In all situations, the goal was the same: to help farmers to succeed in their crop diversification and identify the issues being faced. Researchers played a monitoring and advisory role, but they also promoted innovation through the production of new scientific knowledge. The major advantage of these types of exchanges was that they included both theoretical and practical knowledge within a framework where farmer feedback and discussion were valued. Co-created knowledge between researchers and farmers, integrating resulting discoveries into farming practices, is positively impacted the dynamic of CDEs (Lang et al. 2012).

Some farmers involved in the CDEs felt that practical knowledge such as management schemes was lacking. A potential compensatory mechanism is knowledge transformation, which focuses on providing practical knowledge and means that can be used to bring sustainable innovation in agricultural systems (Wuelser et al. 2012). In this context, it is essential to highlight the importance of the co-production of knowledge, knowledge transformation, and engagement with actors outside of academia over the longer term that characterize transdisciplinarity (Schneider and Buser 2018). Researchers from different disciplines collaborate with non-academic actors to generate information that helps provide concrete solutions to crucial problems (Mauser et al. 2013; Popa et al. 2015). Scientific efforts

focused on agricultural transitions should promote transdisciplinary approaches because they help ensure that jointly developed innovations correspond to local values, increasing their impact and likelihood of acceptance (Macken-Walsh et al. 2022; Rossing et al. 2022).

Furthermore, the relationship between researchers and farmers is also dependent on ideals. This manifests itself in the willingness of farmers to participate in applied research projects. One interviewee pointed out that their participation in an experiment required farmers to be willing to question their management strategy.

3.2.5 Advisors–farmers

In seven CDEs, advisors made the link between theoretical knowledge and practical knowledge. They sought out solutions and reliable information; they kept track of experiments on certain topics; and they provided guidance to farmers based on local conditions. For example, the agricultural service of a French commercial company learned about lentils management schemes tested in different regions and advised farmers locally. Advisors also learned from the farmers' work and helped diffuse knowledge to other actors.

Farmers followed the advisors' guidance when it fit with farming conditions and was practical to implement. When advisors raised awareness about specific issues (i.e., water protection areas), farmers were more sensitive about the subject and could understand the knowledge behind the advice.

Relationships between farmers and advisors that are based on shared awareness and on trust favor the development of the CDE. Different interviewees emphasized the role of trust, which grows around a personal connection, noting that "this contributes to the success of the water protection here" (Institution, Continental).

Building trust requires a certain level of shared ideals and the ability of the advisors to put themselves in the farmer's shoes and anticipate risks. However, a sustainable relationship can be hindered by competing interests, market competition for advisory services, and/or a lack of technical knowledge (e.g. to adapt pest management practices). An institutional actor pointed out "some problems linked to some reluctant concurrent advisers who are our partners in the region. They do not say anything but they do not move and they try to put obstacles to our efforts by influencing farmers. As soon as they do not want to move, they will make trouble" (Institution,Atlantic).

Advisors appeared to act as intermediaries in the conversion of formal knowledge to informal knowledge. As emphasized elsewhere, advisors support farmers in the decision-making process, but action only results if the two parties have a high level of trust and share common goals (Garini et al. 2017; Macken-Walsh et al. 2022; Rossing et al. 2022). However, in our study, advisors found toward the bottom of the SCMs did not trigger structural changes. Their role was to guide pre-existing crop diversification efforts and to provide counsel aimed at customizing techniques/technologies. A previous study showed that advisors working at private companies could have a vested interest in input sales, and they tended to adopt conservative positions when farmers sought counsel about redesigning cropping systems; in tandem, advisors with agroecological expertise were scarce (Garini et al. 2017). This finding stresses the importance of educating advisors about the long-term benefits of crop diversification (Baccar et al. 2020; Meynard et al. 2018) and highlights the risks of replacing public-sector advisory services with private-sector advisory services.

3.2.6 Relationships between public institutions and farmers, European institutions–farmers and local authorities–farmers

Public institutions at all levels, European institutions and local authorities, also play an important role in the development of CDEs. The relationships between these institutions and farmers were mainly associated with administration, funding, and the underlying ideals.

