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Research article

Diverging agri-environmental, social and economic impacts when diversifying Mediterranean farming systems

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ABSTRACT

Mediterranean diets are based on cereals with ~200 kg per capita consumption per year. Cereals are threatened by declining soil quality and climate change, expected to alter crop yields and quality and increase food insecurity. This study assessed the agri-environmental, social, and economic performance of diversified farming systems across three case studies. We compared continuous cereal cropping as a reference system (RS) to various types of diversified systems (DIV), including grain legumes, rapeseed, and legume-cereal intercropping in the Ebro valley in Spain (ES), Thessaloniki in Greece (GR), and Setif in Algeria (DZ). The assessment was based on impact indicators validated by local stakeholders. The results showed that DIV improved social aspects, followed by agri-environmental and economic impacts, with large variation between sites. In Spain, DIV showed higher nitrogen and energy use efficiencies and resulted in lower production costs (−26 % on average). In Greece, DIV had higher agri-environmental and social performance than RS, with intercropping outperforming rapeseed and legume systems. Intercropping was the only Greek DIV with positive gross margins (186 EUR ha^{-1} $year^{-1}$). Despite European DIV improving some resource use efficiencies and food quality indicators compared to RS, their economic returns (without subsidies) remain mostly lower than those of continuous cereal cropping. The Algerian DIV had 10 out of 23 impact indicators outperforming continuous cereal cropping, mainly in social and economic dimensions. We conclude that diversification practices can result in divergent impacts in the Mediterranean. Our study serves as a foundation not only for the co-design of appropriate systems in the region but also for policies supporting systems' changes.

1. Introduction

Pasta, flatbreads, couscous, and bulgur, all staple Mediterranean dishes, are made from wheat, the traditionally preferred crop, which has been part of the Mediterranean agriculture for over 8000 years (Mefleh, 2021). The Mediterranean countries have the highest per capita wheat consumption around 200 kg, which is 60 kg more than the global average (UNEP/MAP and Plan Bleu, 2021). Thus, nearly half of the region's agricultural land for annual crops is devoted to winter cereals (42 %), leaving only 5 % for rapeseed and 3 % for legumes (Zdruli, 2014), while the rest is for horticulture, fodder, etc. Mediterranean agricultural systems are highly specialized and predominantly based on cereal

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cropping systems (Hossard et al., 2024; Vanino et al., 2022). Due to rainfed conditions, cereal production is limited to one crop/year, typically growing in cool and wet winter season, followed by a summer fallow season. (Ryan et al., 2012).

The productivity of rainfed cereals is threatened by low and unpredictable rainfall patterns, low soil organic carbon, and a legacy of conventional tillage practices that have deteriorated soil fertility, resulting in agrochemical reliance (Musto et al., 2023). Climate change is expected to adversely affect crop yields and quality, increasing the risk of food insecurity, particularly in North Africa (Mefleh, 2021), where reliance on food imports is growing. The Mediterranean basin, home to 7 % of the world's population, accounts for nearly one-third of global cereals imports. Over half of these countries' wheat consumption comes from Russia and Ukraine (Behnassi and El Haiba, 2022). Russia-Ukraine war starting in 2022 led to the disruption of agricultural production and trade, affecting these food-importing countries' ability to meet consumers' needs (UNCTAD, 2022). While the Euro-Mediterranean countries have shown resilience in terms of food security, the war has increased the costs of agricultural inputs,and energy, increasing production costs and affecting consumer prices.

Farming systems diversification (e.g., diversified rotations, intercropping, etc.) has been credited as a viable strategy for supporting productivity with fewer inputs and higher ecosystem services (Reckling et al., 2023). Crop rotation is an array of crops (e.g. cereals, rapeseed, legumes) that alternate over a cycle of years. Their benefits include improved soil health, reduced weed and pest pressure, and saved fuel and chemical costs (Lago-Olveira et al., 2023). Additionally, they can improve farm profitability and reduce economic risks (Khakbazan et al., 2022). Furthermore, incorporating legumes can reduce N fertilizer use as they fix N from the atmosphere. Moreover, grain legumes are a staple source for protein and minerals (Ryan et al., 2012). Thus, diversification plays a crucial role in achieving sustainable, low-input agriculture while reducing negative environmental and social impacts (Liu et al., 2022).

