Cost Benefit Analysis of diversified farming systems across Europe: Incorporating non-market benefits of ecosystem services

Francisco Alcon[1], Jose A. Albaladejo-García[1], Victor Martínez-García[1], Eleonora S. Rossi[2], Emanuele Blasi[2], Heikki Lehtonen[3], Jose M. Martínez-Paz[4], Jose A. Zabala[4]*

[1] Departamento de Economía de la Empresa. Universidad Politécnica de Cartagena. Paseo Alfonso XIII 48, 30203 Cartagena, Spain

[2] Department for Innovation in Biological, Agro-food and Forest systems (DIBAF), University of Tuscia, Via San Camillo del Lellis snc, Viterbo 01100, Italy

[3] Natural Resources Institute Finland (Luke), Latokartanonkaari 9, PL 2, 00791, Helsinki, Finland

[4] Departamento de Economía Aplicada, Universidad de Murcia, Campus de Espinardo, 30100 Murcia, Spain

ABSTRACT

Crop diversification can enhance farm economic sustainability whilst reducing the negative impact on the environment and ecosystem services related. Despite the market and non-market benefits of crop diversification, monocropping is a widely used dominant practice in Europe. In this context, this works aims to assess the overall economic impact of several crop diversification systems across Europe and compared it to the monocropping system. For this purpose, an economic evaluation by integrating market and non-market values for eight case studies distributed across three different European pedoclimatic regions (Southern Mediterranean, Northern Mediterranean and Boreal) is proposed. The economic valuation was conducted both in the short and medium-long term. For the short-term we conducted a social gross margin analysis, while for the medium-long term a cost-benefit analysis is developed. The results show an improvement in social gross margins for most of the diversification scenarios assessed when environmental and socio-cultural benefits are considered in the short-term. In the medium and long-term the transformation of cropping towards a more diversified agriculture is encouraged by greater economic benefits. These results provide a first insight in global economic performance of diversified cropping systems, whose main contribution relies on the integration of market and non-market values of ecosystem services from crop diversification. They are expected to be useful for guiding policy makers to promote crop diversification practices as a key instrument for building resilience in farming systems for an adaptive management to climate change.

Keywords: Agriculture, Diversification, Social gross margins, Sustainability, Environmental benefits.

1. Introduction

The growth of agricultural productivity in Europe in the last two decades is mainly related to intensive monocrops, mechanization, and dependence on external inputs (Tilman et al., 2011). This has led to more simplified, monocropping, agricultural systems with little genetic diversity and increased homogeneity of landscapes by cropping only the most profitable crops (Franco et al., 2022).

Despite the high productivity achieved in monocropping systems, the intensive use of pesticides and fertilizers has caused significant environmental impacts on agroecosystems and the provision of ecosystem services (Tilman et al., 2011). Also, intensified cropping systems has led to the development of numerous negative externalities such as water pollution, soil erosion or deforestation that have resulted in the reduction of ecosystem services derived from agriculture (Wezel et al., 2018). Consequently, there is a growing awareness that, in addition to food production, it is essential to preserve the quality of the environment (Weituschat et al., 2022) and the provision of ecosystem services (D´Hose et al., 2014). Moreover, it is also important to highlight that this intensive agriculture jeopardizes the adaptability of current cropping systems to climate change (Purwanto & Alam, 2020) and imply higher economic risks for European farmers (Damalas & Eleftherohorinos, 2011).

European Commission began in 2020 a transition of European agriculture from the current external input-based dependent cropping systems to biodiversity-based ones, especially through the Common Agricultural Policy and the European Green Deal (Clora et al., 2021). Consequently, crop diversification emerges as a strategy capable of optimising the entire agricultural value chain in response to environmental, technical, and socioeconomic constraints (Alletto et al., 2022).

Crop diversification could contribute, through cover crops, intercropping, crop rotation or agroforestry (Wezel et al., 2014, Lamichhane, 2023), to the agro-ecological transition of the European agricultural sector by adapting the whole value chain (Nunes et al., 2018). It has been shown in the literature that crop diversification can contribute to increase food security (Scherer et al., 2018), it provides no negative economic returns for farmers (Zabala et al., 2023; De Roest et al., 2018; Nilsson et al., 2022; Sánchez et al., 2022) and enhances environmental sustainability of farms, as it contributes to the provision of ecosystem services such as pest control, biodiversity, erosion control, carbon sequestration, rural jobs, cultural heritage, and landscape aesthetics (Hunt et al., 2019; Alcon et al., 2020; Francaviglia et al., 2020; Morugán-Coronado et al., 2022). Thus, crop diversification can mitigate the effects of climate change (Lin, 2011) and address the social and environmental challenges currently facing agriculture (Kremen & Miles, 2012). Monocropping farmers also recognize the potential role of diversified cropping systems in adapting to climate change (Roesch-McNally et al., 2018).

However, despite the evidence of productivity improvements, both in economic and environmental terms (Tamburini et al., 2020), monocropping systems continue to be dominant across Europe. Questions move then to the reasons why farmers apparently choose to continue growing under monocropping systems when the environmental benefits of crop diversification are well-known, even among monocropping farmers. Recent research indicates that the adoption of crop diversification practices by farmers is mostly hampered by limited access to knowledge, lack of technical assistance in the path of adoption, supply chain pressures up- and down-stream of the farm, and even the farmers' concern about the consistency of policies about the promotion of such practices (Lancaster & Torres, 2019; Rodriguez et al., 2021; Brannan et al., 2023). Other factors hindering adoption might be that farmers have easy access to synthetic fertilizers and pesticides so that the agrochemical industry benefits from the existence of monocrops (Mortensen & Smith, 2020). In addition, the negative externalities associated with monocropping systems, such as the reduction of ecosystem services, are not usually internalised in agricultural commodities or food prices in the markets, thus disincentivizing the adoption of more complex cropping systems such as crop diversification (Robertson & Swinton, 2005).

The adoption of diversification practices by monocropping farmers is therefore challenging. This raises the need to provide key studies and tools that address the contributions of crop diversification practices to society and along the food value chain (Alletto et al., 2022). Economic evaluation through cost-benefit analysis (Keck & Hung, 2019) is one of the useful tools to compare the benefits of conventional monocropping and diversified cropping systems. This provides a better understanding of the benefits generated at both market (private benefits) and non-market (environmental and socio-cultural benefits) levels, social gross margins being appropriate for this purpose.

Given the differences between monocropping and diversification systems, both in terms of market and non-market values, both systems must be carefully evaluated to ensure consistent comparison of the two systems. Despite the existing differences, there are relatively few studies that consider both monocrop and crop diversification in economic analysis starting from farms and value chain technical and financial data (Martin-Gorriz et al., 2022; Benini et al., 2023; Zabala et al., 2023). Moreover, there is a gap in the literature when it comes to integrating both market and non-market values in the economic evaluation of monocrops and crop diversification. Likewise, no studies exist that make a comparative economic evaluation of monocrops and diversification between pedoclimatic regions where bio-physical production conditions and socioeconomic contexts are different. It is important to understand the main factors and reasons for the differences in economic and environmental performance between monocropping and diversified systems, and if the same or different factors explain the differences in various regions. The economic comparison and evaluation of cross-case studies are needed to assess the impact of diversified cropping systems between pedoclimatic regions, using the knowledge provided by all stakeholders on the characteristics of their region.

In this context, this work aims to assess the economic impact of crop diversification systems in selected pedoclimatic regions across Europe, comparing diversification with the reference monocropping system. For this purpose, eight European field case studies under diversified and monocropping systems were analysed in the short-term, through the social gross margins analysis, and in the medium and long-term, through the cost-benefit analysis. It thereby provides first insight in global economic performance of diversified cropping system.

The contribution of this work to the scientific literature is twofold. First, it integrates market and non-market values into the economic evaluation, a novel combination in the literature about crop diversification. It thereby serves to analyse all the main positive and negative impacts of crop diversification by using common monetary terms. This provides policymakers, a powerful tool to guide the new horizon of agricultural policies in the face of climate change adaptation and mitigation strategies. The results are also valuable for food chain actors (e.g. food industry, retail, farms) when aiming to improve sustainability. Second, monocrops and diversifications are examined in three different pedoclimatic regions across Europe (South Mediterranean, North Mediterranean, and Boreal) and by the implementation of different diversification strategies (intercropping, rotation), which allows to delve into main diversified systems from an economic point of view, which represent a novelty itself.