European institutions influenced farmers' choices, farming practices, and agricultural transitions through CAP legislative and funding measures. They had concrete impacts on farm management that were either direct, via the greening program that required to introduce a rotation, or indirect via research programs for example. Local authorities provided concrete support to farmers via the municipal, regional, and/or national objectives they had established through regulations, funding opportunities, and/or specific projects. They served as a functional intermediary between European institutions and farmers.

The CAP's first pillar includes the greening program. One of the practices required by the program is crop diversification by introducing a minimum of three crops into the total land use. Five interviewees mentioned this requirement as marking a turning point for them. Farmers with too many hectares in monocultures had to introduce a rotation. It also brought about changes in agrifood systems because it helped establish a greater range of markets, such as the market for green manure seeds in Hungary. The farmer involved noted that "there were additional payments, […]. It was not much, but I was glad that we were appreciated. In the past, I overcame incredible difficulties. Today my son sees no other way than organic production" (Farmer, Continental).

However, the CAP exhibits certain weaknesses in regard to crop diversification. EU subsidies drove farmers' choices through their policy requirements. While some farmers implemented crop diversification for personal reasons, others were seeking to boost earnings. It was possible to adopt a crop diversification system and meet subsidy requirements

without considering the sustainability of nutrient cycles and water management. Furthermore, the CAP reforms changed the subsidy regime. If farmers rely on the subsidies to make up for lower yields, the movement toward crop diversification will stop if those subsidies are no longer available. Two French farmers talked about previous subsidies for grain legumes such as peas, which decreased drastically. Farmers that adopt crop diversification for monetary reasons only may have gaps in knowledge of this approach. A good level of knowledge and ownership is however important to effectively manage risk such as unfavorable weather conditions. Farmer engagement can be boosted by using policies based on transferring knowledge and encouraging independence in the choice of production systems and measures such as the approach taken by outcome-oriented policies (Burton and Schwarz 2013; Wezel et al. 2018).

At regional and national levels, local authorities employed research and monitoring to develop effective policies that encouraged farmers to adopt certain farming practices. Research efforts could be part of a broader project involving several different actors, advisors and/or researchers, farmers, and to a lesser extent value chain actors. Actors would discuss common goals and reach a state of mutual agreement. Such approaches could avoid situations in which farmers were faced with strict administrative requirements and regulations that were viewed as constraining and demeaning. In one CDE, it was reported that a positive lever was the strong, trust-based collaboration that was established between farmers and local authorities (municipal level): "It has something to do with trust. That's very important, I think. If a farmer, or we, promise or promise something, the spoken word is true and you can count on it. This has created a certain basis of trust over the years. It used to be that way and I think that's very important" (Institution, Continental).

However, according to different actors in four CDEs, farming policies were not always adapted to local conditions. They may be copied from other countries and lack specificities of farms or of the region (e.g., region including basin with water reservoirs). Fundings supported by those policies may then be limited. For example, a farmer in Hungary brought an end to his crop diversification process because the small size of his farm made it impossible to respect the required isolation distances between sunflowers and corn.

In addition, certain incentives may disappear when a sustainable practice becomes widespread, as it was the case in Switzerland for the cultivation of grain legumes, or when sustainability objectives are reached, such as reaching a better water quality level in a water conservation area. Such can give rise to a paradoxical situation in which farmers receive no recompense for good work but are rewarded for harmful work.

Many actors also expressed frustration over general policy differences related to crop diversification among areas, regions, and countries. These differences made it hard for farmers and other actors to understand current legislation and access funding, given that similar funding sources may impose different requirements.

The relationships of public institutions with farmers fit with previous work (Garini et al. 2017; Weituschat et al. 2022) in suggesting the following: although there is as yet no general agreement, highly standardized EU policies show limited or even negative effects on the implementation of crop diversification, while policies adapted to local conditions seem to hold more promise. Our results highlight that it is important for policies to be context-sensitive and to allocate funding to farmers committed to genuine crop diversification practices. This simultaneously raised questions about policy fairness and legitimacy because farmers would discuss how different rules were being applied in different contexts. Inconsistencies also exist among policies at different levels (Lamprinopoulou et al. 2014; Borremans et al. 2018).