Nevertheless, crop rotations perform differently depending on species types, pedoclimatic conditions, and growing regimes (Lago-Olveira et al., 2023). Assessing the performance and sustainability of farming systems calls for an integrated framework of impact indicators (Vanino et al., 2022). An indicator simplifies, quantifies, and communicates complex information about a system's agri-environmental, social, and economic dimensions (Silva et al., 2020). In addition to measuring changes, indicators can help identify problems, set locally relevant goals, and determine suitable management strategies (Reed et al., 2006). The selection of indicators is usually done by experts and/or through participatory approaches, in combination with literature reviews (Mascarenhas et al., 2015). Active involvement of stakeholders (bottom-up approach) at the beginning of the assessments (e.g., indicators selection) enhances the consideration of the various perspectives on local knowledge, aspirations, and challenges (Reed et al., 2006). It improves ownership and acceptance of assessment outcomes, enhancing transferability and the likelihood of practice implementation (Chopin et al., 2021).

A growing number of studies have assessed the impacts of diversification in Mediterranean farming systems (Kherif et al., 2023; Simon-Miquel et al., 2024; Vanino et al., 2022). Further, these studies tended to focus on one or two dimensions, often favoring economic or environmental factors (Lago-Olveira et al., 2023; Rebolledo-Leiva et al., 2022). However, bottom-up approaches to selecting indicators are still outnumbered by top-down approaches in the Mediterranean region. Exceptions to this can be found, for example, in Di Bene et al. (2022) study on stakeholder perceptions of diversification.

Crop rotations are low-degree adaptations (Zagaria et al., 2023), requiring relatively little time and effort to implement, thereby increasing their likelihood of adoption by farmers. Most often, the assessment scale of Mediterranean diversified arable crops is restricted to the plot level, despite the farmers making the strategic and management practice decisions at the farm level (Chopin et al., 2021). Thus, it is vital to assess their performance across various dimensions to determine which diversified system would be the most suitable.

In this study, we aim to evaluate the performance of Mediterranean-based cereal cropping systems in the Ebro valley in Spain, in the Thessaloniki region in Greece, and the Setif region in Algeria. Our objectives were to assess, i) the agri-environmental, ii) the social, and iii) the economic performances of cereal-based cropping systems using impact indicators selected by local stakeholders. We considered two types of cereal-based cropping systems: i) continuous cereal cropping, considered as a reference system (RS), and ii) diversified cereal cropping (DIV), which involved grain legumes, rapeseed, or intercropping, compared to the continuous cereal cropping.

We hypothesize that diversification improves agri-environmental, social, and economic impacts of diversified options compared to continuous cereal cropping systems.

2. Material and methods

2.1. Description of the cropping systems

Due to their north-to-south and west-to-east gradients around the Mediterranean Sea, Spain, Greece, and Algeria represent a wide range of pedoclimatic and socioeconomic conditions for agricultural systems, representative of the basis of the ''healthy Mediterranean" (Bach-Faig et al., 2011). These countries produce 12 % and 31 % of Mediterranean wheat and barley, respectively (FAOSTAT, 2021). Each of the countries ranks as the second largest cereal producer in its respective Mediterranean region: Spain in the northwest (behind France), Greece in the east (behind Turkey), and Algeria in the southwest (behind Morocco) (Mrabet et al., 2020).

