Crop diversification practices in Europe. An economic cross-case study comparison

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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 farm level. CDPs are compared with conventional cropping systems and clustered in terms of their gross margins (GMs) results and variations. Farm level assessment show 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 GMs with low economic impact , and (3) there is a great likelihood that the CDPs facilitate the build-up of more resilient farming systems.

Keywords: gross margin, cluster analysis, cropping systems, value chain, SWOT

1. 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 are pushing institutions and private organizations 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 approach to address these concerns, although empirical evidence is still incomplete and the research is evolving (Bowles, 2020). One of the latest trends to enhance sustainability and resilience of agricultural systems is based on diversification practices (Lahmar, 2010). Diversification can be defined as 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 characterized by different type of stakeholders and its competitiveness and efficacy depend strongly on the degree of collaboration and coordination between different actors in the value chains (Revoyron, 2022). Therefore, the acceptance of CDPs must be viewed within the whole product value chain. This entails considering interlinked relationship among consumers, farmer, producers and brokers expectations about sustainability within heterogeneous food systems (Weituschat et al, 2023a).

Diversified farming systems constituted the bulk of the agricultural production in Europe until 1960s (Ferrari & Knickel, 2018). However, since the 70's diversifications practices were replaced with alternative approaches, focusing mainly on monocultures aiming at maximising productivity per crop. Thus, farmer shifted their focus towards the adoption of novel technologies and modern production techniques, such as the adoption of high-yield plant varieties, intensive mechanization and use of agro-chemicals (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 of 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 by a highly specialized and intensive mono-cropping agricultural system could be tackled through the adoption of CDPs at both farm and value chain level (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 (Francisco - Wezel et al., 2014). The combination of different type of CDPs may produce trade-offs between environmental and economic benefit (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, 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-stabilizing for farmers, smoothing seasonality peaks of labour demand and reducing the risk of crop failure.

Currently, the adoption of CDPs among European farmers is hampered by a range of costraints, resulting in their adoption being largely confined in niches of innovation, adopted by farmers that experiments 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 the 1,5% of the arable land in Europe was allocated to the cultivation of grain legumes, which constitute one of the main emblematic crop 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 models proposition 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, the studies of the viability of diversification from 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 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 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 farmer's choices (Carlisle, 2016; Knowler and Bradshaw, 2007; Carlisle, 2016 and Knowler and Bradshaw, 2007). Overall, despite this limitations, farm level profitability of adoption of CDPs can play a key role for the improvement of the resilience of agricultural systems, especially in Europe (Alcon et al., 2020).

In this context, this paper aims to enhance iur understanding of economic agroecosystem goods and services fluxes along with the consequences of implementing CDPS across various European regions by exploring if there exists common pattern in the impacts of CDPs on the economic farm's performance. To this end, the farms that implemented CDPs are compared with those employing - conventional cropping systems in terms of economic performance based on three-year field experiment. Thus, farm level profitability of crop diversification practices is assessed in 16 case studies in 6 different regions of Europe. The case studies included the application of CDPs in different pedoclimatic region: Spain, Italy, Netherlands, Germany, Hungary and Finland. Results fulfil the gap of 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.

2. Methodology:

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

[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.

Annex.

__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

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 alleys intercropping along with traditional monocrop mandarin, which includes regulated deficit irrigation for the main crop to maintain water consumption from monocrop.
- **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.
- **CS3b:** involves two diversifications in irrigated cereals, located in Northeast Spain. Diversification consists of two different rotations withing the same year (Multiple cropping system) along with maize monocrop.
- **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 monocrop.
- **CS16:** Melon crop with cowpea intercropping.

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

Atlantic pedoclimatic region

Case studies in the Atlantic pedoclimatic region are located in Netherlands and comprehends 2 out of 16 of the field short-term 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 with 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.

Continental pedoclimatic region

The case study located in the Continental pedoclimatic region is located in 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 compared with grapevine monocrop was compared:

Pannonian Pedoclimatic Region

Case studies in the Pannonian pedoclimatic region are located in Hungary and comprehend 2 out of 16 of the field short-term 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.