We examine the extent to which economic benefits vary through crop diversification to answer the following research questions: (1) Is crop diversification socioeconomically profitable in the short and medium-long-term? (2) How does the inclusion of non-market values of the ecosystem services affect the social gross margins of monocropping systems and crop diversification? Are non-market values more important than market values? and (3) Do the social gross margins generated for the different European agroecosystems follow the same general trend?

2. Materials and methods

The material and methods applied for the integrated economic valuation of ecosystem services from crop diversification combines field results from diversified farming systems, providing the quantification of the ecosystem services, with their socioeconomic value both for farmers and the entire society. The quantified ecosystem services from crop diversification are then translated into economic values through their socioeconomic valuation by using market and non-market techniques. The market side of the economic value of ecosystem services mostly applies to the valuation of provisioning services, namely food provision, thereby summarising the farmers' (private) perspective of the economic valuation. This is mainly approached by using farm gross margins. On the other side, the contribution of non-marketed regulating and cultural services is addressed by using non-market valuation techniques, such as choice experiment or contingent valuation. This encompasses the value of such ecosystem services for the entire society. In sum, the contribution of crop diversification to the provision of ecosystem services is economically valued by integrating market and non-market values. In addition, such contributions can be different depending on the analysis horizon of the benefits obtained by the ecosystem services from crop diversification. It is expected a higher change in the provision levels of ecosystem services from monocropping to diversified farming systems in the long term. Hence, the economic value of ecosystem services is determined both in the short and in the long term by using horizon-adapted techniques: social gross margins in the short term and cost-benefit analysis in the long term. Figure 1 summaries the methodological framework followed, which is applied to each of the case studies assessed.

[Figure 1 about here]

2.1. Case study

Field case studies are distributed across Europe in 3 countries, covering 3 pedoclimatic regions, and integrating perennial and annual crops by using intercropping and rotation strategies for crop diversification practices. As such, they are distributed among Spain, Italy and Finland, in the South-Mediterranean, North-Mediterranean and Boreal regions, respectively. Perennial crops are only located in the South-Mediterranean region, the same as for intercropping practices. Table 1 provides a summary of the 8 field case studies under diversified (DX) and monocropping systems analysed in this work.

[Table 1 about here]

Most field case studies comprehend only 1 diversification practice, perennial intercropping of almond and citrus orchards in the South Mediterranean region being an exception with 2 diversified cropping systems. Main crop summarises the business as usual, or baseline, situation, mostly referred to as just monocrop (CS1, CS2, CS3, CS4, CS7). Some cereal rotations were also included as they represent the conventional system for the case study (CS5, CS6, CS8), thereby proposing additional rotations with unconventional crops as alternative diversification practices. Each of these case studies was designed to have a three-year crop cycle (2018-2020). More detailed information about the experimental case studies can be found in Zabala et al. (2023).

2.2. Social gross margin analysis

Gross margin (GM), widely used in farm-level economic assessment and management, is the difference between the value of crop production and the (variable or semi-fixed) cost of production, per hectare at a farm. GMs are based purely on the financial outcome of different crops produced on farms, without considering the overall costs and benefits that diversification practices contribute to the environment and to the societies in which these practices are applied. Diversification practices also generate benefits and costs through increased flows of ecosystem services and biodiversity in the diversified agroecosystems (Beillouin et al., 2021). These benefits and costs involve regulating and cultural services. Hence the value of crop diversification ought to include not only private benefits, but also both environmental and sociocultural benefits.

Regulating and cultural ecosystem services are characterized by a lack of monetary value. No active markets exist in which these services can be commercialized and reflect their economic value, as is the case with provisioning services (Kremen & Miles, 2012). This non-market character means that estimating their value becomes challenging, but feasible, and so it might be incorporated into the economic analysis of crop diversification, together with market values (Latvala et al., 2021).

The integration of market and non-market values of the ecosystem services provided by crop diversification is firstly assessed by social gross margins (SGMs). This indicator includes the private and social impacts of crop diversification under the scope of the economic evaluation. SGM is defined according to Alcon et al. (2013) as follows:

$$SGM = GM + Environmental\ benefits/costs + Sociocultural\ benefits/costs \qquad (1)$$

GMs are estimated based on crop-specific inputs, crop production and price data collected, specifically by crop and cropping system (monocropping and diversified). Depending on the inputs considered per crop, two levels of costs were identified: variable costs, including machinery use (e.g., fuels, lubricants), raw materials (irrigation water, fertilizers, pesticides) and labour, and fixed costs, including asset depreciation. Data on inputs, yields and farm management practices were yearly collected at the crop and plot level, and aggregated by cropping system down to the farm level. Technical information, related to both variable and fixed costs, was collected directly from the case study experimental plots, while market prices and subsidy values were obtained from farmers' suppliers and each region's official agricultural statistics, respectively. Where unavailable or incomplete data were found, gaps were filled by extrapolating average, from surveys of farmers in each region. Thus, both farm costs and revenues were obtained as the average of the actual costs and revenues for farmers in the areas where the case studies were conducted. All the information about farm-level economic data and results is available at Lehtonen et al. (2020).

Stated preference methods are non-market valuation techniques implemented to estimate the environmental and sociocultural benefits of crop diversification. Choice experiment and contingent valuation methods were applied to estimate social demand for regulating and cultural ecosystem services provided by crop diversification. Both methods are based on eliciting economic values directly to individuals through surveys simulating hypothetical markets. These hypothetical markets assume changes in the provision levels of regulating and cultural ecosystem services by which the individuals are willing to pay to incentivise (positive changes) or undermine (negative changes) them. Such willingness to pay summarises the non-market value of the ecosystem service provided to the society. The reliability and validity of their results carefully depends on the goodness of the surveys designed. As such, their survey-based nature makes these methods become complex and costly to develop. The fundaments and limitations of these methods can be found in Champ et al. (2017).

Specifically, the value of environmental and sociocultural benefits was derived in specific regions of Spain (Alcon et al., 2020), Italy (Blasi et al., 2023) and Finland (Latvala et al., 2021), encompassing CS1, CS2 and CS3 in the Southern Mediterranean region, CS4, CS5 and CS6 in the Northern Mediterranean region, and CS7 and CS8 in the Boreal region. Hence, the non-market value of the ecosystem services provided by crop diversification is site-specific, with the valued regulating and cultural services being of notable significance for each region. Ecosystem services to be valued were selected based on scientific literature and expert consultation in each region. Biodiversity, erosion control, carbon sequestration, cultural heritage and landscape aesthetics, were valued in the Spanish case studies, while biodiversity, carbon sequestration, water pollution risk reduction and landscape beauty were valued in the Italian case studies. The scope of regulating and cultural ecosystem services valued in the Finnish case studies was broader, including adaptation to climate change, reduction of runoff leakage, soil carbon enhancement, increased rural employment and maintenance of local food tradition. As such, marginal values associated with each of these regulating and cultural services were estimated for every pedoclimatic region. All the details about the non-market valuation of ecosystem services are available in Alcon et al. (2020) [Spain], Blasi et al. (2023) [Italy] and Latvala et al. (2021) [Finland].

The economic value of the environmental and sociocultural benefits is linked to changes in the flows of regulating and cultural ecosystem services from monocropping to diversified systems. Changes in the physical values of regulating ecosystem services and biodiversity were obtained from biophysical indicators measured at plot level in each of the field case studies (Loczy et al., 2022; Canfora et al., 2022). Land erosion index, soil carbon content, bacteria and enzyme biodiversity, and presence of inorganic mineral contaminants in soil were used as indicators (supplementary material), which were categorised according to the attributes and levels used for the economic valuation of the ecosystem services. Categorised indicators representing the changes in the provision level of ecosystem services between monocropping and diversification practices is available in Piccini et al. (2022). Therefore, these changes in ecosystem services biophysical flows, measured by each case study, are translated into economic values using specific results for each crop diversification and their related marginal economic value. The environmental and sociocultural benefits were transformed into terms of land use (€/ha year) to be integrated accordingly. Furthermore, if there is a reduction in the provision of ecosystem services due to crop diversification practices, the environmental costs are also accounted for. Similarly, monocropping practices can be associated with environmental and sociocultural costs. When such costs have been socially valued given the disutility they provide, as is the case in the Spanish and Italian case studies, environmental and sociocultural costs are included for the estimation of the SGMs of monocropping practices. Hence, SGMs are understood as a summary of the short-term economic value of crop diversification at the regional level. Additionally, all actual monetary values are homogenized to the European Union's average standard of living using Purchasing Power Parity (PPP) to ensure comparability.