In these countries, Hossard et al. (2024) established a typology of currently practiced systems using data from national statistics and expert knowledge. A SWOT analysis revealed challenges across the economic, environmental, and social dimensions of sustainability. Most frequently, challenges were related to the economy (e.g., production costs, volatile market prices, etc.) and the environment (e.g., water scarcity, pests, climate change, etc.). The current practiced systems served as reference systems against which future diversified systems were designed and compared. During co-design workshops in each region, local actors proposed diversified systems to counter the above challenges using substitution and redesign strategies. In this study, we considered the local stakeholders-designed cropping systems as reported by Hossard et al. (2024). In particular, we evaluated two cropping scenarios for each country. The RS, a barley-wheat rotation (continuous cropping of cereals), and the DIV, which were based on the same cereal crops as in RS but also included other species (legumes and rapeseeds) and other crop configurations (intercrops). For each case study, only one reference system was considered. For diversified systems, Spain had two options while both Greece and Algeria had three alternative systems each. (Fig. 1).

The Ebro valley case study in Spain (ES) represents conventional cultivated systems on clay and loamy soils. These systems receive on average 250 mm of rainfall, with around 300 mm of support irrigation during drought periods (Blanc et al., 2024). Crop grains are sold either for animal feed or as brewing and bread-making materials. Diversifying the cereal continuous cropping system by incorporating either rapeseed or pea in the rotation (Fig. 1) was accompanied by reduced tillage and use of pig slurry for fertilization.

The Thessaloniki case study in Greece (GR) represents conventional and strictly rainfed (~400 mm) systems, cultivated on loamy soils. Both grains and straw are sold. The cereal continuous system was diversified through the incorporation of rapeseed, pea, or vetch-barley intercropping at a proportion of 70 % for common vetch and 30 % for barley.

The Setif case study in Algeria (Dzayer in local accents, DZ) represents conventional and rainfed (average 260 mm) systems that are cultivated on clay-loamy soils. Grains and straw are either sold in

