Sustainability Science (2023) 18:2691–2706
https://doi.org/10.1007/s11625-023-01413-1

ORIGINAL ARTICLE

Crop diversification practices in Europe: an economic cross-case study comparison

J. A. Zabala[1] · V. Martínez-García[2] · J. M. Martínez-Paz[1] · E. I. López-Becerra[3] · M. Nasso[4] · E. Díaz-Pereira[5] · V. Sánchez-Navarro[6] · J. Álvaro-Fuentes[7] · M. González-Rosado[6] · R. Farina[8] · C. Di Bene[8] · E. Huerta[9] · A. Jurrius[10] · K. Frey-Treseler[11] · D. Lóczy[12] · L. Fosci[4] · E. Blasi[4] · H. Lehtonen[13] · F. Alcon[2]

Received: 28 June 2023 / Accepted: 31 August 2023 / Published online: 13 October 2023

Abstract
Crop diversification practices (CDPs) are alternative strategies aimed to achieve sustainable cropping systems and food production overcoming the agro-environmental impacts of conventional cropping systems such as monoculture. Thus, this paper aims to improve the knowledge of implementing CDPs in different European pedoclimatic regions by assessing the economic performance at the farm level. CDPs are compared with conventional cropping systems and clustered in terms of their gross margin (GM) results and variations. Farm-level assessment shows that CDPs provide positive economic results, representing an adaptive management strategy for ecological transition, without compromising economic sustainability. Particularly, the main findings show that (1) the impact of diversification depends more on crop type than on the selected CDPs, (2) most farms exhibited a low GM with low economic impact, and (3) there is a great likelihood that the CDPs facilitate the buildup of more resilient farming systems.

Keywords Gross margin · Cluster analysis · Cropping systems · Value chain · SWOT

Handled by Julia Bentz, Nova University Lisbon, Portugal.

✉ F. Alcon
francisco.alcon@upct.es

1 Department of Applied Economics, Universidad de Murcia, Campus de Espinardo, 30100 Murcia, Spain

2 Department of Business Economics, Universidad Politécnica de Cartagena, Paseo Alfonso XIII, 48, 30203 Cartagena, Spain

3 Department of Economy and Social Sciences, Universitat Politècnica de València, Camino de Vera, s/n Edificio 7J, 46022 Valencia, Spain

4 Department for Innovation in Biological, Agro-Food and Forest Systems (DIBAF), Via San Camillo del Lellis, 01100 Viterbo, Italy

5 Spanish National Research Council (CEBAS-CSIC), Campus de Espinardo, Espinardo, 30100 Murcia, Spain

6 Sustainable Use, Management, and Reclamation of Soil and Water Research Group, Department of Agricultural Engineering, Universidad Politécnica de Cartagena, Paseo Alfonso XIII, 48, 30203 Cartagena, Spain

7 Spanish National Research Council (CSIC), POB 13034, 50080 Saragossa, Spain

8 Council for Agricultural Research and Economics, Research Centre for Agriculture and Environment (CREA-AA), via della Navicella 2-4, 00184 Rome, Italy

9 Department of Environmental Sciences, Wageningen University, Droevendaalsesteeg 3, 6708PB Wageningen, The Netherlands

10 Ekoboerderij de Lingehof, Hemmensestraat 17, 6668LB Randwijk, The Netherlands

11 Weingut Dr. Frey, Alter Weg 9, 54441 Kanzem, Germany

12 Institute of Geography and Earth Sciences, Faculty of Sciences, University of Pécs, Ifjúság u.6., 7624 Pécs, Hungary

13 Natural Resources Institute Finland, PL 2, 00791 Helsinki, Finland

Introduction

Sustainable food production ensuring food security for a growing global population is one of the crucial challenges of this century. Intensive monocultures have a negative impact on agricultural output and, as a result, on agrifood systems (Lin 2011). However, growing global population, resources scarcity, water pollution and extensive land utilisation are factors converging with the impact of climate change. All these factors push institutions and private organisations to escalate the implementation of strategies to enhance the resilience of the farming systems and protect agroecosystems and food security locally and globally. Among the possible actions to be undertaken, the implementation of management strategies that enhance both resilience and environmental sustainability across different segments of food systems' value chains has been identified to be one of the most effective approaches to address these concerns, although empirical evidence is still incomplete and research is evolving (Bowles et al. 2020). One of the latest trends to enhance the sustainability and resilience of agricultural systems is based on diversification practices (Lahmar 2010). Diversification can be defined as a multi-level process which involves all actors of the agri-food value chain and the context in which they are embedded. Crop diversification practices (CDPs) encompass a range of cropping techniques, such as rotations, multiple cropping, intercropping and including minor crops incorporation within cropping systems (IPES-Food 2016; Di Bene et al. 2022). CDPs are often combined with a broader set of low-input practices, e.g., reduced or no tillage, mulching and integrated pest control (Kassam et al. 2015; Knowler and Bradshaw 2007). Nonetheless, the agri-food sector is complex and characterised by different types of stakeholders, and its competitiveness and efficacy depend strongly on the degree of collaboration and coordination between different actors in the value chains (Revoyron et al. 2022). Therefore, the acceptance of CDPs must be viewed within the whole product value chain. This entails considering the interlinked relationship among the expectations of consumers, farmers, producers and brokers about sustainability within heterogeneous food systems (Weituschat et al 2023a).

Diversified farming systems constituted the bulk of the agricultural production in Europe until the 1960s (de Roest et al. 2018). However, since the 1970s diversification practices have been replaced with alternative approaches, focusing mainly on monocultures aiming at maximising productivity per crop. Thus, farmers shifted their focus towards the adoption of novel technologies and modern production techniques, such as the adoption of high-yield plant varieties, intensive mechanisation and use of agrochemicals (Blasi et al. 2017). The consequences of monoculture encompass reduced crop diversification and an increase in the use of chemical products. This has resulted in increasing risks of systemic spread of pest and diseases, ground and surface water contamination, and declining soil health and biodiversity. Additionally, it has contributed to an overall greater economic risk for farmers (Magrini et al. 2016; Roest et al. 2018; Alcon et al. 2020). These social, economic and environmental issues arising from a highly specialised and intensive monocropping agricultural system could be tackled through the adoption of CDPs at both farm and value chain levels (Blasi et al. 2017; Kremen et al. 2012; Pretty and Bharucha 2014).

Crop diversification can be implemented by farmers using different approaches, such as cover crops, crop rotation, intercropping and agroforestry (Wezel et al. 2014). The combination of different types of CDPs may produce trade-offs between environmental and economic benefits (e.g., cover crops may favour biodiversity while reducing the yield of the main crop) (Rosa-Schleich et al. 2019; Sánchez et al 2022). In this regard, recent research and trial reported positive impacts related to the adoption of CDPs by farmers, such as the reduction of agrochemicals and the related pollution, improvement in soil quality, reduction in the greenhouse gas emissions and an overall improvement of ecosystem services and biodiversity (Castaneda-Vera and Garrido 2017; Duru et al. 2015; Knowler and Bradshaw 2007; Lahmar 2010; Reckling et al. 2016; Roest et al. 2018; Van den Broeck et al. 2013; De Roest et al. 2018). It was also reported that CDPs can be a viable solution to limit the negative impacts related to climate change (Basch et al. 2015; FAO 2018), being at the same time both profitable and income-stabilising for farmers, smoothing seasonality peaks of labour demand and reducing the risk of crop failure.

Currently, the adoption of CDPs among European farmers has been hampered by a range of constraints, resulting in their adoption being largely confined to niches of innovation, adopted by farmers who experiment with novel approaches to farm management. In fact, the adoption of CDPs in Europe nowadays is still low compared with other regions (Lahmar 2010). For instance, in 2014 only 1,5% of the arable land in Europe was allocated to the cultivation of grain legumes, which constitute one of the main emblematic crops of diversification, while they were grown on 14,5% of arable land globally (Watson et al. 2017).

Nevertheless, the viability of innovative farming systems must be carefully evaluated through collaborative trials co-designed by actors, to test crop management practices, new business model propositions and the integration of supply value chains. However, the main barrier for the advancement of CDPs lies in the complexity of these systems compared to monocropping counterparts. The current conventional value chains, and the wider institutional context in which they are embedded, are not the most favourable framework for their adoption and diffusion (Lamichhane 2023). Furthermore, a critical gap identified in the literature is the insufficient comprehension of drivers and barriers behind the adoption and diffusion of CDPs in Europe (Borremans et al. 2018). In fact, there is a large body of studies on minor crops and their potential to diversify crop production and land use, but they mostly focus on bio-physical aspects. These encompass topics such as how minor crops can mitigate N leaching, provide beneficial pre-crop effects for primary crops and similar issues. However, studies of the viability of diversification from a whole value chain-level perspective are limited or at least much less available. Thus, the current scientific research is mainly focused on the effects of adoption of CDPs on soil and crop levels rather than on the broader transition and adoption process by farmers and their interactions with other value chain actors and stakeholders (Morel 2020; Revoyron 2022). To assess the decision-making process itself, and not only the effects after the adoption of CDPs, information and knowledge at the farm level together with contextual information shall be included in the analysis.