2.3. Cost-benefit analysis

Cost-benefit analysis is a widely used decision-making tool used to assess public investments (Alcon et al., 2013). It serves to comprehensively compare the benefits and costs of policy actions or programmes, considering their medium and long-term impact. It includes both the private benefits and costs for those who develop the actions, together with the social benefits and costs implied. As such, cost-benefit analysis includes both market and non-market costs and benefits. It addresses increases or decreases in social well-being so that intergenerational equity and sustainability criteria can be added.

The application of cost-benefit analysis to the specificities of crop diversification requires integrating all the impacts of diversification practices in the medium and long term at the regional scale. The private component of the cost-benefit analysis comprises the benefits and costs to farmers, i.e., revenues and variable and fixed costs, respectively, namely GMs. The social component of the cost-benefit analysis includes environmental and sociocultural benefits and costs, derived from the expected changes in the provision of regulating and cultural ecosystem services from diversification in the long term. Predictions for long-term indicators include soil organic carbon over the next 30 years and soil erosion, when available (Cerasuolo & Begum, 2020; Iserloh & Seeger, 2022). Organic carbon and erosion indicator levels were also categorised to be homogeneous to the attributes and levels used for the economic valuation of ecosystem services. These categorised indicators are available in Piccini et al. (2022). Data for the private component of the cost-benefit analysis are obtained from economic results at farm-level (Lehtonen et al., 2020), while environmental and sociocultural benefits and costs apply marginal values of regulating services to the predicted changes of their associated biophysical indicators to integrate them accordingly. Additionally, all actual monetary values are transformed in terms of land use (€/ha year) and homogenized using Purchasing Power Parity (PPP).

To compare the integrated economic performance of diversification practices carried out under monocropping and diversification systems, the net present value (NPV) and the benefit-cost ratio (B/C ratio) are used as profitability indicators. They are defined as follows (EC, 2015):

$$NPV = -K + \sum_{t=1}^{t}\left(\frac{B_t - C_t}{(1+r)^t}\right) + \sum_{t=1}^{t}\left(\frac{B_t^e - C_t^e}{(1+r\prime)^t}\right) \tag{2}$$

Where B_t and C_t represents the private benefits and costs, respectively, B_t^e and C_t^e the environmental and socio-cultural benefits and costs, r is the discount rate, K is the investment cost and t is the period for which the NPV of crop diversification is measured. The discount rate of 3.5% is considered for environmental and socio-cultural flows, following Almansa & Martínez-Paz (2011). Investment costs are considered only for perennial crops (almonds in CS1 and mandarins in CS2), assuming to be zero for annual crops. NPV is estimated for a period of 25 years, which is considered the lifespan of the assessed perennial crops and applied the same period for annual crops to ensure their comparison in the long term.

The B/C ratio is defined according to the equivalent annual cost (EAC) and the equivalent annual benefit (EAB). The net present cost (NPC) and net present benefit (NPB) are estimated as follows (EC, 2015):

$$ {}^{B}\!/_{C}\, ratio = \frac{EAB}{EAC} = \frac{NPC\frac{r}{1-(1+r)^{-t}}}{NPB\frac{r}{1-(1+r)^{-t}}} \tag{3}$$

$$NPC = -K + \sum_{t=1}^{t}\left(\frac{C_t + C_t^e}{(1+r)^t}\right) \tag{4}$$

$$NPB = \sum_{t=1}^{t}\left(\frac{B_t + B_t^e}{(1+r)^t}\right) \tag{5}$$

Where B_t and C_t represents the private benefits and costs, respectively, B_t^e and C_t^e the environmental and socio-cultural benefits and costs, r is the discount rate (3.5%), K is the investment cost and t is the period for which the ${}^{B}\!/_{C}\, ratio$ of crop diversification is measured (25 years).

3. Results

3.1. Short-term economic value of crop diversification

The short-term economic value of crop diversification is measured by considering both the financial economic performance of crop diversification for farmers and the derived non-market benefits and costs. Table 2 provides a summary of the SGMs for the field case studies, describing their main market and non-market components: GMs, environmental benefits, sociocultural benefits and SGM.

[Table 2 about here]

Results show an enhancement of the margins for most of the diversification practices assessed when environmental and sociocultural benefits are considered. This is very relevant in cases with negative GM values, such as CS1-D2, where environmental and sociocultural benefits turn negative GM into positive SGM. In other words, what a priori may be rejected because of its low private profitability, may become desirable from a social point of view if such benefits are considered. Thus, the consideration of non-market benefits makes it possible to increase the social profitability of agriculture, mainly for those diversification practices that have positive SGMs.

While the contributions of environmental and socio-cultural benefits are significant, these cannot far outweigh the market outcomes of crop diversification, at least in the short term. Only in the case of diversifications where private GMs are relatively low, the contribution of non-market benefits is large enough to outweigh farm-level economic outcomes. This is most representative of diversifications within CS1, whose private GMs are around 200 €/ha per year in D1, but the environmental and sociocultural benefits amount to more than 650 €/ha per year.

However, the provision of ecosystem services under diversification conditions does not always improve. Although it may be considered extraordinary, it does happen in CS2 and CS5 in the short-term for the biodiversity indicators in both case studies and soil carbon for only CS5. The regulating ecosystem services reduction in the short-term also is translated into terms of non-market values, as revealed in Table 2, by considering environmental costs (negative sign) instead of benefits. Hence, the inclusion of non-market value serves to include the impact of human activities on the environment.

The contribution of monocropping systems to the provision of agroecosystem services could be understood, similarly, as environmental and sociocultural costs. Thus, the socioeconomic contribution of agriculture should be considered as including the non-market value of these expected negative contributions. Table 2 shows the environmental and socio-cultural costs that monocropping systems can generate for society. This can become very significant when the environmental and socio-cultural costs transform economic benefits at the farm level into negative social outcomes. This is the case of monocrops in CS1 and CS3 as shown in Figure 2. The low market profitability of rainfed almond monocrops in CS1 and melon monocrops in CS3 is absorbed by the large reported environmental and sociocultural costs of monocropping systems in the southern Mediterranean region. This indicates that profitable cropping systems for farmers may not be a good alternative from a social point of view in the short term.

[Figure 2 about here]

3.2. Medium and long-term economic value of crop diversification

Decisions on the adoption of crop diversification must consider both, the current impact of cropping systems and the expected medium and long-term effects. In this sense, the cost-benefit analysis contributes to enhancing decision-making from a policy point of view by integrating into a common assessment the expected market and non-market effects of diversified and monocropping systems over the next 25 years. Figure 3 displays the results of the cost-benefit analysis showing the NPV and B/C of the assessed field case studies.

[Figure 3 about here]

In the medium and long term, most diversifications perform economically better than the expected results of monocrops. The cumulative market and non-market benefits of crop diversification are derived from a greater increase in the provision of regulating ecosystem services (compared to the short-term), along with the expected improvement in soil fertility. In contrast to the short-term socioeconomic outcomes of crop diversification summarized by SGM, the consideration of the long-term effects derived from cropping systems encourages the transformation towards a more sustainable agriculture that considers the impact, not only for the current generation but also for generations to come.

In this regard, CS1 is one of the most representative case studies assessed, given the economic results shown both in absolute and relative terms. If only market returns are included in the analysis, rainfed almond monocrop (Base MC) is profitable, as it is currently the case in the farm in the business-as-usual situation. However, if the negative impacts that monocrop can cause to the environment in the long term are considered, the positive socioeconomic results become negative. This socially undesirable situation could be overcome by adopting intercropping in the alleys of the almond orchards, in one of which thyme is grown for essential oil. Thus, the intercropping of almonds and thyme not only provides benefits at the farm level, but also for the environment and the social system. These benefits, measured and integrated in common monetary terms, greatly exceed those that could be obtained with any of the other cropping systems assessed. The positive economic performance of crop diversification over the long term is evident in both absolute and relative terms, given the improved NPV and B/C ratios of D1 and D2 compared to any other MC estimation.