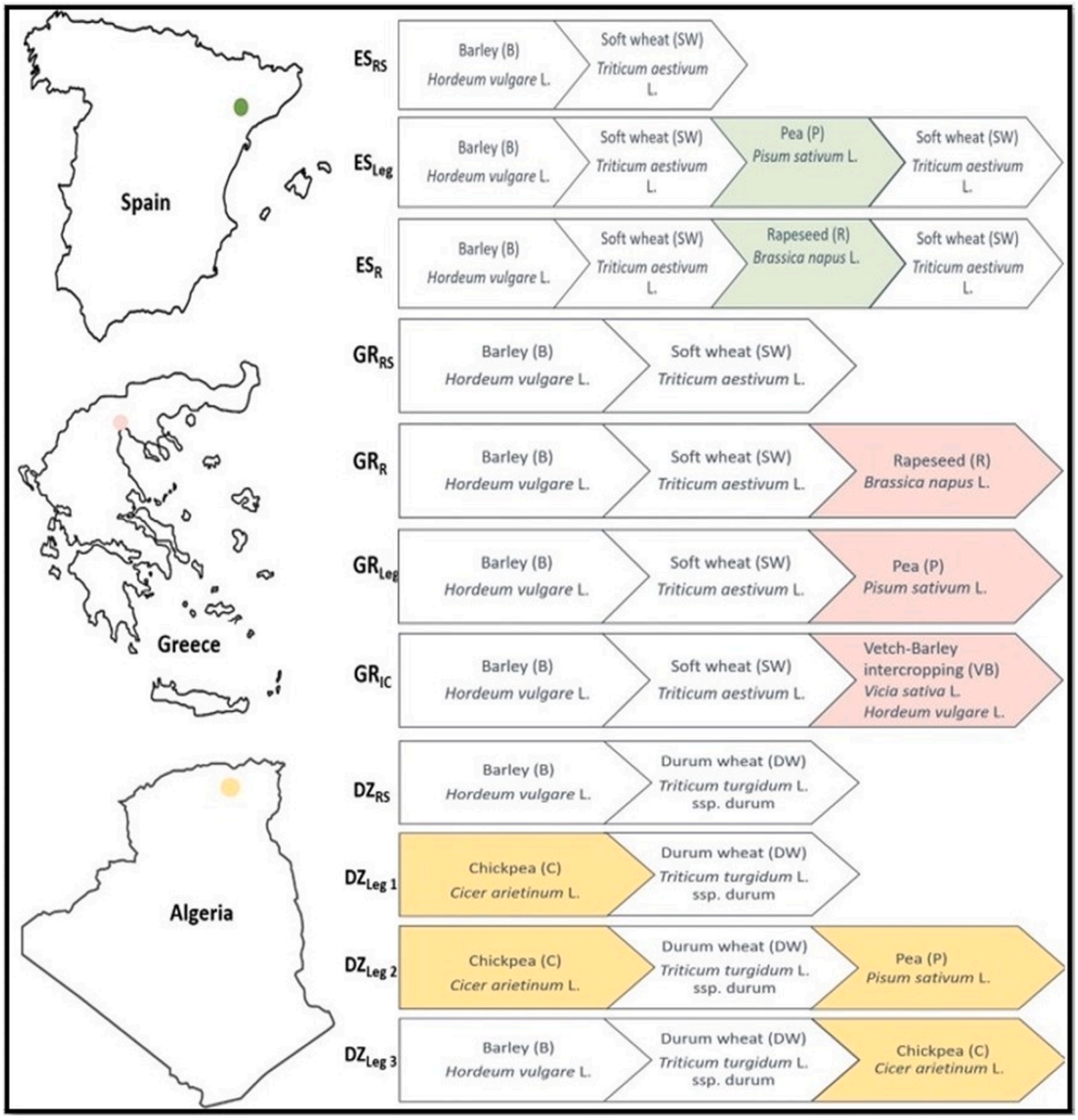

Fig. 1. Assessed farming systems (continuous cereals and diversified systems) in Spain (Ebro valley region, ES), in Greece (Thessaloniki region, GR) and in Algeria (Setif region, DZ).

markets or used for self-consumption (food and feed). The continuous cereal cropping was diversified by integrating chickpea and pea into the rotation. The site characteristics for each country are described in Table A in Supplementary Material 1.

2.2. Assessment indicators

The indicators were selected in two steps: i) literature review and ii) stakeholders validation, following the approach used by Rezgui et al. (2024). The literature review regarded the commonly assessed impacts of Mediterranean farming systems and was conducted to compile a list of indicators representing agri-environmental, social, and economic dimensions. System productivity-related inputs, such as water, fertilizer, energy, and pesticide use, were the basic impact categories, frequently appearing when reviewing impact categories and indicators for the agri-environmental dimension. The basic impact categories for the social dimension focused mostly on human capital (e.g., working hours, skills and training received by workers, etc.) and the nutritional quality of the system's output (e.g., protein content). For the economic dimension, the main assessed impacts relate to profitability (e.g., costs, revenues, etc.). Stakeholders from the regional case studies were later invited, through an online survey, to score the indicators that reflected their aspirations for what needs to be measured. The survey measured the indicators' performance, using a five-point Likert scale ranging from 1 (least important) to 5 (very important) concerning the following criteria: context relevance (the ability to adapt to the local context), clearness (clearness in content and expression in coherent units) and ease of interpretation (its value being easily understandable by the user). Additionally, respondents were allowed to suggest additional indicators when deemed necessary. The authors pre-tested the survey for language and content accuracy. The survey was conducted electronically from June 2021 to December 2021. Following low response rates, the survey

was reopened from March to May 2022. The responses received (n = 42: $n_{ES} = 9$, $n_{GR} = 16$, $n_{DZ} = 17$) came from a range of stakeholders (farmers, advisors, and researchers) with the common feature of being local actors in the agricultural field of each country (Table B, supplementary material 1).