Farmers stand at the heart of decisions on farm management and cropping diversification, and at this level profitability is one of the key aspects to consider for the development of CDPs. However, concentrating only on a farmer's decision of adopting CDPs is inadequate to explain their decision-making process, since farmers do not exist independently from their surroundings. Consequently, a multi-level approach to identify the institutional and business environment is needed to broaden the analysis of farmers' choices (Carlisle 2016; Knowler and Bradshaw 2007). Overall, despite these limitations, farm-level profitability of adoption of CDPs can play a key role in the improvement of the resilience of agricultural systems, especially in Europe (Alcon et al. 2020).

In this context, this paper aims to enhance our understanding of economic agroecosystem goods and services fluxes along with the consequences of implementing CDPs across various European regions by exploring if there exists a common pattern in the impacts of CDPs on the farm's economic performance. To this end, the farms that implemented CDPs are compared with those employing conventional cropping systems in terms of economic performance based on a three-year field experiment. Thus, farm-level profitability of crop diversification practices was assessed in 16 case studies in 6 different regions of Europe. The case studies included the application of CDPs in different pedoclimatic regions: Spain, Italy, Netherlands, Germany, Hungary and Finland. The results fulfil the gap in the literature and explore the decision-making process related to choices of farmers to adopt CDPs in Europe from a broad context, including the crucial role of value chain organisation as a potential vehicle in sustainability transitions.

Methodology

Case study description

Diversification strategies were proposed in the framework of Diverfarming project[1] by using a multi-stakeholder approach and considering the climate, soil and biographic characteristics of each pedoclimatic area. Crop rotation, intercropping and multiple cropping were implemented in perennial and annual crops and compared with conventional monocropping systems in terms of their environmental, agronomic and economic performance. More specifically, to monitor and understand the economic drivers, enablers and drawbacks of diversified cropping systems across Europe, 16 field case studies under diversified and monocropping systems were analysed. Annex.

Table 1 summarisea the main characteristics of the short-term case studies developed and the CDPs implemented. Each of these case studies was designed to have a 3-year crop cycle (2018–2020). A detailed summary of each case study is available in the Annex I.

The South Mediterranean pedoclimatic region

The South Mediterranean pedoclimatic region comprehends 5 out of 16 field case studies covering cereal, woody and vegetable systems located in different Spanish areas.

- **CS1:** Involves two types of diversifications in rainfed almond orchards in south-eastern Spain with permanent caper (*Capparis spinosa*) for food (D1) and with permanent thyme (*Thymus hyemalis*) for essential oil (D2).
- **CS2:** Two diversifications in mandarin orchards were implemented in south-eastern Spain. Diversification consists of two different types of alley intercropping along with traditional monocrop mandarin, which includes regulated deficit irrigation for the main crop to maintain water consumption from the monocrop.
- **CS3a:** Involves two diversifications in rainfed cereals, in Northeast Spain. Diversification consists of two different rotations with wheat and barley monocrops, respectively, for comparison.
- **CS3b:** Involves two diversifications in irrigated cereals, located in Northeast Spain. Diversification consists of two different rotations within the same year (multiple cropping system) with a maize monocrop.

[1] Diverfarming Project aims to develop and test different diversified cropping systems under low-input practices, for conventional and organic systems for 16 field case studies to increase land productivity and crops quality, and reduce machinery, fertilisers, pesticides, energy and water demands. How the diversified cropping systems can increase the delivery of ecosystem services is also explored. More details about Diverfarming project can be found in http://www.diverfarming.eu.

Table 1 Summary of the 16 case studies

Case study	Country	Pedoclimatic region	Crop type	Main crop	Type of diversification	Diversified crop
CS1	Spain	South Mediterranean	Perennial	Almond	Intercropping	D1: Caper D2: Thyme
CS2	Spain	South Mediterranean	Perennial	Mandarin	Intercropping	D1: Vetch/Barley + Fava bean D2: Fava bean + Purslane + Cowpea
CS3a	Spain	South Mediterranean	Annual	Wheat Barley	Rotation	D1: Wheat + Barley + Pea D2: Wheat + Barley + Vetch
CS3b	Spain	South Mediterranean	Annual	Maize	Multiple cropping	D1: Maize + Pea D2: Maize + Barley
CS4	Spain	South Mediterranean	Perennial	Olive	Intercropping	D1: Oat D2: Saffron D3: Lavender
CS16	Spain	South Mediterranean	Annual	Melon	Intercropping	D1: Cowpea
CS5	Italy	North Mediterranean	Annual	Maize	Rotation	D1: Tomato + Pea/ Tomato + Durum wheat
CS6	Italy	North Mediterranean	Annual	Durum Wheat–barley rotation	Rotation	D1: Tomato + Pea/ Tomato + Durum wheat
CS7	Italy	North Mediterranean	Annual	Tomato-Tomato-Durum wheat rotation	Rotation	D1: Tomato + Pea/ Tomato + Durum wheat
CS8	Netherlands	Atlantic	Annual	Biodynamic maize	Intercropping	D1: Beans
CS9	Germany	Continental	Perennial	Grapevine	Intercropping	D1: Thyme D2: Oregano
CS10	Hungary	Pannonian	Perennial	Asparagus	Intercropping	D1: Pea D2: Oat
CS11	Hungary	Pannonian	Perennial	Grapevine	Intercropping	D1: Yarrow D2: Grass
CS12	Finland	Boreal	Annual	Barley	Rotation	D1: Oilseed rape
CS13	Finland	Boreal	Annual	Fodder rotation	Rotation	D1: Barley + 30% Grass ley + Barley
CS15	Netherlands	Atlantic	Annual	Biodynamic vegetable rotation	Rotation	D1: Onion + Pea + Potato + Spelt + Red beet + Grass clover D2: Onion + Red beet + Pea + Onion + Potato + Spelt D3: Red beet + Onion + Pea + Red beat + Potato + Spelt

- **CS4:** Different types of annual and perennial crops grown as alley crops in olive yards in south Spain, to observe the effect of intercropping in contrast to monocropping.
- **CS16:** Melon crop with cowpea intercropping.

The North Mediterranean pedoclimatic region

The North Mediterranean pedoclimatic region comprehends 3 out of 16 field case studies, covering cereal and vegetable systems located in different Italian areas.

- **CS5:** Rotations of rainfed cereals and irrigated vegetables intercropped with legumes were established in north Italy to observe the effect of diversification compared to maize monocrop.
- **CS6:** Rotations of rainfed cereals and irrigated vegetables intercropped with legumes were established in north Italy to observe the effect of diversification compared to traditional rainfed cereal-based crop rotation.
- **CS7:** Rotations of rainfed cereals and irrigated vegetables intercropped with legumes were established in north Italy to observe the effect of diversification compared to traditional rotation of growing tomato and durum wheat.

The Atlantic pedoclimatic region

Case studies in the Atlantic pedoclimatic region, located in the Netherlands, comprised 2 out of the 16 short-term field experiments. They include irrigated annual crops.

- **CS8:** Intercropping of maize and beans was established in a biodynamic dairy farm in northern Netherlands to understand the improvement of diversification practices in comparison to traditional irrigated maize monocrop.
- **CS15:** Different rotations of biodynamic vegetable crops were tested in a biodynamic farm in northern Netherlands and compared with the business-as-usual vegetable rotation which includes grass clover for feed.

The Continental pedoclimatic region

The case study located in the Continental pedoclimatic region is from Germany. This comprises rainfed perennial woody crops as the main crop.

- **CS9**: Intercropping of rainfed organic vineyards with aromatic herbs was established in western Germany, where the effects of intercropping were compared with grapevine monocrop.

The Pannonian pedoclimatic region

Case studies in the Hungary Pannonian pedoclimatic region comprise 2 out of 16 short-term field experiments. They include irrigated and rainfed perennial crops diversified through intercropping.

- **CS10:** Intercropping of asparagus with legumes and cereals was established in the central region of Hungary and compared with traditional irrigated asparagus monocrop.
- **CS11:** Intercropping of grapevine with herbs and grass was established in south Hungary and compared with traditional rainfed grapevine monocrop.

The Boreal pedoclimatic region

2 out of 16 field case studies in the Boreal pedoclimatic region were included, both covering rainfed cereal systems located in south-east Finland.

- **CS12:** A rotation of cereals was compared with the traditional rainfed cereal monocropping system.
- **CS13:** Rotation of cereals and grass for fodder was developed in a dairy farm providing milk for specialised small-scale artisan cheese production. This diversification practice seeks to increase grass ley production compared with the business-as-usual rotation strategy.

Farm-level economic analysis

Comparison between conventional (monocropping) and CDPs systems allows a better understanding of how the presence of greater diversity in agricultural landscapes is translated into an increase in the provision of ecosystem services, whose economic value goes beyond the farm gate. The farm-level economic analysis investigates the cross-case study patterns regarding the gross margin results of CDPs considering crop types, diversification strategies and regions. It seeks to explore the economic performance of crop diversification and identify if there are any common patterns among the impact of CDPs on farm-level economic performance.