Even in the case diversified systems show negative NPV, they perform better than monocrops in the medium and long term. The environmental and sociocultural benefits associated with crop diversification compensate for the negative market performance of monocropping systems. This is of high relevance for Boreal case studies, where fodder crops, associated with low GMs, display a significant improvement in their economic performance when non-market benefits are considered. As such, non-market benefits need to be considered to comprehensively understand the overall impact of crop diversification.

4. Discussion

The integration of the market and non-market benefits and costs associated with crop diversification across different crops, diversification strategies and European regions has evinced the economic viability of crop diversification practices as alternatives for extending monocrops. The results have shown the economic and social sustainability of crop diversification along different time spans, which adds to and supports the overstudied environmental sustainability (Morugán-Coronado et al., 2022; Viguier et al., 2023) and farm-level financial profitability (Sánchez et al., 2022; Zabala et al., 2023). The integration of environmental, financial, and sociocultural benefits, and costs, by using a common unit -monetary values- becomes one of the main novelties of the method employed. As such, the overall positive economic impact of crop diversification across Europe has been demonstrated for the European regions under consideration. Through a social gross margin analysis and a cost-benefit analysis, it has been possible to answer the three main questions formulated in this work.

(1) Is crop diversification socioeconomically profitable in the short and medium-long-term?

It has been shown that crop diversification is not just a vestige of the past, but a profitable agricultural system that would improve yields. An improvement of SGMs for monocropping has been observed in most of the diversification scenarios analysed. Perennial crops and vegetables reveal better performance when crop diversification is included. Such kinds of crops are usually linked to higher farm incomes and more rural employment, therefore enhancing economic and social returns of crop diversification (De Roest et al., 2018). Despite the greater labour needs, crop diversification in vegetables also works as a strategy for farmers to reduce market risks and mitigate climate change impacts (Ali, 2015; Martin-Gorriz et al., 2022). Thus, the contribution of crop diversification to increased food security and nutrition is mostly positive (Feliciano, 2019). These results are also in line with Beillouin et al. (2019) on the overall improvement of the productive performance of cropping systems with diversification strategies; and Makate et al. (2016) on the positive impact of crop diversification in poorly developed areas.

Therefore, the promotion of crop diversification to improve agricultural sustainability will also allow to maintenance of a sufficient level of food production (Bullock et al. 2017). In addition, as argued by Lin (2011) and Lenssen et al. (2014), diversified systems can be a solution to maintain production levels in more frequent extreme climatic conditions (droughts, floods...) and with water resource scarcity as are the case of some studies of the Southern Mediterranean analysed in this work.

(2) How does the inclusion of non-market values of the ecosystem services affect the social gross margins of monocropping systems and crop diversification? Are non-market values more important than market values?

Non-market values of ecosystem services improve SGMs of crop diversification regarding monocropping. The adoption of diversified farming systems would improve the ecosystem services and it could be considered as a way to conserve land productivity while being environmentally friendly (Phalan et al., 2011). Also, enhancing diversity within agricultural systems could combine food production with environmental quality (Lemaire et al., 2015). These results are in line with Kremen & Miles (2012) and Rosa-Schleich et al. (2019) who highlight the positive effects of crop diversification on biodiversity and the environment.

Diversification strategies and crops, together with the management of the reference monocropping system determine the value of the non-market benefits. Higher values for environmental and sociocultural benefits were suggested in South Mediterranean case studies, where the changes in the agroecosystems were greater because of diversification practices. Intercropping between perennial crops represents a deep change in ecosystem services and landscape features, increasing both services their provision levels. In contrast, non-market values seem to be lower in the Boreal region, where the degree of diversification intensity is also lower (diversified farming systems are similar to the reference monocropping systems in terms of diversification strategies and crops). Hence, it is suggested that the greater the change in the agronomic and landscape features regarding the reference system (diversification intensity), the greater the impact of diversification, and so the higher their non-market values.

If non-market values were not considered in the economic analysis, gross margins from crop diversification would be much lower (Martin-Guay et al., 2018). Furthermore, our results showed that non-market benefits cannot outweigh market values in the short term, and that needs time to be realized. Even so, the non-market benefits are significant enough to ensure the overall profitability of such practices. Therefore, to value the contribution of non-market values of crop diversification is essential, especially in the long term when deep changes from monocropping to diversified systems are expected, such as those presented in this paper.

The significance of the non-market values here are conditioned to the ecosystem services selected and measured for each diversification farming system. However, the range of ecosystem services provided by crop diversification is wider. Crop diversification practices may also reduce greenhouse gas emissions, increase soil fertility, encourage the presence of natural pollinators in agroecosystems, increase water retention, and enhance other forms of biodiversity, among other ecosystem services (Morugán-Coronado et al., 2022; Sánchez-Navarro et al., 2023; Marcos-Pérez et al., 2023). Also considering the non-market value of such these ecosystem services provides a deeper insight in the global economic performance of crop diversification. Therefore, the estimations here presented should be understood as a first, and conservative, approximation of the actual economic value of crop diversification, which is expected to be higher when the global provision of ecosystem services is considered and quantified.

The challenge is to replace the traditional approach based on simplifying cropping systems to maximize productivity with a new approach based on optimizing benefits considering environmental and cultural impacts together with land productivity (Lemaire et al., 2014). The higher profitability of diversification compared to monocrops suggests the development of agricultural systems based on new agricultural practices able to provide socioeconomic and environmental results (Franzluebbers et al., 2011) to achieve more sustainable agriculture.

Additional challenges also need to be addressed, such as knowledge transfer and technical assistance regarding diversification practices, economic incentives for farmers from agricultural policy, and the adaptation of the agrifood value chain (Brannan et al., 2023). Thus, applying a multidisciplinary approach could facilitate the understanding of a transition from monocropping to diversified systems.

(3) Do the social gross margins generated for the different European agroecosystems follow the same general trend?

The socioeconomic and environmental performance of crop diversification strategies is known to be context-dependent (Duru et al., 2015). However, the comprehensive economic approach followed in this work suggests that diversification practices provide positive impacts on both the farm economic performance and the environment, regardless of the region assessed. Thus, the trend is clear: SGMs become more positive (CS1 and CS3 of the Southern Mediterranean and in CS4 and CS5 of the Northern Mediterranean) or less negative (CS6 of the Northern Mediterranean and in the two cases of the Boreal) considering diversification practices, with different NPV results depending on crop types and practices used and to climatic and agronomic conditions

(Rosa-Schleich et al., 2019). This trend suggests the social acceptability of diversification practices in terms of wellbeing gains, in both the short and long term.

The analyses proposed in this work have provided a better representation of what agriculture is and what it provides to society, compared to an analysis based on short-term market-valued outcomes only. Results may have relevant implications for the design of agricultural policies and the selection of more appropriate farming practices for farmers and various other actors in value chains. Both policymakers and value chain actors may be under pressure or process to find and evidence improved sustainability. The results may guide the understanding of the subsidies that different European diversified systems may receive. Thus, it is advised that crop diversification provides increasing socioeconomic benefits, supporting the development of agricultural policies for promoting the adoption of crop diversification practices among European farmers. For example, policies based on the use of 5-year contracts called agri-environmental schemes from the Common Agricultural Policy may be relevant in Boreal regions where there are, a priori, farm-level financial losses at least at some farms in the case study region. In this way, these subsidies can sustain farmers' extrinsic motivation to grow crops with diversification practices (Sauquet, 2023). Even if the CAP helps to harmonize approaches towards more diversified management of agricultural land, the added value of sustainability will have to be generated and supported by more engaging relationships between agri-food supply chain operators. The reconfiguration of agri-food value chains adapted to alternative crop diversification systems should consider different policy tools. For example, the combined joining to agri-environmental measures and the possibility to access cultivation contracts that provide product collection guarantees, direct technical assistance to farmers, agri-food chain premiums and/or better management of agricultural risk (through insurance policies) seeking to overcome some of the main barriers for its adoption (Pancino et al., 2019; Rodriguez et al., 2021; Brannan et al., 2023). Traditional agricultural economic reasoning recommends such actions providing technical or market-based benefits rather than increased reliance on subsidies which lead to some welfare loss (due to reduced market signals). Awareness of farmers on the potential yield gains such as pre-crop values in crop rotations, and cost savings due to diversification, may already provide significant gains if utilised in farm management (Tzemi & Lehtonen 2022).