Boreal pedoclimatic region

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

- **CS12:** A rotation of cereals was compared with 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 practices seek to increase grass ley production compared with the business-as-usual rotation strategy.

2.2. Farm level economic analysis

Comparison between conventional (monocropping) and CDPs systems allows to better understand 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 economic performance of crop diversification and to identify if there are any common pattern 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. (2020) procedure. Calculations utilising crop specific input use, crop output and specific price data gathered 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, being GM= VSP + CAP - Inputs 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. GM indicator is used to 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 farms expenditure in the areas where the case studies have been 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.

2.3. 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 has been made by an unsupervised classification using K-means as a centroid model-free clustering algorithm. This approach has been used due to no prior assumptions on the distribution of the data and the process is 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 minimized (Hartigan and Wong, 1979). In order to determine the right number of clusters, k^* from the set of K solutions, scree plots are used and search for a kink in the curve generated from the within-cluster sum of squares.

2.4 SWOT Analysis

To investigate the CDPs adoption under a broader perspective, a SWOT analysis has been developed based on the results obtained. SWOT is a strategic planning method for addressing and positioning the resources and environment of organizations, 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 factors 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.

3. Results

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

3.1. Farm level economic analysis

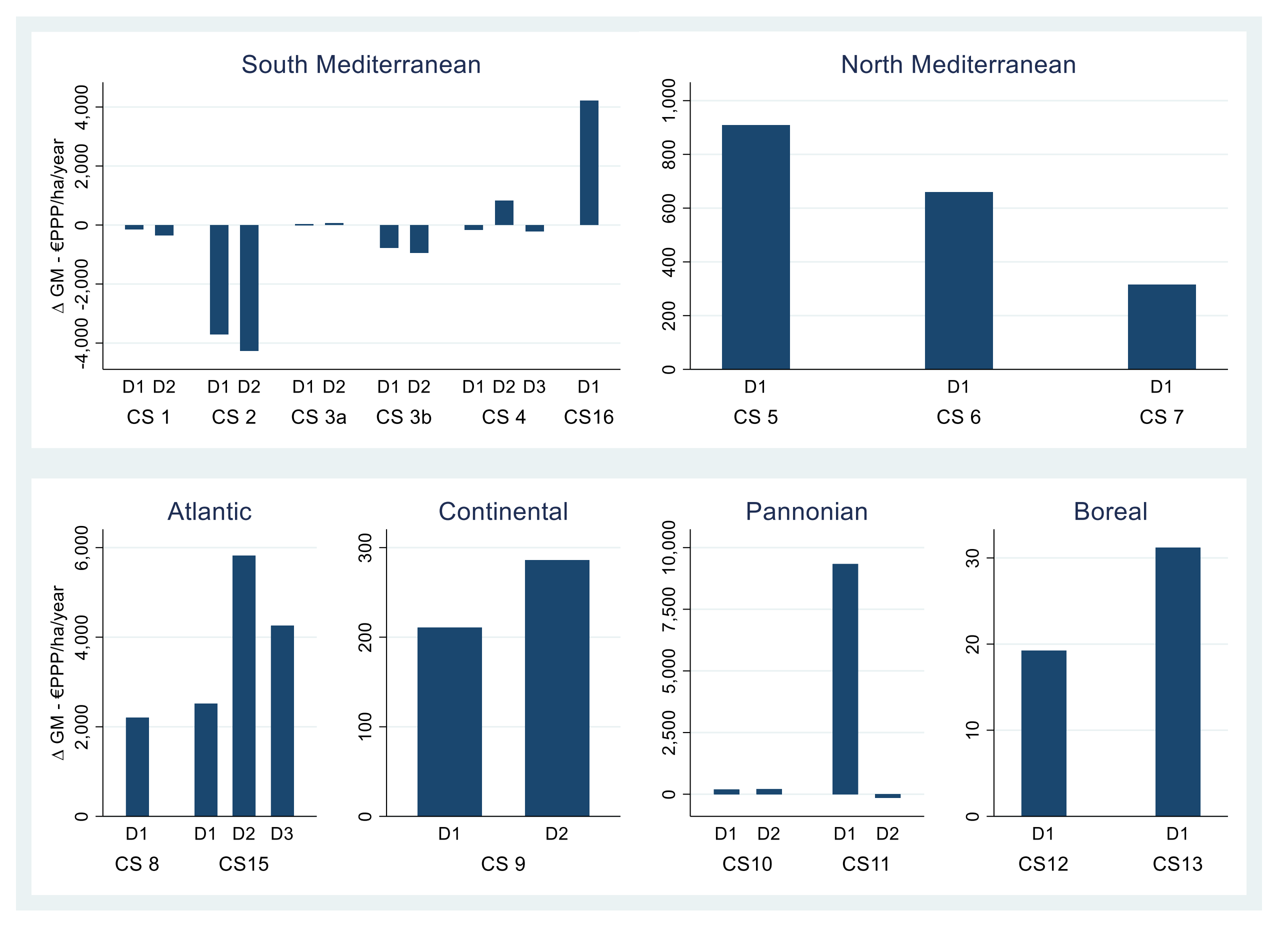
The farm level economic performance of crop diversification shows a wide dispersion in the results across case studies and regions in Europe. Figure 1 shows the obtained GMs per case study, differentiating between diversification and monocropping practices. This wide dispersion among the results is mainly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