Farm-level economic analysis has been based on gross margin (GM) estimations following Fernandez et al.'s (2020) procedure. Calculations utilising crop-specific input use, crop output and specific price data were made per crop and cropping system (conventional and diversified). Depending on which factors of production are accounted for per crop, several levels of GMs can be identified. In this paper, GM that includes only variable factors, except labour, as costs is utilised due to the easy comparability among case studies and to avoid any disturbance that may arise from different definitions of own labour and fixed costs. GM estimations include revenues, as the value of saleable production (VSP) and CAP subsides, and variable costs that include both input and operational costs, with GM = VSP + CAP – input costs – operational costs. This is the financial result determined solely on the basis of technical cultivation and pedoclimatic conditions, without considering the own labour and the cost of own capital conferred directly by the landowner farmer. The GM indicator is used to obtain uniform results between case studies and because it provides a value closer to the value that farmers consider when they decide to adopt new techniques or to include new crop in their cropping plan.

Inputs, yields and agricultural management practices-related data were collected yearly at plot level per crop and aggregated by cropping system up to the farm level. Technical information, referring to variable costs, was gathered directly from the case study plots, while market prices and subsidy values were derived from farmer's suppliers and official regional statistics, respectively. Therefore, the revenues and variable costs obtained correspond to real cost and revenues from farm expenditure in the areas where the case studies were carried out.

In addition, all the current monetary values are homogenised to the average standard of living of the European Union through the purchasing power parity (PPP) (World Bank 2021). Finally, GM differences between crop diversification and monocropping practices are estimated to analyse the contribution of crop diversification to the farm-level economic results.

Cluster analysis

Cluster analysis is employed to find dependencies between the characteristics (unifying and distinguishing factors) of the data by grouping similar observations, or variables, into clusters. In this study, the farm-level economic results of crop diversification across the Diverfarming case studies are clustered according to their GM and their contribution with respect to monocropping margins (ΔGM).

The clustering process was made by an unsupervised classification using K-means as a centroid model-free clustering algorithm. This approach was used because there were no prior assumptions on the distribution of the data and the process was based on dissimilarity measures. With K-means, each of the data points can be assigned to only one cluster (hard clustering) with the nearest mean (cluster centroid) so that the variance within each cluster is minimised (Hartigan and Wong 1979). To determine the right number of clusters, k^* from the set of K solutions, scree plots are used and a kink is searched in the curve generated from the within-cluster sum of squares.

SWOT analysis

To investigate the CDPs adoption under a broader perspective, a SWOT analysis was developed based on the results obtained. SWOT is a strategic planning method for addressing and positioning the resources and environment of organisations, initiatives, plans or strategies in four regions: strengths, weaknesses, opportunities and threats (Alcon et al. 2014; Phadermrod et al. 2019). SWOT analysis is used to identify the factors that encourage the adoption of CDPs by farmers (internal factors) and along the food value chain, comprising also the contextual and environmental factors that may influence such adoption (external factors). Considering the SWOT analysis from the standpoint of diversification, internal factors (strengths and weakness) are those related to the characteristics and features of diversification itself, such as the ease of adoption for farmers (operational, investment and transaction costs) and its expected farm-level profitability. External factors (opportunities and threats) include the European agricultural, economic, social and legislative context that may ease or hinder the adoption of crop diversification practices.

Results

Economic result comparison of CDPs and monocultures between European case studies were made at the farm gate level and clustered by using GM and CDPs economic differences.

Farm-level economic analysis

The farm-level economic performance of crop diversification shows a wide dispersion in the results across case studies and regions in Europe. Figure 1 shows the obtained GMs per case study, differentiating between diversification and monocropping practices. This wide dispersion among the results is mainly determined by the crop types assessed.

The highest GMs are related to diversification practices among vegetable crops, such as melon in CS16 (Spain), asparagus in CS10 (Hungary), the biodynamic rotation of onion, potato and reed beet in CS15 (Netherlands) and grapevine in CS11 (Hungary). In contrast, the lowest gross margins, in some cases even negative, refer to cereals and perennial crops in rainfed conditions, such as barley and wheat in CS3a (Spain), barley and grass rotations in Finland (CS12–CS13) and rainfed almond crops in CS1 (Spain). However, despite the mentioned fact, there is no a priori clear pattern among the farm-level economic results.

To account for the impact of crop diversification on farm economic performance, differences in GM between diversified and monocropping practices are estimated and reported. Figure 2 shows changes in GM for each case study by pedoclimatic region. Once again, the data shows a great dispersion of the impact of crop diversification on farm-level economic performance within and across the European regions. Notwithstanding, it should be highlighted that, in most cases, there is a positive impact of crop diversification in margins, although some of such increments are low or very low compared with their respective total GM. The highest increments take place in the grapevine of CS11 in the Pannonian region, followed by the biodynamic vegetable rotations of CS15 in the Atlantic region, and melon crop of CS16 in the South Mediterranean region. Intercropping in mandarin orchards in CS 2 (Spain) and multiple cropping in maize in CS 4 (Spain) reveal negative contributions to farm-level economic results. However, the statistical analysis of such case studies showed no significant differences between monocropping and diversification practices, given the high internal variability of their farm-level economic results (Martin-Gorriz et al. 2022). As such, the contribution of crop diversification to the farm-level GMs is expected to be positive or, at least, not significantly negative.

Cluster analysis

To establish a clear pattern in the economic performance of crop diversification, the assessment of GMs and their variations regarding monocropping practices is further explored. Hence, the focus shifts to the analysis of these two variables in an integrated way, intended to isolate the crop diversification contribution. Cluster analysis explores the economic patterns that arise from the assessment of farm-level

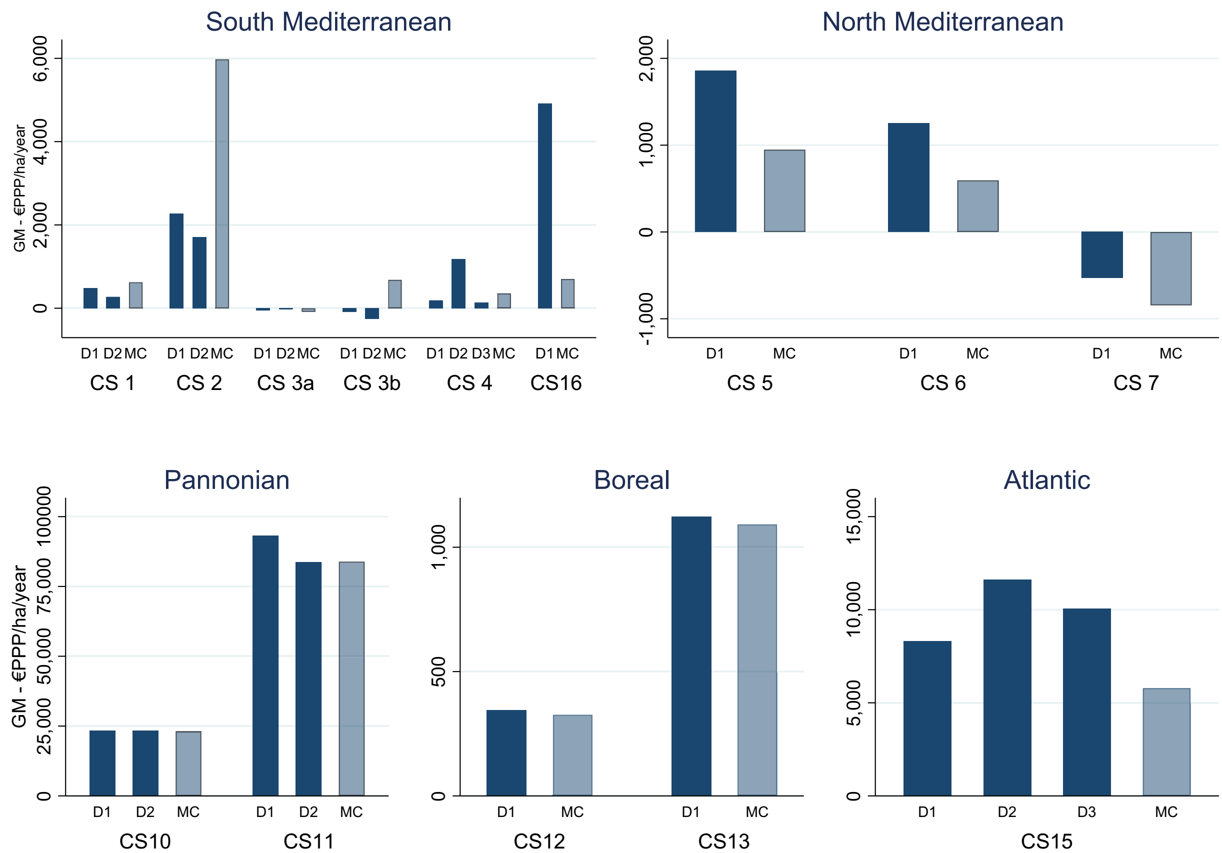


Fig. 1 Gross margin (GM) by case study and region (€$_{PPP}$/ha/year)

economics, as a result of the analysis. Figure 3 shows graphically the clustering carried out for the 16 case studies. The optimal number of clusters is determined by analysing the WSS curve, which resulted in a set of six clusters.