When farmers begin moving toward crop diversification, they face risks in terms of yields and market fluctuations. Interviewees called for authorities to offer better financial support regimes, similar in design to current subsidies for sustainable production systems. Such was also noted by Antier et al. (2021). Moreover, policies must be structured to persist over the longer term. Indeed, a change in policy planning involving a change in financial incentives may mislead farmers in their choices, discouraging them from adopting crop diversification.

3.3 Value chain actors relationships

Besides the eight key relationships previously highlighted, value chain actors played an important role to practically enable farmers to produce, value, and market their diversified crops. Actors pointed out that "[Our] initiative is certainly successful because the different involved actors in the supply chain are satisfied. There is an economic return for all levels" (Farmer, Mediterranean).

Processors were the third most central actors. They played a key role in the CDEs because they attributed new value to crops, created new value chains, and/or processes adapted to intercrop productions. For example, in order to value sugar beet as biogas in Germany, a cooperative treated the beets differently and processed them directly from the field through the mashing unit. An essential part of value creation is owning the necessary mechanical equipment. Processors must also adapt their quality criteria to different production types. For example, they have to manage peas that might be a bit too wet or vegetables that are a bit damaged. However, two processors in Poland felt restricted by controlling institutions which did not adapt their requirements to the field reality. They also claimed recognition by local authorities of organic processing. This actor group was concerned about profitabil-

ity because of their position in the middle of the value chain. They must therefore balance the necessity of paying farmers a fair price and selling to consumers at an affordable price.

Retailers faced the same issue as they occur at the interface between producers or processors and consumers. Seven retailers mentioned that selling to consumers locally grown products (mustard, lentils, quinoa, potatoes, or vegetable juice) was profitable for the farmers and for them. So, they "[we] try to be as seasonal as possible, sometimes we experiment by removing bananas and stuff like that, to really expose the national produce and try to buy from the smallest producers first, and if they don't have what we need we go up the chain, still focusing on being as sustainable as possible" (Downstream value chain actor, Continental).

In three of these cases, the coordination of the whole value chain by a federation or a commercial company helped to guarantee earnings at all levels. All the steps were presumed to be transparent to all. Retailers gathered information from producers and consumers. They kept each other informed of their expectations, and they responded to requirements imposed by producers, consumers, institutions (e.g., federations), and/or local authorities, and then they "[we] have transparency between us. On what the agriculture sector of our company can collect from farmers as info. Or on what the food sector of our company can collect from their customers as info. On them, their ideas of innovations to put in place, products to deploy. There is a lot of exchange. It's interesting" (Downstream value chain actor, Atlantic).

Retailers also had influence over producers and consumers because they chose which products to market. At local scales, consumers could be involved to help retailers make decisions around prices, as it occurs in cooperative supermarkets. At multinational scales, farmers found an advantage in having a greater diversity of retailers. It contributed to stability and helped adapt crops and contracts to market fluctuations. Over time, long-term partnerships gave rise to trust and shared economic responsibility and, as a consequence, room for experimentation of different crop combinations.

Seed suppliers were directly involved in five CDEs. In six CDEs, seeds were supplied as part of research projects. Seed development was driven by the suppliers' ideals, the market demands made on farmers, and/or societal expectations around greater sustainability. However, people's resistance to novelty was an impediment in research and development related to new crop varieties. A Dutch seed producer mentioned that early maize varieties could be more sustainable than corn cultivation, which most people don't know about. In addition, crop diversification requires a range of specialized equipment. Interviewees from different CDEs mentioned the lack of sorting and storing machines for mixed crops, a harvesting machine for hemp, a mowing machine for grass clover, and special machines for no-till agriculture. Often, the necessary financial investment presented a major barrier for different value chain actors: "Yes, we do not sort, at least for now, because we estimate that the cost is very high in order to invest in it" (Downstream value chain actor, Atlantic).

In five CDEs, farmers or collectors bought the required tools altogether. One of them mentioned that it might become a problem when the farms are located far away from each other and need the shared machine at the same time.