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

In order 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 regions. 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) reveals 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.

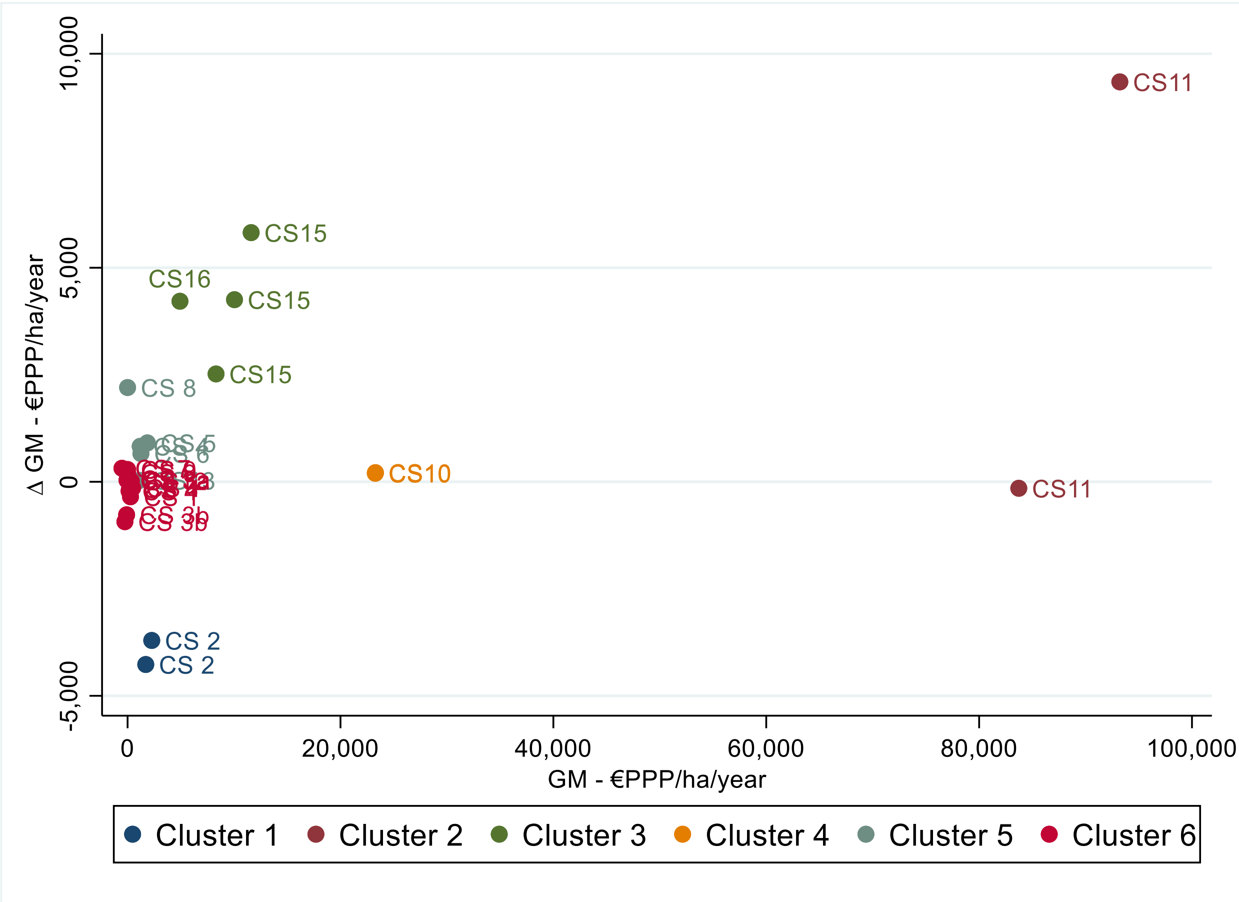
Figure 2 *- Change of gross margin (GM) from monocrop to diversification, by case study and region. (€PPP/ha/year)*