The first identified cluster indicates the two diversifications of CS2, with relatively low GMs and negative differences regarding the economic performance of the monocrop. It refers to the intercropping of mandarins with vetch/barley for fodder and fava bean for food (D1) and the annual rotation of three intercropping of fava bean, purslane and cowpea for food (D2).

On the other hand, the second cluster encircled CS11, which reveals the highest GMs and increases in the margins regarding monocropping. It includes grapevine intercropped with yarrow for essential oil (D1) and with grass for fodder (D2). Promising results, in terms of the profitability of CDPs, are shown in the case of the intercropping of grapevine with yarrow for essential oil, given the high positive increase of 10% in GM from grapevine monocrop to such diversification.

Cluster 3 comprises diversifications with relatively medium GMs, but high increases regarding their respective monocrops. It includes the biodynamic and organic vegetables located in the Netherlands (CS15) and Spain (CS16), respectively. More specifically, CS15 includes the annual rotation of biodynamic onion, pea, potato, spelt and red beet, while CS16 refers to melon intercropped with cowpea. The third cluster also shows promising results, given the capability of such diversification to provide positive economic results that clearly overcome the monocropping economic values. In addition, cluster 4 also relates to vegetable crops. It includes asparagus (CS10) intercropped with pea (D1) and oat (D2) in Hungary, in the Pannonian region, showing high GMs but low impact of crop diversification.

Most case studies were located in clusters 5 and 6, which include those diversifications with low or even negative GMs and around null net economic impact derived from CDPs adoption. Figure 4 shows the graphical representation of such clusters, as a zoom of Fig. 3, with the dispersion and variability of the farm-level economic results. From a general perspective, clusters encircle cereals and/or crops under rainfed conditions, independently of the European region.

Nonetheless, some differences are found between such clusters that might be underlined. Cluster 5 indicates those diversifications with higher GM and higher impact regarding farm-level economic results from monocropping practices, independently of the crop type and pedoclimatic region. It includes the Italian rotations of wheat and tomato

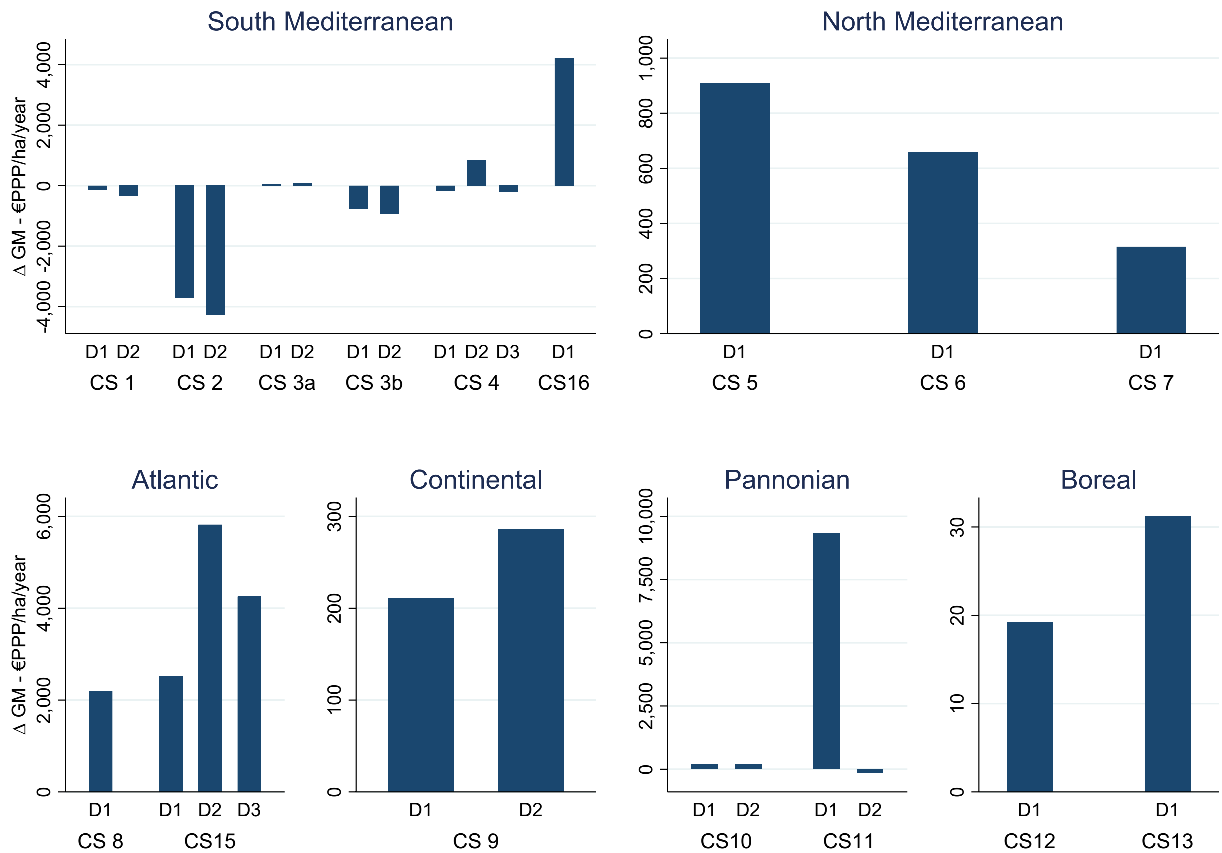
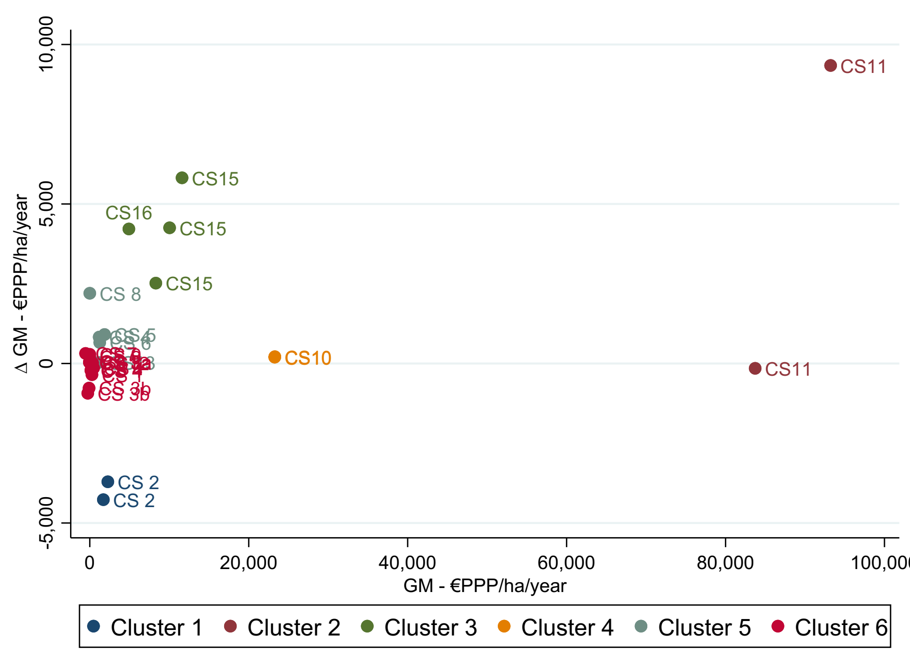


Fig. 2 Change of gross margin (GM) from monocrop to diversification, by case study and region. (€$_{PPP}$/ha/year)

Fig. 3 Clusters of the 16 case studies considering their gross margin (GM) and the increase of GM due to CDPs with regard to monocropping (ΔGM)



intercropped with pea with a better economic performance. Such vegetables are categorised together with rainfed cereals from the Finnish CS13 and rainfed olive trees in the Spanish CS4, showing wide differences among crop types within such a cluster. At this stage, it is important to highlight that CS4 becomes the only case study whose diversifications are