To obtain the total Likert scale score, the most common strategy is to sum its item scores. The Likert scale type itself is based on the assumption that it has internal consistency (Martinez-Martin, 2010). Therefore, each indicator was tested for reliability using Cronbach alpha (Munyanduki et al., 2016). The reliability of the scores is a measure of their internal consistency. When an indicator has a Cronbach's alpha of one, it means that respondents' scores accurately reflect their true status according to the criteria being measured. Usually, Cronbach alpha of 0.7 is considered adequate (Gay et al., 2014).

In our case, the Cronbach alpha was equal to or superior to 0.7 for all indicators (Fig. 1A, supplementary material). Consequently, total score performance (S_i) was computed for all indicators with Eq. (1).

$$S_i = \frac{\sum_{i=1}^{n} v_i}{p^*n} * 100 \quad (1)$$

Where S_i denotes the total performance score of indicator i in percent, v_i denotes the sum of Likert score criteria of indicator i, n denotes the total number of criteria per indicator (n = 3), and p denotes the highest possible score of the Likert response format (p = 5).

All indicators scored above 50 % and were retained (Fig. 2A, supplementary material). Other indicators were included based on stakeholders' suggestions (e.g., Nutrient Density Unit, Pesticide Load Index, etc.). The indicators shortlisted for this study are summarized in Table C in supplementary material 1. The indicators that require a detailed description are listed below by dimension.

2.2.1. Agri-environmental indicators

Energy input and output, expressed as MJ ha^{-1}, were calculated by multiplying each element of the inputs and outputs by the coefficient of equivalent energy (Table E, Supplementary Material 1), as reported by Zahedi et al. (2015):

$$\text{Energy} = \text{Element}_i * \text{coefficient of equivalent energy} \quad (2)$$

Based on Eq. (2), energy use efficiency (ratio of energy output to the energy input) was calculated for 1 ha area per year.

The Pesticide Load Index (PLI) is defined as the amount of the applied product multiplied by its toxicity to non-target organisms (PL per 1 kg of active substance $ha^{-1}year^{-1}$). It consists of three sub-indicators: the PL for human health (PLHH) (effect on human health), the PL for ecotoxicology (PLECO) (effect on living organisms like mammals, fish, algae, earthworms, etc.) and PL for environmental fate (PLFATE) (effect on soils and underground waters). See more details in Kudsk et al. (2018).

$$PLI = PLHH + PLECO + PLFATE \quad (3)$$

2.2.2. Social indicators

To evaluate the crops' nutritional quality, we used the Nutrient Density Unit ($NDU_{P\text{-}F}$), considering protein and fiber content to recommended daily values and energy intake.

$$NDU_{P-F} = \frac{\left(\frac{Protein}{DV\ protein}\right) + \left(\frac{Fiber}{DV\ fiber}\right)}{2^*(En_i/En_d)} \quad (4)$$

Where Protein is the amount of protein in 100 g of the product (g), Fiber is the amount of fiber in 100 g of the product (g). DV protein is the recommended daily value intake of protein for humans (DV protein = 50g), DV fiber is the recommended daily value intake of fiber for humans (DV fiber = 25g), En_i is the kilocalorie energy content in 100 g of the product and En_d is the recommended daily intake of energy (2000 kcal) (Costa et al., 2021).

2.2.3. Economic indicators

The economic analysis was performed by estimating the associated economic impacts per hectare of inputs and outputs over the time horizon of the rotation. The Net Present Value (NPV), in euros per hectare, was computed with Eq. (5):

$$\text{NPV} = \sum_{k=0}^{n} \frac{CFk}{(1+r)^k} \quad (5)$$

where CF_k represents the annual cash flow obtained from the difference between cash inflows and cash outflows in euros; k is the cash flow time in years; n is the rotation duration in years; and r is the discount rate (Kadigi et al., 2020), which we consider here as 5 %. If the NPV is positive, the rotation generates profits over the period considered. Conversely, where NPV is negative, funds invested in the rotation are lost as the rotation's costs outweigh the profits. In our case, the arable crops are a year-long cultivation, therefore, the initial investment was considered null. Profits and cash flows were calculated with and without European Common Agricultural Policy (CAP) subsidies for the case of Spain and Greece. Since intercropping was not specifically subsidized in Greece, we based our calculations on the legume subsidies for $GR_{IC,}$ as vetch covered 70 % of the mixture. In Algeria, agricultural subsidies are included in input prices (e.g., fertilizers and seeds) (Aidat et al., 2023). Thus, we used the subsidized prices, and we did not account for separate subsidies like we did for Greece and Spain.