3.2. Cluster Analysis

In order to stablish a clear pattern in the economic performance of crop diversification, the assessment of GMs and their variations regarding to 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 economic, as a results 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.

Figure 3 *- Clusters of the 16 case studies considering their gross margin (GM) and the increase of GM due to CDPs regarding monocrop (ΔGM).*



The first identified cluster comprehends the two diversifications of CS2, which shows relatively low GMs and negative differences regarding the economic performance of 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 monocrop. 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-A from grapevine monocrop to such diversification.

Cluster 3 comprises diversifications with relatively medium GMs but high increases regarding their respective monocrops. It comprises the biodynamic and organic vegetables located in 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 with oat (D2) in Hungary, in the Pannonian region, showing high GMs but low impact of crop diversification.

Most case studies lied 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 Figure 3, given 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 comprehends 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 intercropped with pea with the better economic performance. Such vegetables are categorised together with rainfed cereals from the Finnish CS13 and rainfed olive trees in the Spanish CS4, showing the wide differences among crop types within such cluster. At this stage, it is important to highlight that CS4 becomes the only case study whose diversifications are included within two different clusters: cluster 5 and cluster 6. Indeed, it clearly reveals that the type of diversification developed may significantly change the farm level economic performance, and hence, shows the importance of diversified crop selection for ensuring good farm level economic results. In such 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 a dairy farming.

Figure 4 *- Clusters 5 and 6 of Diverfarming case studies considering their gross margin (GM) and the increase of gross margin regarding monocrop(ΔGM).*

Cluster 6 becomes the cluster with the greatest number of case studies. It includes a total of 7 different case studies, with the common feature that almost all of them are grown under rainfed conditions. That is the case of rainfed trees such as those in CS1, with almond trees intercropped with capers (D1) and thyme (D2), and in CS4, with 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 for the case of conventional crops during the first year of experiment. This result reveals the extent of the 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; that there exists a great frequency of low GMs with low economic impact, and, above all; that 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.

3.3. SWOT Analysis

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

Table 2 *- Description of SWOT factors to 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, not negative
s2	Crop diversification benefits usually overcome total costs (including market, social and environmental costs and benefits)
s3	Access to new markets and reduce monocropping income dependence (market risk reductions)
s4	Expected financial and economic gain in the long-term
s5	Improve farm health and quality (soil quality, biodiversity, landscape, CO_2 balance, etc.)
s6	Greater stability production
s7	Diversification practices are suitable for all crop types
s8	Diversification help 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 farm level
OPPORTUNITIES (External reasons that could favour the adoption of diversification)	
o1	Obtain better sales contract and trustfully relationships with 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 to use diversification
o5	Adapting farm to the 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, subsides) 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

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.