The analysis carried out in this work could be extended in future research by considering other European pedoclimatic regions, such as the Eastern Mediterranean or Atlantic, other crops and diversification strategies, and longer time spans. Results from eight case studies, mostly combining rotation and intercropping strategies, might not be enough to draw global conclusions, but it does provide a first good insight on the expected economic impact of crop diversification. Further regional comparisons could be made within each pedoclimatic region with which to create a more comprehensive economic assessment framework. However, despite the limited number of crops and case studies, similarities regarding market values tend to arise when comparing with results of diversified farming systems in other pedoclimatic regions and with other crops. As such, Viguier et al. (2023) reveals that, independently the diversification strategy followed, diversified farming systems does not provide different results than conventional farming systems in terms of their economic and social performance. They assess the sustainability of diversified farming systems in France, Atlantic pedoclimatic region, with cereals, legumes and oil rapeseed as representing crops. Also, Zabala et al. (2023) suggested that crop diversification practices tend to not provide different financial outcomes for farmers than monocropping ones, even considering a wider variety of crops, diversification strategies and most pedoclimatic European regions. The same applies even to the case of diversification practices in coffee systems (Teixeira et al., 2022).

The methods here applied, which combines environmental and sociocultural benefits, market and non-market valuation, and the consideration of different time spans, are expected to be the inspiration for integrated economic assessment of agricultural practices independently the region where developed. However, this method is not exempt of limitations. The use of non-market valuation methods relaying on social preferences becomes a source of subjectivity for the results. Besides this, some uncertainty about the ecosystem services flows and their economic value may arise as long-term values are mostly based on expected outcomes, which also depends on the discount rates employed and time span. As such, the approach taken in this study is well suited to sensitivity analysis in terms of varying discount rates or time spans.

5. Conclusions

The economic evaluation of crop diversification in three European pedoclimatic regions has shown the usefulness of such studies in supporting farmers and land managers to better understand the benefits of implementing these farming practices.

When environmental and socio-cultural benefits/costs associated with crop diversification and monocropping practices are integrated into the economic analysis, social gross margins become more positive, or less negative, for diversification practices, suggesting the social acceptability of diversification practices in terms of ecosystem services and well-being gains, in both the short and the long-term. The expected long-term economic outcome is also more influenced by the crop assessed than by the diversification applied. This acquires greater relevance when considering the environmental and sociocultural costs of monocrops.

We can conclude that these results are useful to guide not only farmers' decisions on crop choice and cultivation practices but also other actors in the value chain and agrifood policies. Sustainable agroecosystems and improved ecosystem services provision are increasingly appreciated socially (given the relevance of various environmental and sociocultural benefits in different regions), could be respected by farmers (due to the low impact on farm economic performance) and are expected to be supported by policymakers (due to their long-term positive returns). Therefore, while direct market-based economic gains for farmers may be small in the short run, diversification practices are shown to be a cost-effective instrument to increase the resilience of farming systems in the face of climate change, whilst social well-being is enhanced at short, medium and long-term.

Acknowledgments

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].

References

Alcon, F., Martin-Ortega, J., Pedrero, F., Alarcon, J. J., & de Miguel, M. D. (2013). Incorporating non-market benefits of reclaimed water into cost-benefit analysis: a case study of irrigated mandarin crops in southern Spain. Water Resources Management, 27, 1809-1820.

Alcon, F., Marín-Miñano, C., Zabala, J. A., de-Miguel, M. D., & Martínez-Paz, J. M. (2020). Valuing diversification benefits through intercropping in Mediterranean agroecosystems: A choice experiment approach. Ecological Economics, 171, 106593.

Alletto, L., Vandewalle, A., & Debaeke, P. (2022). Crop diversification improves cropping system sustainability: An 8-year on-farm experiment in South-Western France. Agricultural Systems, 200, 103433.

Ali, J. (2015). Adoption of Diversification for Risk Management in Vegetable Cultivation. International Journal of Vegetable Science, 21(1), 9-20.

Almansa, C., & Martínez-Paz, J. M. (2011). What weight should be assigned to future environmental impacts? A probabilistic cost benefit analysis using recent advances on discounting. Science of the Total Environment, 409(7), 1305-1314.

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., & Makowski, D. (2021). Positive but variable effects of crop diversification on biodiversity and ecosystem services. Global Change Biology, 27(19), 4697-4710.

Beillouin, D., Ben-Ari, T., & Makowski, D. (2019). Evidence map of crop diversification strategies at the global scale. Environmental Research Letters, 14(12), 123001.

Benini, M., Blasi, E., Detti, P., & Fosci, L. (2023). Solving crop planning and rotation problems in a sustainable agriculture perspective. Computers & operations research, 159 10.1016/j.cor.2023.106316.

Blasi, E., Rossi, E.S., Zabala, J.A., 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. Science of The Total Environment, 893, 164783.

Brannan, T., Bickler, C., Hansson, H., Karley, A., Weih, M., & Manevska-Tasevka, G. (2023). Overcoming barriers to crop diversification uptake in Europe: A mini review. Frontiers in Sustainable Food Systems, 7, 1107700.

Bullock, J. M., Dhanjal-Adams, K. L., Milne, A., Oliver, T. H., Todman, L. C., Whitmore, A. P., & Pywell, R. F. (2017). Resilience and food security: rethinking an ecological concept. Journal of Ecology, 105(4), 880-884.

Canfora, L., Orrú, L., Ros, M., Cuartero, J., Nuutinen, V., Dittrich, F., Lwanga, E.H., Sánchez-Navarro, V., Zornoza, R., & Thiele-Bruhn, S. (2022). D4.3. Report on improvements in above and belowground biodiversity by adoption of diversified cropping systems, and relationships between biodiversity, functioning and soil quality. © 2022 DIVERFARMING Project and Consortium. https://cordis.europa.eu/project/id/728003/results/es

Cerasuolo, M., & Begum, K. (2020). D7.2. Development of routines to simulate C sequestration of diversified cropping systems. © 2020 DIVERFARMING Project and Consortium. http://www.diverfarming.eu/images/deliverables/D7_2.pdf

Champ, P.A., Boyle, K., & Brown, T.C. (2017). A Premier on Nonmarket Valuation. Springer Nature, Dordrecht, The Netherlands. https://doi.org/10.1007/978-94-007-7104-8.

Clora, F., Yu, W., Baudry, G., & Costa, L. (2021). Impacts of supply-side climate change mitigation practices and trade policy regimes under dietary transition: the case of European agriculture. Environmental Research Letters, 16(12), 124048.

Damalas, C. A., & Eleftherohorinos, I. G. (2011). Pesticide exposure, safety issues, and risk assessment indicators. International Journal of Environmental Research and Public Health, 8(5), 1402-1419.

De Roest, K., Ferrari, P., & Knickel, K. (2018). Specialisation and economies of scale or diversification and economies of scope? Assessing different agricultural development pathways. Journal of Rural Studies, 59, 222-231.

D'Hose, T., Cougnon, M., De Vliegher, A., Vandecasteele, B., Viaene, N., Cornelis, W., Van Bockstaele, E., & Reheul, D. (2014). The positive relationship between soil quality and crop production: A case study on the effect of farm compost application. Applied Soil Ecology, 75, 189-198.

Duru, M., Therond, O., & Fares, M. H. (2015). Designing agroecological transitions; A review. Agronomy for Sustainable Development, 35, 1237-1257.

European Commission (EC) (2015). Guide to Cost-Benefit Analysis of Investment Projects. Publications Office of the European Union, Luxembourg.

Feliciano, D. (2019). A review on the contribution of crop diversification to Sustainable Development Goal 1 "No poverty" in different world regions. Sustainable Development, 27(4), 795-808.

Francaviglia, R., Álvaro-Fuentes, J., Di Bene, C., Gai, L., Regina, K., & Turtola, E. (2020). Diversification and management practices in selected European regions. A data analysis of arable crops production. Agronomy, 10(2), 297.

Franco, S., Pancino, B., Martella, A., & De Gregorio, T. (2022). Assessing the Presence of a Monoculture: From Definition to Quantification. Agriculture, 12(9), 1506.

Franzluebbers, A. J., Sulc, R. M., & Russelle, M. P. (2011). Opportunities and challenges for integrating North-American crop and livestock systems. Grassland productivity and ecosystem services, 208-218.