2.3. Data collection

We collected regional average data on crop rotation and crop management for the 11 cropping systems we considered for RS and DIV. As this is an ex-ante assessment for crops that are not widely practiced, the data were collected primarily from local experts. In fact, expert agronomists in the three countries collected all data mentioned above locally, ensuring it was robust and relevant for crop management and agronomic performance. Nevertheless, the sources from which this data was derived varied between the countries. Experts used field experiments, modelling, and surveys to design crop management data. This data corresponds to information regarding hours of operation (hha^{-1}), diesel consumption (Lh^{-1}), fertilizers and agrochemicals application ($kgha^{-1}$), active ingredients, and grain yields (tha^{-1}). For socio-economic data (labor classification and wages, energy and protein content, crop price, subsidies, and variable costs) regional experts used official websites (e.g., FAO, Eurostat, etc.) to fill data gaps. In particular, the coefficients for the calculations of protein production were compiled from literature (Table F, Supplementary Material 1). Nutrient Density Unit inputs (fiber and energy) were taken from Heuzé et al. (2017). All collected data from each case study were compared to national references and then verified with regional experts for plausibility.

2.4. Performance assessment

The impact indicators were calculated for each crop per hectare and year. To represent the full rotation, each indicator was averaged over the rotation period. With this study, we aim to compare the mean performance of diversified systems with legumes and rapeseed against continuous cereal cropping. We considered outperforming RS whenever the DIV impact indicator exceeded 5 % of the RS value (Notz et al., 2023).

To account for the variability of the input data, we calculated the coefficient of variation (CV) for grain yields based on FAO data from 2000 to 2022 (Tables D in supplementary material 1 and 2). Yield-dependent indicators (NUE, PUE, WUE, EUE, protein output, revenues, gross margins, and NPV) were calculated considering the CV from their base values, representing low and high yield years.

$$NUE_{low\ yielding\ year} = \frac{((baseline\ yield) - (CV^{*}baseline\ yield))^{*}\%\ N\ content)}{N_{fertilization}\ input} \quad (6)$$

Eq. (6) is an example of NUE calculation for low-yielding years using the CV. The baseline yield is the original yield data without variation, and % N content represents the nitrogen content of different crop grains. We considered the indicators that are not influenced by yield (PLI, TFI, working hours, NDU) as constant since they depend more on management practices and less on climate variability.

3. Results

3.1. Farming systems performance in the Ebro valley, Spain

The diversification of continuous cereal cropping systems improved nitrogen use efficiency (NUE) (Table 1). ES_{Leg} had the highest NUE value of 1.3 kg N crop (kg N fertilizer)$^{-1}$ ha^{-1}, higher than that of ES_{RS} and ES_R (+0.5 and + 0.4 kg N crop (kg N fertilizer)$^{-1}$ ha^{-1}, respectively). Within low-yielding years, represented by minimum variability ranges, the DIV systems still outperformed RS. Phosphorus use efficiency (PUE) showed higher values within RS (+24 kg P crop (kg P fertilizer)$^{-1}$ ha^{-1}compared to both ES_{Leg} and ES_R. This effect remained independent of yield variation. Water use efficiency (WUE) of ES_{RS} was the highest, with crops in DIV having on average 13 % lower WUE than those in RS. For energy use efficiency (EUE), ES_{Leg} and ES_R had higher values than ES_{RS}, with ES_{Leg} having the highest value of 8.8 and ES_R the value of 7.6. Even in low-yielding years, DIV systems had higher EUE than RS in average yield years. This was also the rotation with the largest share of renewable energy of 59 % compared to that of 45 % for ES_R and 30 % for ES_{RS}.