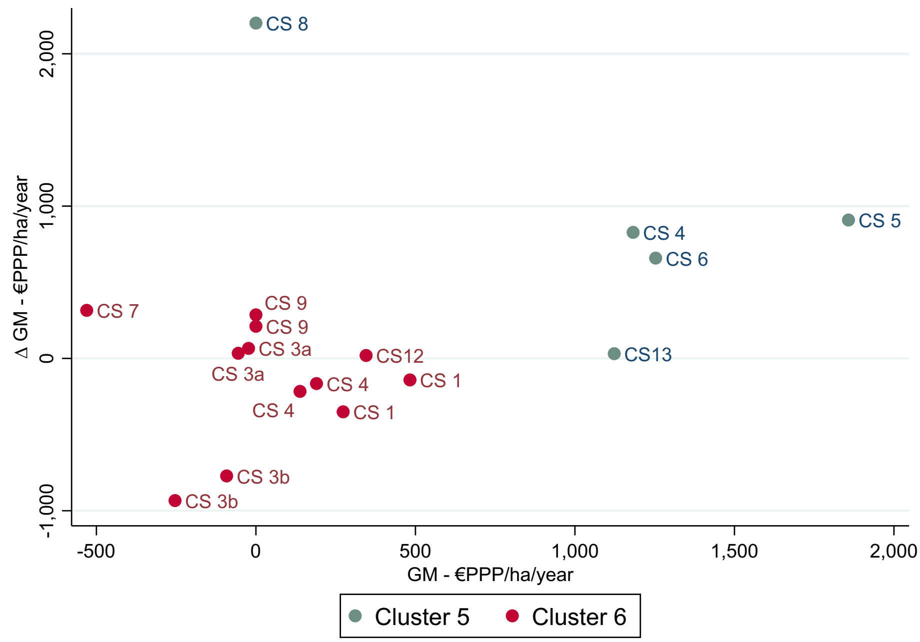


Fig. 4 Clusters 5 and 6 of Diverfarming case studies considering their gross margin (GM) and the increase of gross margin with regard to monocropping (ΔGM)

included within two different clusters: cluster 5 and cluster 6. Indeed, it clearly reveals that the type of diversification developed may significantly change the far- level economic performance, and hence shows the importance of diversified crop selection for ensuring good farm-level economic results. In such a case, olive intercropping with saffron is the within diversification (D2) of the CS4 that provide these positive results. Finally, CS8 is also included within cluster 5, given the cost savings provided by the biodynamic intercropping of maize and beans for fodder in the context of dairy farming.

Cluster 6 is the cluster with the greatest number of case studies. It includes a total of seven different case studies, with the common feature that almost all of them were grown under rainfed conditions, such as the case of rainfed trees in CS1, almond trees intercropped with capers (D1) and thyme (D2) and in CS4 olive trees intercropped with oat (D1) and lavender (D3). Similar conditions apply to the rotation of cereals in CS3a. All these three case studies have in common that, in addition to their rainfed condition, they are located in the South Mediterranean region and provide a worse farm-level economic performance than their respective monocrops. Besides this, cluster 6 encompasses rainfed cereals in the Finnish CS12 (Boreal), rainfed grapevine in the German CS9 (Continental), the rotation of irrigated vegetables and rainfed cereals in the Italian CS7 (North Mediterranean) and irrigated multiple cropping of maize and pea/barley in the Spanish CS3b (South Mediterranean). All the mentioned diversifications share their low GM-A coupled with a low (almost zero) farm-level impact. Case C7 presents the worst figure, due to the substantial loss of two crops (peas and tomato) in CDPs instead of one as in the case of conventional crops during the first year of the experiment. This result reveals the extent of risk due to the management of new cropping systems in years that experience extreme climatic events.

In sum, the assessment of the farm-level economic results shows that the impact of diversification depends more on the crop type than on the type of crop diversification; there exists a great frequency of low GMs with low economic impact; and above all, there is a great likelihood that crop diversification provides positive farm-level economic results or, at least, no significant impacts. In any case, crop diversification allows farmers to reduce their income dependence on price variability of only one product, that is, to reduce their market risks.

SWOT analysis

SWOT factors could influence the adoption of CDPs in Europe by farmers' and stakeholders' value chain. Table 2 provides a glance of the economic SWOT that encourages and hinders this process.

Internal factors were derived mainly from farm-level economic results, together with some technical issues that have been found to be significant in farmers' decision making. External factors are those unrelated to the characteristics and features of crop diversifications itself that could favour or hinder its adoption. External factors are mainly related to the current socio-political environment.

Table 2 Description of SWOT factors for the adoption of crop diversification

STRENGTHS (Internal reasons why farmers should adopt diversification)	
s1	Crop diversification has a positive impact on farm-level economic results or, at least, no negative impact
s2	Crop diversification benefits usually overcome total costs (including market, social and environmental costs and benefits)
s3	Access to new markets and reduced monocropping income dependence (market risk reductions)
s4	Expected financial and economic gain in the long term
s5	Improved farm health and quality (soil quality, biodiversity, landscape, CO_2 balance, etc.)
s6	Greater stability production
s7	Diversification practices suitable for all crop types
s8	Diversification helps to mitigate climate change impact
WEAKNESSES (internal reasons why farmers do not adopt diversification)	
w1	Diversification does not always show a clear positive financial profitability
w2	Invisibility of environmental benefits
w3	In some cases, investments are necessary (start-up costs)
w4	Lack of knowledge about the crop behaviour at field level (cognitive values, beliefs and assumptions)
w5	The necessary technology is not always available for use at the farm level
OPPORTUNITIES (external reasons that could favour the adoption of diversification)	
o1	Obtain better sales contract and trustful relationships with the buyer
o2	There is a societal demand for environmentally friendly produced food
o3	Possibility to obtain differentiated products (labels)
o4	The existence of previous studies to help farmers use diversification
o5	Adapting farm to ecological transition (green deal)
o6	Political will to support sustainable ways of agricultural production
THREATS (external reasons that could hinder the adoption of diversification)	
t1	Pathways to adopt crop diversification (labelling, subsidies) depend on the context and stakeholders' acceptability
t2	Additional transaction and operation and maintenance costs for such pathways
t3	Lack of awareness of the existence of diversification
t4	Lack of trust about the diversification gains
t5	Lack of agricultural experts with some knowledge of crop diversification

Discussion

The assessment and understanding of the economic performance of each CDP by and across case studies has provided interesting insights, not only on the GM expected by crops and country, but also on the expected impacts of CDPs across Europe. Farm-level economic analysis showed the contribution of CDPs adoption to farm benefits and costs. This is highly relevant, since the economic rationale behind CDPs constitutes the first step for ensuring the adoption of CDPs among European farmers. Also, CDPs clusters, by GMs and their variations, suggest that it is expected that for most of the diversification practice adoption, low, or even negative GMs and around zero net economic impact is achieved, except for vegetable crops. Non-negative GM impact, together with the improvement in ecosystem services, represents the main strength of CDPs. However, such strengths need to be exalted against the invisibility of environmental benefits, the presence of higher start-up and labour costs and lack of adapted technologies, which may act as weaknesses to undermine the adoption of CDPs by farmers. Although adoption would take place on the first steps of the food value chain, intermediaries also play a key role as facilitators (or detractors) for enabling the CDPs adoption. Brokers, manufacturers, wholesalers and retailers represent the interlink between societal demand for more sustainable products, such as those produced in diversified cropping systems, and farmers. Therefore, the food value chain should be understood as a whole, where relationships among agents should be considered, as they may provide an opportunity for the scaling of crop diversification. On the one hand, consumers and society as a whole are the beneficiaries of the environmental and socio-cultural benefits provided by CDPs. On the other hand, consumers have the potential to emerge as the main drivers of cropping system transformation, shaping the way in which food is produced through their growing preference for sustainable products. Thus, the economic ramifications of crop diversification extend far beyond the confines of the farm gate.

In general, the farm-level economic results have evidenced positive impacts of crop diversification on the farm profits, or, at least, non-negative impact, which may become the first enabler for adopting crop diversification. This results are encouraging due to the positive environmental and societal benefits, at no or little cost for a farmer, that diversification often implies (Latvala et al. 2021). Therefore, the transition from monocrop to diversification, which may become a critical phase for its implicit and explicit costs, is shown as an ordinary farm activity without any significant negative impact on results.

The presence of more than one crop in the farm may be translated into a reduction in market risk for farmers, given that their farm profitability does not depend on a single product. Besides this, another great enabler for the adoption of crop diversification is the wide range of suitable diversification practices to be implemented (intercropping, rotations or multiple cropping). All these benefits are then confirmed for the long term, which make the most to increase the resilience of agriculture to counteract the negative effects from climate change, another crucial enabler to favour the adoption of crop diversification by farmers.

Considering the SWOT analysis, weaknesses derived from economic results could be barriers for CDPs adoption. Given that there are no clear positive effects of crop diversification (non-negative) on farm economic analysis, it may become challenging to persuade farmers to switch to diversified farming given that they are not going to receive any significant direct economic premium in the near term. This represents the first economic weakness of crop diversification adoption. Besides this, the environmental and socio-cultural benefits, if not directly compensated to farmers for their generation, become invisible to them, resulting in a direct barrier for the adoption of crop diversification.

On the other hand, when diversified crops are cultivated in the same field for more than 1 year, such as caper and thyme in CS1 or saffron in CS4, they require initial *investment costs*. This may be an additional barrier on adoption, together with the fact that usually these crops require a period of maturity before producing, which also increases these starting-up costs. The lack of knowledge about crop behaviours and operations needed for crop diversification at field level are also viewed as a weakness. As it has turned out in the case studies, farmers may be unaware of the different types of alternative diversifications available for their crops, or, if they are aware, they do not know how to deal with them properly at field level (Rodriguez et al. 2021; Brannan et al. 2023; Rossi et al. 2023). This barrier could be easily overcome by training sessions with farmers and dissemination activities.