Hunt, N. D., Hill, J. D., & Liebman, M. (2019). Cropping system diversity effects on nutrient discharge, soil erosion, and agronomic performance. Environmental Science & Technology, 53(3), 1344-1352.

Iserloh, T., & Seeger, M. (2022). D7.3. Prediction of soil erosion for different scenarios. © 2022 DIVERFARMING Project and Consortium. https://cordis.europa.eu/project/id/728003/results/es

Keck, M., & Hung, D. T. (2019). Burn or bury? A comparative cost–benefit analysis of crop residue management practices among smallholder rice farmers in northern Vietnam. Sustainability Science, 14, 375-389.

Kremen, C., & Miles, A. (2012). Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. Ecology and Society, 17(4).

Lamichhane, J.R. (2023). Knowledge gaps on agricultural diversification. Nature Food. 10.1038/s43016-023-00837-3.

Lancaster, N.A., & Torres, A.P. (2019). Investigating the Drivers of Farm Diversification Among U.S. Fruit and Vegetable Operations. Sustainability, 11(12), 3380.

Latvala, T., Regina, K., & Lehtonen, H. (2021). Evaluating non-market values of agroecological and socio-cultural benefits of diversified cropping systems. Environmental Management, 67, 988-999.

Lehtonen, H., Blasi, E., Alcon, F., Martínez-García, V., Zabala, J. A., de Miguel, M. D., Weituschat, S., Deszo, J., Loczy, D., Lopez, E., Frey-Treseler, K., Treseler, C., Purola, T., & Grosado, M. (2020). D8.3. Farm level economic benefits, costs and improved sustainability of diversified cropping systems. © 2020 DIVERFARMING Project and Consortium. http://www.diverfarming.eu/index.php/en/repository-2

Lemaire, G., Franzluebbers, A., de Faccio Carvalho, P. C., & Dedieu, B. (2014). Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. Agriculture, Ecosystems & Environment, 190, 4-8.

Lemaire, G., Gastal, F., Franzluebbers, A., & Chabbi, A. (2015). Grassland–cropping rotations: an avenue for agricultural diversification to reconcile high production with environmental quality. Environmental Management, 56, 1065-1077.

Lenssen, A. W., Sainju, U. M., Jabro, J. D., Iversen, W. M., Allen, B. L., & Evans, R. G. (2014). Crop diversification, tillage, and management system influence spring wheat yield and water use. Agronomy Journal, 106(4), 1445-1454.

Lin, B.B. (2011). Resilience in agriculture through crop diversification: adaptive management for environmental change. BioScience, 61(3), 183-193.

Loczy, D., Martínez-Mena, M. Boix-Fayos, C., Sánchez-Navarro, V., Álvaro-Fuentes, J., Lozano-García, B., Parras, L., González-Rosado, M., Farina, R., di Bene, C., Lwanga, E.H., Seeger, M., Iserloh, T., Dezso, J., Regina, K., & Zornoza, R. (2022). D5.4. Benefits and drawbacks of diversified cropping systems to reduce the environmental impact and improve the delivery of ecosystem services. © 2022 DIVERFARMING Project and Consortium. https://cordis.europa.eu/project/id/728003/results/es

Makate, C., Wang, R., Makate, M., & Mango, N. (2016). Crop diversification and livelihoods of smallholder farmers in Zimbabwe: adaptive management for environmental change. SpringerPlus, 5, 1-18.

Marcos-Pérez, M., Sánchez-Navarro, V., Martínez-Martínez, S., Martínez-Mena, M., García, E., & Zornoza, R. (2023). Intercropping organic melon and cowpea combined with return of crop residues increases yields and soil fertility. Agronomy for Sustainable Development, 43, 53.

Martin-Gorriz, B., Zabala, J. A., Sánchez-Navarro, V., Gallego-Elvira, B., Martínez-García, V., Alcon, F., & Maestre-Valero, J. F. (2022). Intercropping Practices in Mediterranean Mandarin Orchards from an Environmental and Economic Perspective. Agriculture, 12(5), 574.

Martin-Guay, M. O., Paquette, A., Dupras, J., & Rivest, D. (2018). The new green revolution: sustainable intensification of agriculture by intercropping. Science of the Total Environment, 615, 767-772.

Mortensen, D. A., & Smith, R. G. (2020). Confronting barriers to cropping system diversification. Frontiers in Sustainable Food Systems, 4, 564197.

Morugán-Coronado, A., Pérez-Rodriguez, 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. Agriculture, Ecosystems & Environment, 329, 107867.

Nilsson, P., Bommarco, R., Hansson, H., Kuns, B., & Schaak, H. (2022). Farm performance and input self-sufficiency increases with functional crop diversity on Swedish farms. Ecological Economics, 198, 107465.

Nunes, M. R., van Es, H. M., Schindelbeck, R., Ristow, A. J., & Ryan, M. (2018). No-till and cropping system diversification improve soil health and crop yield. Geoderma, 328, 30-43.

Pancino, B., Blasi, E., Rappoldt, A., Pascucci, S., Ruini, L., & Ronchi, C., (2019). Partnering for sustainability in agri-food supply chains: the case of barilla sustainable farming in the Po Valey. Agricultural and Food Economics 7 (1). https://doi.org/10.1186/s40100-019-0133-9.

Phalan, B., Onial, M., Balmford, A., & Green, R. E. (2011). Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science, 333(6047), 1289-1291.

Piccini, C., Vanino, S., Marchetti, A., & Farina, R. (2022). D7.4. Distribution maps for thematic variables and territorial data to provide a decision support system for policy makers and planners. © 2022 DIVERFARMING Project and Consortium. https://cordis.europa.eu/project/id/728003/results/es

Purwanto, B. H., & Alam, S. (2020). Impact of intensive agricultural management on carbon and nitrogen dynamics in the humid tropics. Soil Science and Plant Nutrition, 66(1), 50-59.

Robertson, G. P., & Swinton, S. M. (2005). Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. Frontiers in Ecology and the Environment, 3(1), 38-46.

Rodriguez, C., Màrtensson, L.D., Zachrison, M., & Carlsson, G. (2021). Sustainability of Diversified Organic Cropping Systems—Challenges Identified by Farmer Interviews and Multi-Criteria Assessments. Frontiers in Agronomy, 3, 698968.

Roesch-McNally, G. E., Arbuckle, J. G., & Tyndall, J. C. (2018). Barriers to implementing climate resilient agricultural strategies: The case of crop diversification in the US Corn Belt. Global Environmental Change, 48, 206-215.

Rosa-Schleich, J., Loos, J., Mußhoff, O., & Tscharntke, T. (2019). Ecological-economic trade-offs of diversified farming systems–a review. Ecological Economics, 160, 251-263.

Sánchez, A.C., Karnau, H.N., Grazioli, F., & Jones, S.K. (2022). Financial profitability of diversified farming systems: A global meta-analysis. Ecological Economics, 201, 107595. https://doi.org/10.1016/j.ecolecon.2022.107595

Sánchez-Navarro, V., Martínez-Martínez, S., Acosta, J.A., Almagro, M., Martínez-Mena, M., Boix-Fayos, C., Díaz-Pereira, E., Temnani, A., Berrios, P., Pérez-Pastor, A., & Zornoza, R. (2023). Soil greenhouse gas emissions and crop production with implementation of alley cropping in a Mediterranean citrus orchard. European Journal of Agronomy, 142, 126684.

Sauquet, A. (2023). Ex post analysis of the crop diversification measure of CAP greening in France. European Review of Agricultural Economics, 50(2), 717-742.

Scherer, L. A., Verburg, P. H., & Schulp, C. J. (2018). Opportunities for sustainable intensification in European agriculture. Global Environmental Change, 48, 43-55.

Tamburini, G., Bommarco, R., Wanger, T. C., Kremen, C., Van Der Heijden, M. G., Liebman, M., & Hallin, S. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. Science advances, 6(45), eaba1715.

Teixeira, H. M., Schulte, R.P.O., Anten, N.P.R., Bosco, L.C., Baartman, J.E.M., Moinet, G.Y.K., & Reidsma, P. (2022). How to quantify the impacts of diversification on sustainability? A review of indicators in coffee systems. Agronomy for Sustainable Development, 42, 62. https://doi.org/10.1007/s13593-022-00785-5

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences, 108(50), 20260-20264.