Treatment frequency index (TFI) was the highest for ES_R followed by ES_{RS} (3.75 and 3.25 respectively) (Fig. 2). The highest TFI per crop was observed for rapeseed with a value of 6.0, followed by pea with 3.4, and cereals had a TFI of 3. A couple of exceptions were: i) wheat after pea, where TFI decreased to 2, and ii) cereals in RS, where TFI increased to 3.5 due to resistance effects. In terms of relative risks to non-target organisms, PLI was lower for ES_R and ES_{RS} with a value of 2, but it was the highest for ES_{Leg} with a value of 4 (Fig. 2). The ES_{Leg} had both the highest ecotoxicity load (negative effect on living organisms) and fate load (effect on soils and underground waters). In terms of human health load, the three systems had comparable values.

Working hours (WH) for DIV decreased by 29 % compared to ES_{RS} (3.2 and 4.5 h ha^{-1} year^{-1}, respectively) since some management practices (e.g., fertilization, phytosanitary treatment, etc.) were reduced (Table 2). Workers' training on diversification was around 10 h annually. The most prolific system for protein production was ES_R, producing 935 kg ha^{-1} year^{-1}, followed by ES_{Leg} and ES_{RS}. However, low-yielding years favored ES_R as the most protein-producing system (741 kg ha^{-1}year^{-1}). Both DIV had nutrient density values ranging between 1 and 1.4, while ES_{RS} had an NDU of 0.7. In both diversified and continuous cropping systems, wheat and barley tended to have the lowest NDU values. Only pea and rapeseed showed NDU values greater than one.

The RS had the highest costs with 445 EUR ha^{-1} year^{-1} (Table 3). Mineral N fertilization accounted for a third of these costs. The revenues (without subsidies) for ES_{Leg} and ES_R decreased by 6 % and 8 % (69 and 100 EUR ha^{-1} year^{-1}), respectively, when compared to ES_{RS}. When subsidies were considered, ES_{RS} remained more profitable than ES_{Leg} and ES_R, even though they increased by 27 % and 23 % (252 and 233 EUR ha^{-1} year^{-1}), respectively. In low-yielding years, ES_{Leg} had the highest gross margin (1122 EUR ha^{-1} year^{-1}).

The NPV (subsidies excluded) of the three systems was positive, with comparable values ranging from 151 EUR ha^{-1} year^{-1} for ES_{RS} to 147 EUR ha^{-1} year^{-1} for ES_{Leg}. The NPV is comparable between the three systems regardless of yield variation and subsidies.

3.2. Farming systems performance in the Thessaloniki region, Greece

For all four systems, nitrogen use efficiency was greater than 1 (Table 1). While GR_{Leg} and GR_{IC} both had similar NUE values (1.3 kg N crop (kg N fertilizer)$^{-1}$ ha^{-1}), they were still higher than GR_{RS} and GR_R (+0.2 kg (N crop kg N fertilizer)$^{-1}$ ha^{-1})). The NUE for GR_{Leg} and GR_{IC} in low-yielding years was as high as that of GR_{RS} in high-yielding years (1.2 kg (N crop kg N fertilizer)$^{-1}$ ha^{-1}). For phosphorus use efficiency, GR_{Leg} had the lowest value out of all systems (1.4 kg (P crop kg P fertilizer)$^{-1}$ ha^{-1}), 19 % lower than GR_R and GR_{IC}, and 9 % lower than GR_{RS}. The average WUE for GR_{RS} and GR_R was 8 kg m^{-3} ha^{-1}, whereas it was lower for GR_{Leg} and GR_{IC} (−1.1 and −1.8 kg m^{-3} ha^{-1}, respectively). All systems were efficient in terms of energy use (EUE>1), with GR_{Leg} and GR_R having higher values than RS (+10 % and +14 % respectively). All systems received a majority of their energy input from non-renewable sources: 71 %, 77 % and 86 % for GR_{Leg}, GR_{RS} and GR_R, respectively.