Collectors were often part of a wider range of value-chain activities. They established contracts with farmers to guarantee them earnings. Collectors thus supported farmers in their diversification efforts because yields for minor crops (lentils, potatoes, or vegetables depending on the country) are unpredictable, especially because effective growing practices are poorly studied and documented. "Farmers should not go into lentil production without a contract. […] We buy lentils only if they are contracted with us X months before harvest. But that means we do not buy after harvest. If the farmer sows lentils, he has a contract" (Downstream value chain actor, Atlantic).

The results show that it was helpful when the relationships between value chain actors and farmers were coordinated by federations or farmers' unions. Such groups have a fuller understanding of the entire value chain and its actors, which helps to guarantee earnings at all levels (Meynard et al. 2018). They also enabled different actors (e.g., from farmers to retailers) to jointly invest in the equipment needed for minor crops, to produce sufficient volumes of minor crops, and to reduce both collection and management costs (Meynard et al. 2018; Morel et al. 2020). Nevertheless, it requires a shift in how actors view interactions (Morel et al. 2020). The involvement of consumers in the choice of products and prices enabled retailers to raise awareness about local and diversified products, as well as to better identify the needs of the consumers. Selling locally was usually seen as more profitable (Stein and Santini 2022).

Around the value chain actors, controlling institutions and authorities may adapt their quality requirements and recognize the processing of diversified crops (Antier et al. 2022). The development of adapted machinery and seeds for minor crop varieties/cultivars and crop mixtures may also be supported by research and policies (Meynard et al. 2018; Antier et al. 2022).

3.4 Implications of the relationship classes

Sustainably transitioning to crop diversification systems demands shifts at all levels of the agrifood system (Gaitán-Cremaschi et al. 2019). The social network analysis showed that key participants in knowledge sharing and information flows are farmers, advisors, and researchers. Research should seek to strengthen relationships and exchanges

of both knowledge and innovations among all value chain actors, upstream and downstream (Bonke and Musshoff 2020). It is essential to look beyond crop fields and farming systems. Our work here confirms that this systemic perspective is still missing (Lamprinopoulou et al. 2014).

Our results highlighted the importance of trust to support CDEs' success. Building trust was therefore crucial to support knowledge exchanges among actors. That trust needs to be nourished over time via collaborations and shared experiences. Similar results were noted in earlier studies (Hodson and Marvin 2010; Huxham and Vangen 2013; Koole 2020). Trust was an essential component that positively influenced the dynamics of the CDEs because it encouraged reflective learning that went beyond the simple acquisition of knowledge and that strove to translate discoveries into joint actions aimed at achieving common goals (Koole 2020).

Moreover, ideals of actors greatly influence the adoption of crop diversification systems. Our social network analysis identified that farmers, consumers, citizens, retailers, European institutions, and local authorities formed relationships that greatly influenced the ideology of the actors of the agri-food system.

Practically, administrative matters including policies can steer those ideals. Farmers, European institutions, and local authorities are the actors that dealt the most with administrative matters. Both at EU and local levels, policies require farmers to be internally motivated and to take ownership of policy goals (Moller et al. 2006; Garini et al. 2017; Bonke and Musshoff 2020). To ensure policy effectiveness, farmers must possess a certain level of knowledge about the agroecological importance of crop diversification and how to go about implementing such systems. Training programs and advisory services are needed to better disseminate knowledge. Such outcomes fit with previous research (Dedeurwaerdere et al. 2015; Forney 2016; Šūmane et al. 2018) that found that farmers involvement in knowledge co-production and social learning processes helped to boost the implementation of environmentally friendly practices. A DiverIMPACTS policy brief (Messéan et al. 2021b) emphasized that crop diversification could be well suited to the EU Farm2Fork strategy. If such systems are properly implemented at broader scales, food production could become less dependent on fossil fuel-based agricultural inputs, display smaller environmental footprints, and help guarantee food security.

4 Conclusion

The main goal of this research was to arrive at broader lessons about the dynamics in operation in European crop diversification experiences (CDE). Using knowledge-driven modelling approaches, our study gained more insights on the roles of the different actors, their key relationships, cognitive processes, and organisational, technical, economic, and political factors which lead to agricultural change and innovation in the contexts of CDEs.