Tzemi, D., & Lehtonen, H. (2022). The use of pre-crop values to improve farm performance: the case of dairy farms in southwest Finland. International Journal of Agricultural Sustainability, 20(7), 1333-1347.

Viguier, L., Cavan, N., Bockstaller, C., Cadoux, S., Corre-Hellou, G., Dubois, S., Duval, R., Keichinger, O., Toqué, C., Toupet de Cordoue, A. L., & Angevin, F. (2021). Combining diversification practices to enhance the sustainability of conventional cropping systems. European Journal of Agronomy, 127, 126279. https://doi.org/10.1016/J.EJA.2021.126279

Weituschat, C. S., Pascucci, S., Materia, V. C., Tamas, P., de Jong, R., & Trienekens, J. (2022). Goal frames and sustainability transitions: how cognitive lock-ins can impede crop diversification. Sustainability Science, 17(6), 2203-2219.

Wezel, A., Casagrande, M., Celette, F., Vian, J. F., Ferrer, A., & Peigné, J. (2014). Agroecological practices for sustainable agriculture. A review. Agronomy for Sustainable Development, 34(1), 1-20.

Wezel, A., Goris, M., Bruil, J., Félix, G. F., Peeters, A., Bàrberi, P., Bellon, S., & Migliorini, P. (2018). Challenges and action points to amplify agroecology in Europe. Sustainability, 10(5), 1598.

Zabala, J.A., Martínez-García, V., Martínez-Paz, J.M., López-Becerra, E.I., Nasso, M., Díaz-Pereira, E., Sánchez-Navarro, V., Álvaro-Fuentes, J., González-Rosado, M., Farina, R., Di Bene, C., Huerta, E., Jurrius, A., Frey-Treseler, K., Lóczy, D., Fosci, L., Blasi, E., Lehtonen, H., & Alcon, F. (2023). Crop diversification practices in Europe. An economic cross-case study comparison. Sustainability Science, 18, 2691–2706. https://doi.org/10.1007/s11625-023-01413-1

Table 1. Summary of case studies

Case study	Country	Pedoclimatic area	Crop type	Crop(s) of the reference system (MC)	Type of diversification[1]	Diversified farming system[2]
CS1	Spain	South Mediterranean	Perennial	Almond	Intercropping	D1: Almond / Caper D2: Almond / Thyme
CS2	Spain	South Mediterranean	Perennial	Mandarin	Intercropping (rotation and multiple cropping)	D1: Mandarin / (Vetch & Barley + Fava bean) D2: Mandarin / (Fava bean + Purslane + Cowpea)
CS3	Spain	South Mediterranean	Annual	Melon	Intercropping	D1: Melon + Cowpea
CS4	Italy	North Mediterranean	Annual	Maize	Rotation (intercropping)	D1: Tomato + Pea/Tomato + Durum wheat
CS5	Italy	North Mediterranean	Annual	Durum wheat + barley	Rotation (intercropping)	D1: Tomato + Pea/Tomato + Durum wheat
CS6	Italy	North Mediterranean	Annual	Tomato + Durum wheat	Rotation (intercropping)	D1: Tomato + Pea/Tomato + Durum wheat
CS7	Finland	Boreal	Annual	Barley	Rotation	D1: Barley + Winter rapeseed + Barley
CS8	Finland	Boreal	Annual	Barley + 15% grass ley	Rotation	D1: Barley + 30% grass ley + Barley

[1] In brackets other type of secondary diversifications also presented in the case study (e.g., in D1 in CS1, multiple cropping of vetch and barley is rotated with fava bean as alley crop between mandarin rows, meanwhile they both represent an intercropping system regarding to mandarin, the reference system). Complete description of case studies is available in Zabala et al. (2023).

[2] “()” integrates annual crops in diversification with perennial crops; “&” indicates multiple cropping; “+” indicates rotation; “/” indicates intercropping.

Note: “MC” represents the monocropping system; “D1” represents the diversification 1; “D2” represents the diversification 2.

Table 2. Social gross margins (SGMs) and their components of field case studies (CS) (€PPP/ha year)

Components		South Mediterranean								North Mediterranean						Boreal			
		CS 1			CS 2			CS 3		CS 4		CS 5		CS 6		CS 7		CS 8	
		MC	D1	D2	MC	D1	D2	MC	D1	MC	D1	MC	D1	MC	D1	MC	D1	MC	D1
Market valuation	Revenues	890	993	982	9,245	8,231	7,175	9,528	16,242	3,997	4,774	3,555	5,144	2,258	4,274	700	725	2,495	2,495
	Variable costs	266	511	708	3,269	5,962	5,468	8,827	11,324	2,526	2,951	2,606	3,337	2,526	3,318	514	520	2,058	2,006
	Fixed costs	143	268	280	1,222	1,176	1,120	444	486	360	375	269	257	0	0	482	485	878	878
	GM	481	214	-7	4,753	1,093	588	257	4,432	1,110	1,192	680	697	-268	-530	-297	-280	-440	-396
Non-market valuation	Environmental benefits/costs	-302	350	350	-302	-38	62	-302	88	-117	81	-117	-77	-117	81		51		51
	Sociocultural benefits/costs	-174	310	310	-174	310	310	-174	310	-32	41	-32	41	-32	41		46		46
SGM		4	874	653	4,277	1,365	960	-220	4,831	962	1,315	531	662	-417	-407	-297	-183	-440	-299

Note: “MC” represents the monocropping system; “D1” represents the diversification 1; “D2” represents the diversification 2; “PPP” means Purchasing Power Parity.