Finally, another weakness that farmers may face relates to the availability of technology adapted to crop diversification, which allows them to make the farm operations the most efficient (and least costly) way. For instance, this situation is presented in CS1 for thyme harvesting, which is done by hand, due to the unavailability of specialised-adapted machinery in the farm. This is a real obstacle, since the need for additional labour is highly seasonal, and it may be difficult or costly to hire the needed labour. The higher labour costs in diversified farming systems could be overcome by the development of specifically adapted technology (Martin-Gorriz et al. 2022; Sánchez et al. 2022). Machinery developers and vendors may see the markets of such specialised machines as small or uncertain and do not invest in necessary R&I and product development activities.

External factors may act as significant enablers and opportunities when they drive the adoption of crop diversification. For example, the development of crop diversification practices, if well understood by buyers and intermediaries of the food supply chains, may improve the relationships between actors in different value chains and better sales contracts may be offered to farmers. This was explored in the Italian case studies by using sales contracts between farmers and buyers, providing good results for the re-design of diversified food value chains (Weituschat et al. 2023a). In addition, from the supply-side perspective, the current trend in agricultural systems is the general transition to more diversified systems, with a growing number of experiences about good (and bad) crop diversification practices. To pull farmers into this new technical managerial path, it is necessary to increase the relationships between farmers and farmers and between farmers and other value chain actors and advisors.

Other relevant enablers of crop diversification adoption come from the demand side. Mainly, it refers to the increasing social demand for environmentally friendly produced food (Alcon et al. 2020; Latvala et al. 2021). This necessarily requires information systems that truthfully verify such differentiated products by means of labels (Akaichiet al. 2022). Finally, the political context also aids in fostering the adoption of more sustainable ways of producing, where crop diversification plays a significant role. Diversification can be seen therefore as an instrument to support the transition toward more sustainable European food systems, in line with the Green Deal and the Farm to Fork and Biodiversity strategies.

External factors that could hinder the adoption of crop diversification include threats. On the one hand, there are some barriers related to the transition pathways from monocropping to diversified agri-food systems. From the results of the economic assessment of the food value chain of diversified systems, it was evinced that the transition pathways to foster crop diversification (labelling, farm subsidies…) depends on the agricultural products considered, the regions and the type of value chains. Therefore, it is subjected to agri-food stakeholders' acceptability. This makes it challenging to establish a general recipe to encourage the adoption of crop diversification away from the farm gate and easily applied across Europe (Weituschat et al. 2023a). Moreover, each pathway may have some associated transaction, operational and maintenance costs, which adds complexity to the selection of the best pathway for each agricultural product. This became clear in the cases of equipment or agreement needed for yarrow or thyme oil pressing in Hungarian and German case studies. On the other hand, society plays a key role in such a transition. Although society is increasingly worried about environmental concerns and there is a social demand for environmental benefits, there is a lack of awareness of the existence of crop diversification, opportunities for real societal gains and how/where to buy diversified products (Rossi et al. 2023).

The lack of agronomist and agricultural experts with a solid background in crop diversification and ready to advise farmers in the transition becomes an additional barrier. Both farmers and farm advisors in some (at least in Mediterranean region) case studies have expressed their limited knowledge and experience in crop diversification (Weituschat et al. 2022), showing thus some sort of lock-in and specialisation to monocultural farming practices. A dynamic optimisation modelling study on CS 13 dairy farm case showed that utilising empirically evidenced pre-crop values between crops, including also minor crops, such as oilseeds and temporary forage grasses, in deciding crop rotations, may result in significant gains in crop yields and farm economy over several years (Tzemi and Lehtonen 2022). However, farmers are not always aware of the pre-crop effects and not used to utilise them in their management decisions and consider longer time spans instead of management of single crops in the short run.

Finally, the SWOT of economic factors that have been identified for the adoption of crop diversification provides a clear and direct view of the current situation of the main forces that enable or hinder crop diversification in Europe. This assessment may offer key insights and a basis for the development of agri-food strategies focusing on enhancing the farmers' strengths and socio-political opportunities to deal with the weaknesses and threats. For instance, some of these strategies may be in line with increasing dissemination and knowledge transference from the diversification results for both the agricultural sector (farmers) and society (consumers), and expands the support to farmers, at least, in the first stages of the transition to diversified systems. Also, a participatory advisory approach of CDPs communities of practitioners could include specific strategies focused on adapting new managerial and contract solutions (including mitigation risk tools at least in CDPs introduction phase) to socioeconomic, pedoclimatic and supply chain features in their agenda.

In sum, the analysis developed and discussed here suggests forthcoming research lines about crop diversification. On the one side, research about crop diversification should expand the knowledge about the farm-level economic impact of the crop diversification to other crops and pedoclimatic regions so that the results presented here could be deeply contrasted. On the other hand, and more specifically, transfer of knowledge from academy to farmers is key to ensure its adoption and guide the transition to sustainable farming systems. The environmental benefits of crop diversification are widely known (Morugán-Coronado et al. 2022), while the knowledge about its economic impacts is currently growing (Rosa-Schleich et al. 2019; Sánchez et al. 2022). However, the adoption of CDPs by farmers is still stuck. As such, future research seeks to concentrate its efforts to address the lock-ins that delay the adoption of CDPs. Financial incentives might be a possible pathway for deepening knowledge (Weituschat et al. 2023b), as payment for the ecosystem services provided (Alcon et al. 2020; Blasi et al. 2023), among others. Further research is needed on cognitive, social and inherent factors affecting the acceptability of new agricultural practices not only by farmers (Dessart et al. 2019; Weituschat et al. 2022), but also for the different stakeholders along the agri-food value chain (Weituschat et al. 2023a). This will thereby ensure the effectiveness of the transferability of knowledge results about CDPs.

Conclusion

The farm-level economic assessment of crop diversification practices (CDPs) in 16 case studies across Europe has evinced that crop diversification does most often not provide significant changes in farm-level economic results and, in case it does, they are expected to be often positive and even significantly positive for the case of diversification in vegetable production. Moreover, farm-level economic results provide a blinded view of the real contribution of crop diversification to society.

Results are useful to guide both farmer decisions about crop and cropping practices choices, and also other value chain actors and agri-food policies. Sustainable agroecosystems and enhancing ecosystem services provision are demanded by society (given the environmental and socio-cultural benefits), might be respected by farmers (due to the low, but often positive impact on farm-level economic results) and are expected to be supported by policymakers (because of its long-term positive performance). Therefore, crop diversification is shown to be a non-costly practice to build resilience into farming systems as adaptive management for ecological transition in Europe.

Appendix 1: Description of the case studies for each pedoclimatic region

The South Mediterranean pedoclimatic region

The South Mediterranean pedoclimatic region includes 5 out of 16 field case studies, covering cereal, woody and vegetable systems located in different Spanish areas.

- CS1 Almond trees

  CS1 involves two types of diversifications in rainfed almond orchards in south-eastern Spain. Diversification consists of alley intercropping along with traditional monocrop almond:

  Monocrop (MC): almond (*Prunus dulcis*) monocrop.

  Diversification 1 (D1): almond intercropped with permanent caper (*Capparis spinosa*) for food.

  Diversification 2 (D2): almond intercropped with permanent thyme (*Thymus hyemalis*) for essential oil.
- CS2 Citrus trees

  Two diversifications in mandarin (*Citrus reticulata var. Clemenvilla*) orchards were implemented in south-eastern Spain. Diversification consists of two different alleys intercropping along with traditional monocrop mandarin, with regulated deficit irrigation for the main crop to maintain water consumption from monocrop:

  Monocrop (MC): mandarin monocrop.

  Diversification 1 (D1): mandarin intercropped with vetch/barley (*Vicia sativa/Hordeum vulgare*) for feed (January–June) and fava bean (*Vicia faba*) for food (September–January).

  Diversification 2 (D2): mandarin intercropped with fava bean (*Vicia faba*) for food (September–January) in 2018; purslane (*Portulaca oleracea*) for food (March–June) in 2019; and cowpea (*Vigna unguiculata*) for food (June–September) in 2020.
- CS3a Cereal crops

  CS3a involves two diversifications in rainfed cereals, located in Northeast Spain. Diversification consists of two different rotations along with wheat and barley monocrop, respectively, for comparison:

  Monocrop 1 (MC1): wheat (*Triticum durum*) monocrop for food.

  Monocrop 2 (MC2): barley (*Hordeum vulgare*) monocrop for feed.

  Diversification 1 (D1): wheat (*Triticum durum*) – Barley (*Hordeum vulgare*) – Pea (*Pisum sativum*) rotation, where wheat is for food and barley and pea are for feed.

  Diversification 2 (D2): wheat (*Triticum durum*) – barley (*Hordeum vulgare*) – Vetch (*Vicia sativa*) rotation, where wheat is for food and barley and vetch are for feed.
- CS3b Maize

  CS3b involves two different rotations of irrigated maize along with maize monocrop in Northeast Spain:

  Monocrop (MC): maize (*Zea mays*) monocrop.

  Diversification 1 (D1): maize (*Zea mays*) – barley (*Hordeum vulgare*) multiple cropping, where maize is for food and barley for feed.