Novelty in our research refers to the comprehensive view of the farming system obtained through the systemic analysis of the network of actors involved in crop diversification experiences.

We found that farmers are at the core of every crop diversification experience, as they are also the initiators of most CDEs. Farmers are often self-motivated through ideals, environmental and health concerns but also by the desire to make profit and innovate. They cite fellow farmers as their most important partners in sharing knowledge, experience, and materials. Farmers' participation in unions and associations has often favored the initiatives. On a larger scale, however, the actors felt that there is a lack of product recognition in the market, limiting CDEs growth and development.

Another finding of our work was that researchers are the second most important actors as they have also been the initiators of some CDEs through scientific programs, bringing farmers and other key actors together. Most interactions take place at a local level, however, international exchanges often provide solutions and new ideas. The field experiments conducted through the scientific programs provide greater opportunities to test new farming practices that farmers could not afford to risk. Transdisciplinary approaches seem promising as they help ensure that jointly developed innovations correspond to local values and provide concrete solutions to all actors. State and private agricultural advisors provide more practical knowledge on agrotechnology, materials and support mechanisms. It is therefore important to provide training opportunities for the advisors about the design of agroecological systems and stress the importance of long-term planning.

European institutions and local authorities have played an important role in promoting diversification in agriculture through targeted financial support and additional requirements to basic payments. Nevertheless, policies related to crop diversification have often been inadequate to local climatic, social, and organizational conditions. Also, making diversification practices dependent on support mechanisms does not ensure a future of CDEs. Effective policies could help guide these shifts, but it is essential to further develop transdisciplinary projects, network coordination, and communication with citizens in order to support CDEs in the long run.

Crop diversification will not occur without value chain diversification. Value chain actors played a major role in overcoming technological, logistical, and market-related barriers. Research and policy should therefore seek to strengthen

relationships by promoting knowledge exchange and innovation and directing support measures for the diversification of value chains.

In summary, our systemic analysis of crop diversification networks suggests that a broader transition is only possible if there is a shift in the behavior and mindset of all actors involved. Effective policies could help guide these shifts, but it is essential to further develop network coordination and communication with citizens. Our study explored the functional roles played by actors and showed that in the different European countries, similar relationships act as levers or barriers to crop diversification. Future research could study the differences between private and public actors to better understand power dynamics within agrifood systems.

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Author Contributions FVW conceived and designed the methodological approach for the data collection and the data analysis and developed the R-scripts for the data analyses. FVW, RF, IRC, II, SC, LC, PR, JS, LV, DD, and AS lead the data collection in their own countries. MAC performed the qualitative analysis of the data and wrote the first draft of the paper. MAC, RF, IRC, II, SC, LC, PR, JS, LV, DD, AS, DS, and FVW contributed to the orientation of the context of the study, the data analyses, the discussion of the results and the writing of the paper.

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Data Availability As the qualitative interviews could contain sensitive information, the data of this research is not publicly available.

Code Availability Three original R-packages have been used and/or developed in the framework of this study. All of these are publicly available on official repository and/or main DevOps platforms:

- Duckles B, Sholler D, Draper J, Laderas T (2022). `qcoder` Lightweight Qualitative Coding. R package version 0.1.0, https://github.com/ropenscilabs/qcoder.
- Vanwindekens, F. (2019). `cogmapr` Cognitive Mapping Tools Based on Coding of Textual Sources. R-packages, Web Application and User Manual. Hosted on cran (https://CRAN.R-project.org/package=cogmapr) and gitlab for the development version, https://frdvnw.gitlab.io/cogmapr/.
- Vanwindekens, F. (2018). `surveyvisualizr` R-packages, Web Application and User Manual. Hosted on gitlab, https://frdvnw.gitlab.io/surveyvisualizr/dev/.

Declarations

Ethics approval The authors state that the research described in this article was conducted in accordance with the recommended standard principles of objectivity, transparency, and ethics.

Consent to participate Informed consent was obtained from all individual participants of the qualitative interviews.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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