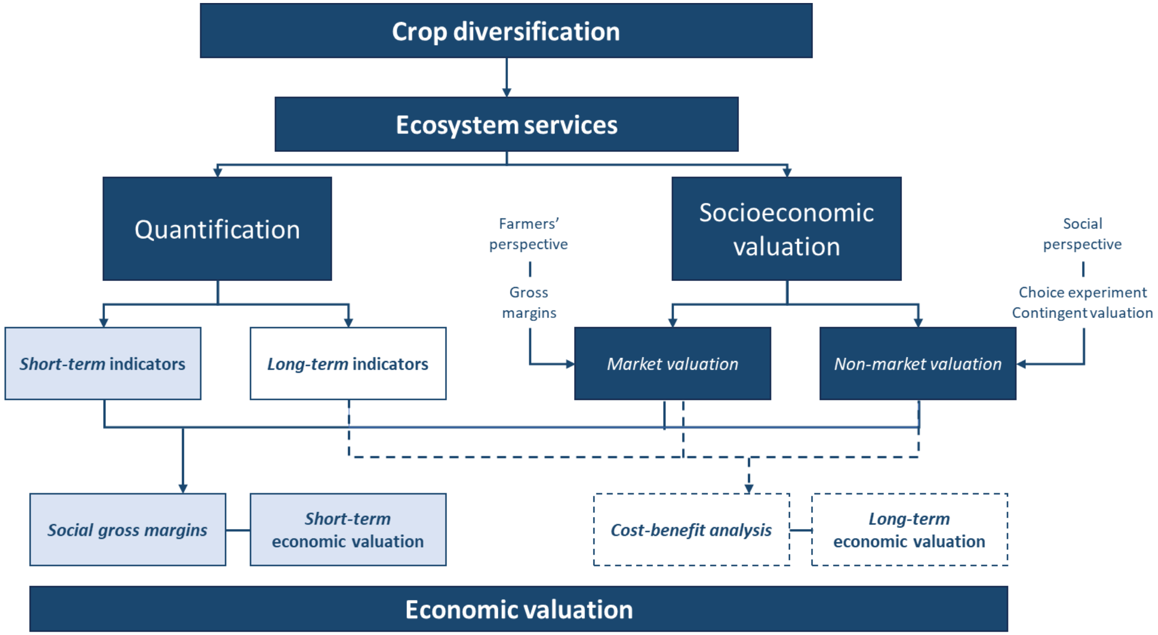

Figure 1. Methodological framework applied for each case study

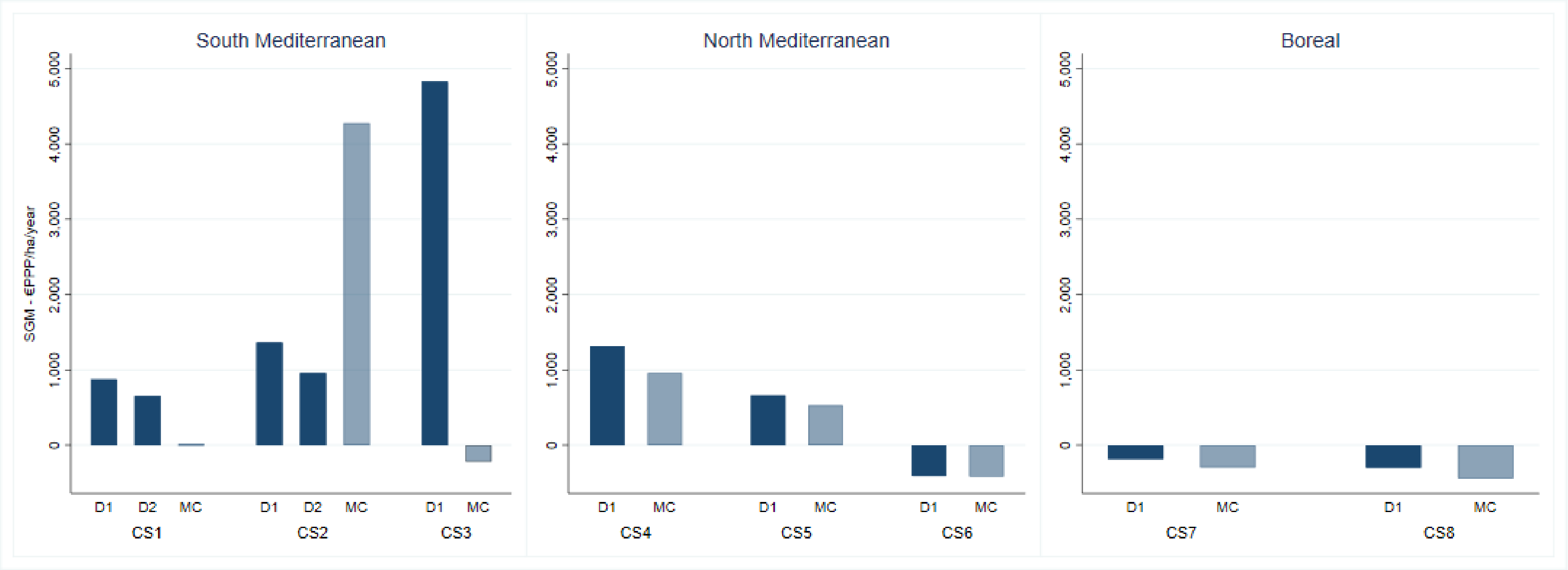

Figure 2. Social gross margins (SGMs) of case studies (CS) (€PPP/ha year). Note: "MC" represents the monocropping system; "D1" represents the diversification 1; "D2" represents the diversification 2; "PPP" means Purchasing Power Parity.

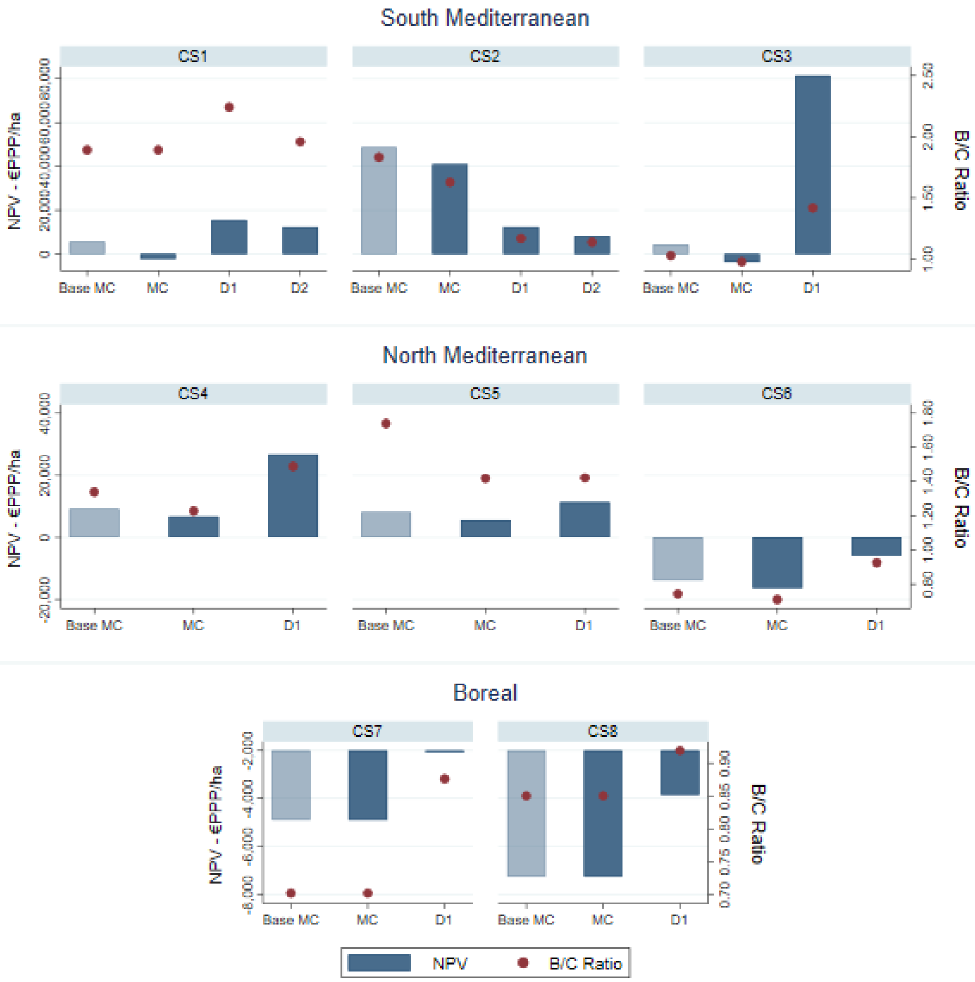

Figure 3. Net present value (NPV), in bars, and benefit cost ratio (B/C Ratio), in points, of field case studies (CS). Note: “MC” represents the monocropping system; “D1” represents the diversification 1; “D2” represents the diversification 2; “PPP” means Purchasing Power Parity. MC, D1 and D2 includes market and non-market benefits and costs. Base MC comprehends only market benefits and costs.

Supplementary material

Biophysical indicators

Land erosion index

Loss of soil due to wind or precipitation. The role of cover crops is crucial in mitigating the impact of atmospheric agents (rain and wind) on soil particles. Land erosion index is measured in t soil/ha, seeking to reduce it by the effect of crop diversification. More information about land erosion is available on Iserloh & Seeger (2022).

Soil carbon content

Soil organic carbon is the main source of energy and nutrients for soil microorganisms, affecting plant growth. It plays a crucial role in aggregate stability and consequently intervenes in the distribution of the porous space, water holding capacity, and soil moisture, amongst other soil properties. Soil carbon content is measured in t C/ha, which is expected to increase because of crop diversification. More information about soil carbon content is available on Cerasuolo & Begum (2020).

Soil bacteria biodiversity

Bacterial communities play an important role in agricultural systems due to their involvement in many different soil processes and functions. They drive nutrient transformation and are directly and indirectly involved in many other ecosystems services such as erosion control or pest and disease regulation. Soil bacteria biodiversity was assessed through alpha-diversity, seeking to increasing it through crop diversification. More information about soil bacteria biodiversity is available on Canfora et al. (2022).

Soil enzyme activity

Soil enzymes are specialised proteins playing a key role in organic matter decomposition and plant nutrient cycling. In agricultural soils, enzymes are involved in breaking down plant residues, processing and providing nutrients to crops. Furthermore, enzymes respond to a wide range of agricultural practices such as crop rotation. Therefore, soil enzymes are regarded as sensitive indicators of soil fertility and soil quality and a key indicator of soil biodiversity. More information about soil enzyme activity is available on Canfora et al. (2022).

Available inorganic mineral contaminants

Inorganic mineral contaminants result from the leaching of nutrients and toxic metals to groundwater, advocating to the degradation of water ecosystems. More information about the impact of crop diversification on the presence of inorganic mineral contaminants is available on Piccini et al. (2022).