  Diversification 2 (D2): maize (*Zea mays*) – pea (*Pisum sativum*) multiple cropping, where maize is for food and pea for feed.
- CS4 Olive trees

  Different types of annual and perennial crops are grown as alley crops in olive yards in south Spain, to observe the effect of intercropping in contrast to monocropping. The three diversifications are as follows:

  Monocrop (MC): olive (*Olea europaea* var. *picual*) monocrop.

  Diversification 1 (D1): olive intercropped with oat (*Avena sativa*) and vetch (*Vicia sativa*) for feed.

  Diversification 2 (D2): olive intercropped with saffron (*Crocus sativus*) for food.

  Diversification 3 (D3): olive intercropped with lavender for (*Lavandula* spp.) essential oil.
- CS16 Vegetable crops

  CS16 involves irrigated organic melon in south-eastern Spain, which has been intercropped with cowpea to observe the effect of diversification in contrast to monocropping. The presence of legumes in the intercropping decreases fertiliser rates by 30%. Therefore, the practices are as follows:

  Monocrop (MC): melon (*Cucumis melo*) monocrop.

  Diversification 1 (D1): melon intercropped with cowpea (*Vigna unguiculata*) for food.

  The North Mediterranean pedoclimatic region

  3 out of 16 field case studies in the North Mediterranean pedoclimatic region are presented, covering cereal and vegetable systems located in different Italian areas.
- CS5 Maize

  Rotations of rainfed cereals and irrigated vegetables intercropped with legumes were established in north Italy to observe the effect of diversification in contrast to maize monocropping. Therefore, the practices under study in this Deliverable D8.5 are as follows:

  Monocrop (MC): maize monocrop.

Diversification 1 (D1): tomato (*Solanum lycopersicum* L.)—pea (*Pisum sativum*)/tomato (*Solanum lycopersicum* L.) intercropping—durum wheat (*Triticum durum Desf.*) rotation for food.

- CS6 Cereal crops

  Rotations of rainfed cereals and irrigated vegetables intercropped with legumes were established in north Italy to observe the effect of diversification compared with traditional rainfed cereal rotation. Therefore, the practices under study in this Deliverable D8.5 are as follows:

  Conventional crop rotation: durum wheat (*Triticum durum Desf.*)—barley (*Hordeum vulgare*)—durum wheat (*Triticum durum Desf.*) for food.

  Diversification 1 (D1): tomato (*Solanum lycopersicum* L.)—pea (*Pisum sativum*)/tomato (*Solanum lycopersicum* L.) intercropping—durum wheat (*Triticum durum Desf.*) rotation for food.

- CS7 Tomato—durum wheat rotation

  Rotations of rainfed cereals and irrigated vegetables intercropped with legumes were established in north Italy to observe the effect of diversification compared with traditional rotation of tomato and durum wheat:

  Conventional crop rotation: tomato (*Solanum lycopersicum* L.)—tomato (*Solanum lycopersicum* L.)—durum wheat (*Triticum durum Desf.*) rotation for food.

  Diversification 1 (D1): tomato (*Solanum lycopersicum* L.)—pea (*Pisum sativum*)/tomato (*Solanum lycopersicum* L.) intercropping—durum wheat (*Triticum durum Desf.*) rotation for food.

  Atlantic pedoclimatic region

  Case studies in the Atlantic pedoclimatic region are located in the Netherlands and include 2 out of 16 of the field short-term experiments. They include irrigated annual crops.

- CS8 Biodynamic fodder crops

  Intercropping of maize and beans was established in a biodynamic dairy farm in northern Netherlands to understand the improvement of diversification practices in comparison with traditional irrigated maize monocrop:

  Monocrop (MC): naize (*Zea mays*) for fodder.

  Diversification 1 (D1): naize intercropped with beans (*Phaseolus vulgaris*) for fodder.

- CS15 Biodynamic vegetable crops

  Different rotations of biodynamic vegetable crops were tested in a biodynamic farm in northern Netherlands and compared with the business-as-usual vegetable rotation which includes grass clover for feed. Therefore, the assessed field experiments are as follows:

  Baseline 1 (BAS1): onion (*Allium cepa*)—pea (*Pisum sativum*)—spelt (*Triticum spelta*)—potato (*Solanum tuberosum*)—grass clover—grass clover rotation, with vegetables for food and grass for fodder.

  Baseline 2 (BAS2): red beet—pea—spelt—potato—grass clover—grass clover rotation, with vegetables for food and grass for fodder.

  Diversification 1 (D1): onion—pea—potato—spelt—red beet (*beta vulgaris* l.)—grass clover rotation, with vegetables for food and grass for fodder.

  Diversification 2 (D2): onion—red beet—pea—onion—potato—spelt rotation for food.

  Diversification 3 (D3): red beet—onion—pea—red beat—potato—spelt rotation for food.

  Continental pedoclimatic region

  The case study was located in the Continental pedoclimatic region and comprised rainfed perennial woody crops as the main crop.

- CS9 Organic vineyards

  Intercropping of rainfed organic vineyards with aromatic herbs was established in western Germany, where the effects of intercropping were compared with grapevine monocropping:

  Monocrop (MC): grapevine (*Vitis vinifera* L.) monocrop for food.

  Diversification 1 (D1): grapevine intercropped with thyme (*Thymus vulgaris* L.) for cover crop and essential oil.

  Diversification 2 (D1): grapevine intercropped with oregano (*Origanum vulgare* L.) for cover crop and essential oil.

  The Pannonian pedoclimatic region

  Case studies in the Pannonian pedoclimatic region are located in Hungary and 2 out of 16 short-term field experiments are considered. They include irrigated and rainfed perennial crops diversified through intercropping.

- CS10 Asparagus

  Intercropping of asparagus with legumes and cereals was established in the central region of Hungary and compared with traditional irrigated asparagus monocropping:

  Monocrop (MC): asparagus (*Asparagus officinalis*) for food.

  Diversification 1 (D1): asparagus intercropped with pea (*Pisum sativum*) for fodder.

  Diversification 2 (D2): asparagus intercropped with oat (*Avena sativa*) for fodder.

- CS11 Organic vineyards

  Intercropping of grapevine with herbs and grass was established in south Hungary and compared with traditional rainfed grapevine monocropping:

  Monocrop (MC): grapevine (*Vitis vinifera* L.) monocrop for food.

  Diversification 1 (D1): grapevine intercropped with yarrow (*Achillea millefolium*) for essential oil.

  Diversification 2 (D2): grapevine intercropped with native grass mixture for fodder.

The Boreal pedoclimatic region

2 out of 16 field case studies, both covering rainfed cereal systems located in south-east Finland, were considered in the Boreal pedoclimatic region.

- CS12 Conventional cereals

  A rotation of cereals was compared with traditional rainfed cereal monocropping system:

  Monocrop (MC): barley (*Hordeum vulgare*) monocrop for feed.

  Diversification 1 (D1): barley—oilseed rape (*Brassica napus*)—barley rotation for feed.

- CS13 Grass forage

  Rotation of cereals and grass for fodder was developed in a dairy farm providing milk for specialised small-scale artisan cheese production. This diversification practices seek to increase grass ley production compared with the business-as-usual rotation strategy:

  Baseline (BAS): barley (*Hordeum vulgare*)—15% grass ley—barley rotation for fodder.

  Diversification 1 (D1): barley—30% grass ley—barley rotation for fodder.

Acknowledgements This work was supported by the *AgriCambio* project (Grant PID2020-114576RB-I00 funded by MCIN/AEI/10.13039/501100011033) and the European Commission Horizon 2020 project Diverfarming [Grant agreement 728003]. Also, we would like to thank the farmers involved in the case studies for their willingness, availability and their time spent to participate in the project and sharing their crop diversification views and food system perspectives.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Akaichi F, Glenk K, Revoredo-Giha C (2022) Bundling food labels: what role could the labels "Organic", "Local" and "Low Fat" play in fostering the demand for animal-friendly meat. Agribusiness 38:349–370. https://doi.org/10.1002/agr.21733

Alcon F, Tapsuwan S, Martínez-Paz JM, Brouwer R, de Miguel MD (2014) Forecasting deficit irrigation adoption using a mixed stakeholder assessment methodology. Technol Forecast Soc Change 83:183–193. https://doi.org/10.1016/j.techfore.2013.07.003

Alcon F, Marín-Miñano C, Zabala JA, DeMiguel MD, Martínez-Paz JM (2020) Valuing diversification benefits through intercropping in Mediterranean agroecosystems: a choice experiment approach. Ecol Econ. https://doi.org/10.1016/j.ecolecon.2020.106593

Basch G, Friedrich T, Kassam A, Gonzalez-Sanchez E (2015) Conservation agriculture in Europe. In: Farooq M, Siddique K (eds) Conservation agriculture. Springer, Cham. https://doi.org/10.1007/978-3-319-11620-4_15

Blasi E, Ruini L, Monotti C (2017) Technologies and new business models to increase sustainability in agro-food value chain: Promote quality and reduce environmental footprint in durum wheat cultivation processes. Agro Food Ind Hi Tech 28:52–55