4. 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 practices adoption a low, or even negative, GMs and around zero net economic impact is achieved, except for vegetables crops. Non-negative GM impact, together with the improvement in ecosystem services, represents the main strength of CPD. 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 CPDs 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 produced in diversified cropping systems, and farmers. Therefore, the food value chain should be understood as a whole, where relationships among agents are encouraged to 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 systems 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, which may become the first enabler for adopting crop diversification. This results, not only the clear and significant positive economic effects of diversification at the farm level, is encouraging due to the positive environmental and societal benefits, at no or little cost for a farmer, that diversification often imply (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, becomes invisible for 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 one 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 type 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 allow them to make the farm operations at 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 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 for 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 in this new technical-managerial path, it is necessary to increase the relationships between farmers & 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 verifies such differentiated products by means of labels (Akaichiet al., 2022). Finally, the political context also aids to foster 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 comprehend threats. On the one hand, there are some barriers related to the transition pathways from monocropping to diversified agrifood 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 agrifood 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 associated some 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 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 for advising 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 provide a clear and direct view of the current situation of the main forces that enable and hinder crop diversification in Europe. This assessment may offer key insights and basis for the development of agrifood 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 CPDs by farmers is still stuck. As such, future research seeks to concentrate its efforts to address the lock-ins that delay the adoption of CPDs. 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), but not the only ones. Further research is needed about 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 agrifood value chain (Weituschat et al., 2023a). This will thereby ensure the effectiveness of the transferability of knowledge results about CPDs.

5. 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.

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Conflict of Interests/Competing Interests

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.

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Annex: Description of the case studies for each pedoclimatic region

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 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:

<u>Monocrop (MC)</u>: Almond (*Prunus dulcis*) monocrop.
<u>Diversification 1 (D1)</u>: Almond intercropped with permanent caper (*Capparis spinosa*) for food.
<u>Diversification 2 (D2)</u>: 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, which includes regulated deficit irrigation for the main crop in order to maintain water consumption from monocrop:

<u>Monocrop (MC)</u>: Mandarin monocrop.
<u>Diversification 1 (D1)</u>: Mandarin intercropped with vetch/barley (*Vicia sativa/Hordeum vulgare*) for feed (January-June) and fava bean (*Vicia faba*) for food (September-January).
<u>Diversification 2 (D2)</u>: 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:

<u>Monocrop 1 (MC1)</u>: Wheat (*Triticum durum*) monocrop for food.
<u>Monocrop 2 (MC2)</u>: Barley (*Hordeum vulgare*) monocrop for feed.
<u>Diversification 1 (D1)</u>: Wheat (*Triticum durum*) – Barley (*Hordeum vulgare*) – Pea (*Pisum sativum*) rotation, where wheat is for food and barley and pea for feed.
<u>Diversification 2 (D2)</u>: Wheat (*Triticum durum*) – Barley (*Hordeum vulgare*) – Vetch (*Vicia sativa*) rotation, where wheat is for food and barley and vetch is for feed.

- **CS3b Maize**

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

<u>Monocrop (MC)</u>: 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 grown as alley crops in olive yards in south Spain, to observe the effect of intercropping in contrast to monocrop. 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 monocrop. The presence of legumes in the intercropping makes to decrease fertilizer 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.

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 Maize**

Rotations of rainfed cereals and irrigated vegetables intercropped with legumes were established in the north Italy to observe the effect of diversification in contrast to maize monocrop. 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 the 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 the 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 Netherlands and comprehends 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): Maize (*Zea mays*) for fodder.
Diversification 1 (D1): Maize 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, being vegetables for food and grass for fodder.
Baseline 2 (BAS2): Red beet – Pea – Spelt – Potato – Grass clover – Grass clover rotation, being vegetables for food and grass for fodder.
Diversification 1 (D1): Onion – Pea – Potato – Spelt – Red beet (*Beta vulgaris L.*) – Grass clover rotation, being 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

Ther case study located in the Continental pedoclimatic region, which comprises 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 compared with grapevine monocrop was compared:

  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.

Pannonian pedoclimatic region

Case studies in the Pannonian pedoclimatic region are located in Hungary and comprehends 2 out of 16 of the field short-term experiments. 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 monocrop:

  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 monocrop:

  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.

Boreal pedoclimatic region

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

- **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.