Blasi E, Rossi ES, Zabala JA, Fosci L, Sorrentino A (2023) Are citizens willing to pay for the ecosystem services supported by Common Agricultural Policy? A non-market valuation by choice experiment. Sci Total Environ 893:164783. https://doi.org/10.1016/j.scitotenv.2023.164783

Borremans L, Marchand F, Visser M, Wauters E (2018) Nurturing agroforestry systems in Flanders: analysis from an agricultural innovation systems perspective. Agric Syst 162:205–219. https://doi.org/10.1016/j.agsy.2018.01.004

Bowles et al (2020) Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. One Earth. https://doi.org/10.1016/j.oneear.2020.02.007

Brannan T, Bickler C, Hansson H, Karley A, Weih M, Manevska-Tasevska G (2023) Overcoming barriers to crop diversification uptake in Europe: a mini review. Front Sustain Food Syst 7:1107700. https://doi.org/10.3389/fsufs.2023.1107700

Carlisle L (2016) Factors influencing farmer adoption of soil health practices in the United States: a narrative review. Agroecol Sustain Food Syst. https://doi.org/10.1080/21683565.2016.1156596

Castaneda-Vera A, Garrido A (2017) Evaluation of risk management tools for stabilising farm income under CAP 2014–2020. Economia Agraria y Recursos Naturales 17(1):3–23. https://doi.org/10.7201/earn.2017.01.01

De Roest K, Ferrari P, Knickel K (2018) Specialisation and economies of scale or diversification and economies of scope? Assessing different agricultural development pathways. J Rural Stud 59:222–231. https://doi.org/10.1016/j.jrurstud.2017.04.013

Dessart FJ, Barreiro-Hurlé J, van Bavel R (2019) Behavioural factors affecting the adoption of sustainable farming practices: a policy oriented review. Eur Rev Agric Econ 46:417–471. https://doi.org/10.1093/erae/jbz019

Di Bene C, Dolores Gómez-López M, Francaviglia R, Farina R, Blasi E, Martínez-Granados D, Calatrava J (2022) Barriers and opportunities for sustainable farming practices and crop diversification strategies in Mediterranean cereal-based systems. Front Environ Sci. https://doi.org/10.3389/fenvs.2022.861225

Duru M, Therond O, Fares M (2015) Designing agroecological transitions: a review. Agron Sustain Dev 35(4):1237–1257

FAO (2018) Catalysing dialogue and cooperation to scale up agroecology: outcomes of the FAO regional seminars on agroecology. FAO, Rome

Fernández JE, Alcon F, Diaz-Espejo A, Hernandez-Santana V, Cuevas MV (2020) Water use indicators and economic analysis for on-farm irrigation decision: a case study of a super high density olive tree orchard. Agric Water Manag 237:106074. https://doi.org/10.1016/j.agwat.2020.106074

IPES-Food (2016) From uniformity to diversity: a paradigm shift from industrial agriculture to diversified agroecological systems. International Panel of Experts on Sustainable Food systems. https://hdl.handle.net/10568/75659

Kassam A, Friedrich T, Derpsch R, Kienzle J (2015) Overview of the worldwide spread of conservation agriculture. Field Actions Science Reports [Online], 8. http://factsreports.revues.org/3966

Knowler D, Bradshaw B (2007) Farmers' adoption of conservation agriculture: a review and synthesis of recent research. Food Policy 32(1):25–48. https://doi.org/10.1016/j.foodpol.2006.01.003

Kremen C, Iles A, Bacon C (2012) Diversified farming systems: an agroecological, systems-based alternative to modern industrial agriculture. Ecol Soc. https://doi.org/10.5751/ES-05103-170444

Lahmar R (2010) Adoption of conservation agriculture in Europe Lessons of the KASSA project. Land Use Policy 27(1):4–10. https://doi.org/10.1016/j.landusepol.2008.02.001

Lamichhane JR, Alletto L, Cong WF, Dayoub E, Maury P, Plaza-Bonilla D, Reckling M, Saia S, Soltani E, Tison G, Debaeke P (2023) Relay cropping for sustainable intensification of agriculture across temperate regions: crop management challenges and future research priorities. Field crops research, vol 291. Elsevier B.V., Amsterdam. https://doi.org/10.1016/j.fcr.2022.108795

Latvala T, Regina K, Lehtonen H (2021) Evaluating non-market values of agroecological and socio cultural benefits of diversified cropping systems. Environ Manage. https://doi.org/10.1007/s00267-021-01437-2

Lin B (2011) "Resilience in agriculture through crop diversification: adaptive management for environmental change. Bioscience 61(3):183–193. https://doi.org/10.1525/bio.2011.61.3.4

Magrini MB, Anton M, Cholez C, Corre-Hellou G, Duc G, Jeuffroy MH, Walrand S (2016) Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system. Ecol Econ 126:152–162. https://doi.org/10.1016/j.ecolecon.2016.03.024

Morel K, Revoyron E, Cristobal MS, Baret P (2020) Innovating within or outside dominant food systems? Different challenges for contrasting crop diversification strategies in Europe. PLoS ONE. https://doi.org/10.1371/journal.pone.0229910

Morugán-Coronado A, Pérez-Rodríguez P, Insolia E, Soto-Gómez D, Fernández-Calviño D, Zornoza R (2022) The impact of crop diversification, tillage and fertilization type on soil total microbial, fungal and bacterial abundance: a worldwide meta-analysis of agricultural sites. Agric Ecosyst Environ 329:107867. https://doi.org/10.1016/j.agee.2022.107867

Pretty J, Bharucha ZP (2014) Sustainable intensification in agricultural systems. Ann Bot 114(8):1571–1596. https://doi.org/10.1093/aob/mcu205

Reckling M, Bergkvist G, Watson CA, Stoddard FL, Zander PM, Walker RL, Bachinger J (2016) Trade-offs between economic and environmental impacts of introducing legumes into cropping systems. Front Plant Sci 7:523. https://doi.org/10.3389/fpls.2016.00669

Revoyron E, le Bail M, Meynard JM, Gunnarsson A, Seghetti M, Colombo L (2022) Diversity and drivers of crop diversification pathways of European farms. Agric Syst. https://doi.org/10.1016/j.agsy.2022.103439

Rodriguez C, Dimitrova Mårtensson L-M, Zachrison M, Carlsson G (2021) Sustainability of diversified organic cropping systems—challenges identified by farmer interviews and multi-criteria assessments. Front Agron 3:698968. https://doi.org/10.3389/fagro.2021.698968

Rosa-Schleich J, Loos J, Mußhoff O, Tscharntke T (2019) Ecological-economic trade-offs of diversified farming systems—a review. Ecol Econ 160:251–263. https://doi.org/10.1016/j.ecolecon.2019.03.002

Rossi ES, Zabala JA, Caracciolo F, Blasi E (2023) The value of crop diversification: understanding the factors influencing consumers' WTP for pasta from sustainable agriculture. Agriculture 13:585. https://doi.org/10.3390/agriculture13030585

Sánchez AC, Kamau HN, Grazioli F, Jones SK (2022) Financial profitability of diversified farming systems: a global meta-analysis. Ecol Econ 201:107595. https://doi.org/10.1016/j.ecolecon.2022.107595

Tzemi D, Lehtonen H (2022) The use of pre-crop values to improve farm performance: the case of dairy farms in southwest Finland. Int J Agric Sustain. https://doi.org/10.1080/14735903.2022.2131042

Van den Broeck G, Grovas RRP, Maertens M, Deckers J, Verhulst N, Govaerts B (2013) Adoption of conservation agriculture in the Mexican Bajío. Outlook Agric 42(3):171–178. https://doi.org/10.5367/oa.2013.0136

Watson C, Reckling M, Preissel S, Bachinger J, Bergkvist G, Kuhlman T, Lindström K, Nemecek T, Topp C, Vanhatalo A, Zander Z, Murphy-Bokern D, Stoddard F (2017) Grain legume production and use in European agricultural systems. Adv Agron 144(1):235–303. https://doi.org/10.1016/bs.agron.2017.03.003

Weituschat CS, Pascucci S, Materia VC et al (2022) Goal frames and sustainability transitions: how cognitive lock-ins can impede crop diversification. Sustain Sci 17:2203–2219. https://doi.org/10.1007/s11625-022-01156-5

Weituschat CS, Pascucci S, Materia VC, Blasi E (2023a) Understanding the role of value chain formation in the scaling of crop diversification. Agron Sustain Dev 43:25. https://doi.org/10.1007/s13593-023-00866-z

Weituschat CS, Pascucci S, Materia VC, Caracciolo F (2023b) Can contract farming support sustainable intensification in agri-food value chains? Ecol Econ 211:107876. https://doi.org/10.1016/j.ecolecon.2023.107876

Wezel A, Casagrande M, Celette F et al (2014) Agroecological practices for sustainable agriculture. A review. Agron Sustain Dev 34:1–20. https://doi.org/10.1007/s13593-013-0180-7

World Bank (2021) PPP conversion factor, GDP (LCU per international $). The World Bank Data. https://data.worldbank.org/indicator/PA.NUS.PPP. Accessed 15 March 2023