Regarding the use of pesticides (Fig. 2), GR_{RS} had the highest TFI value of 2, followed by GR_R, GR_{Leg} and GR_{IC}, both GR_{Leg} and GR_{IC} having all a value of ~1. Cereals had the highest TFI (2), while rapeseed had the lowest value (0.88). A similar trend could be observed for PLI, with GR_{RS} having the highest value (1.67). Across all four systems, the pesticide load for human health (PLHH) was the major contributor to the PLI

Table 1
Resource use efficiencies for the different case studies.

Country	Cropping System	Nitrogen Use Efficiency (NUE)	Phosphorus Use Efficiency (PUE)	Water Use Efficiency (WUE)	Energy use efficiency (EUE)	Energy input	
						Renewable	Non-renewable
		kg N crop kg N fertilizer^{-1} ha^{-1}	kg P crop kg P fertilizer^{-1} ha^{-1}	kg m^{-3} ha^{-1}	Ratio	(MJ ha^{-1} year^{-1})	(MJ ha^{-1} year^{-1})
Spain	**ES_{RS}**	0.8 (0.6–0.9)	33.0 (26.2–39.8)	12.8 (10.2–15.2)	4.9 (3.9–6.0)	6364	14,718
	ES_{Leg}	1.3 (1.0–1.6)	18.7 (14.7–22.7)	11.5 (9.1–13.9)	8.8 (7.0–10.7)	7011	4484
	ES_R	0.9 (0.7–1.0)	19.0 (15.0–23.0)	10.8 (8.6–13.0)	7.6 (6.0–9.1)	5842	7003
Greece	**GR_{RS}**	1.1 (1.0–1.2)	1.5 (1.4–1.6)	8.1 (7.4–8.8)	5.7 (5.2–6.2)	2072	6936
	GR_R	1.1 (1.0–1.2)	1.7 (1.5–1.8)	8.0 (7.2–8.8)	6.3 (5.6–6.9)	1431	8557
	GR_{Leg}	1.3 (1.2–1.4)	1.4 (1.2–1.6)	7.0 (6.1–7.9)	6.5 (5.2–7.8)	2197	5351
	GR_{IC}	1.3 (1.2–1.4)	1.7 (1.5–1.8)	6.3 (5.7–6.8)	5.7 (5.2–6.1)	2341	5220
Algeria	**DZ_{RS}**	0.4 (0.3–0.5)	1.5 (1.2–1.9)	8.1 (6.3–10.0)	2.1 (1.6–2.5)	1912	14,416
	DZ_{Leg1}	0.7 (0.5–0.8)	1.3 (1.0–1.6)	7.2 (5.6–8.9)	3.1 (2.4–3.9)	1933	9710
	DZ_{Leg2}	1.0 (0.8–1.3)	1.3 (1.0–1.6)	7.7 (5.7–9.6)	4.9 (3.0–6.2)	1297	8615
	DZ_{Leg3}	0.9 (0.6–11)	1.4 (1.1–1.7)	7.6 (5.8–9.4)	4.1 (2.6–5.1)	1321	10,162

Values in brackets are the (min-max) representing the variability, calculated on the basis of CV for grain yield for the different systems; ES_{RS}: barley-soft wheat, ES_{Leg}: barley-soft wheat-pea- soft wheat, ES_R: barley-soft wheat-rapeseed- soft wheat, GR_{RS}: barley-soft wheat, GR_R: barley-soft wheat-rapeseed, GR_{Leg}: barley-soft wheat-pea, GR_{IC}: barley-soft wheat-vetch and barley intercropping, DZ_{RS}: barley-durum wheat, DZ_{Leg1}: chickpea-durum wheat, DZ_{Leg2}: chickpea-durum wheat-pea; DZ_{Leg3}: barley-durum wheat-chickpea.

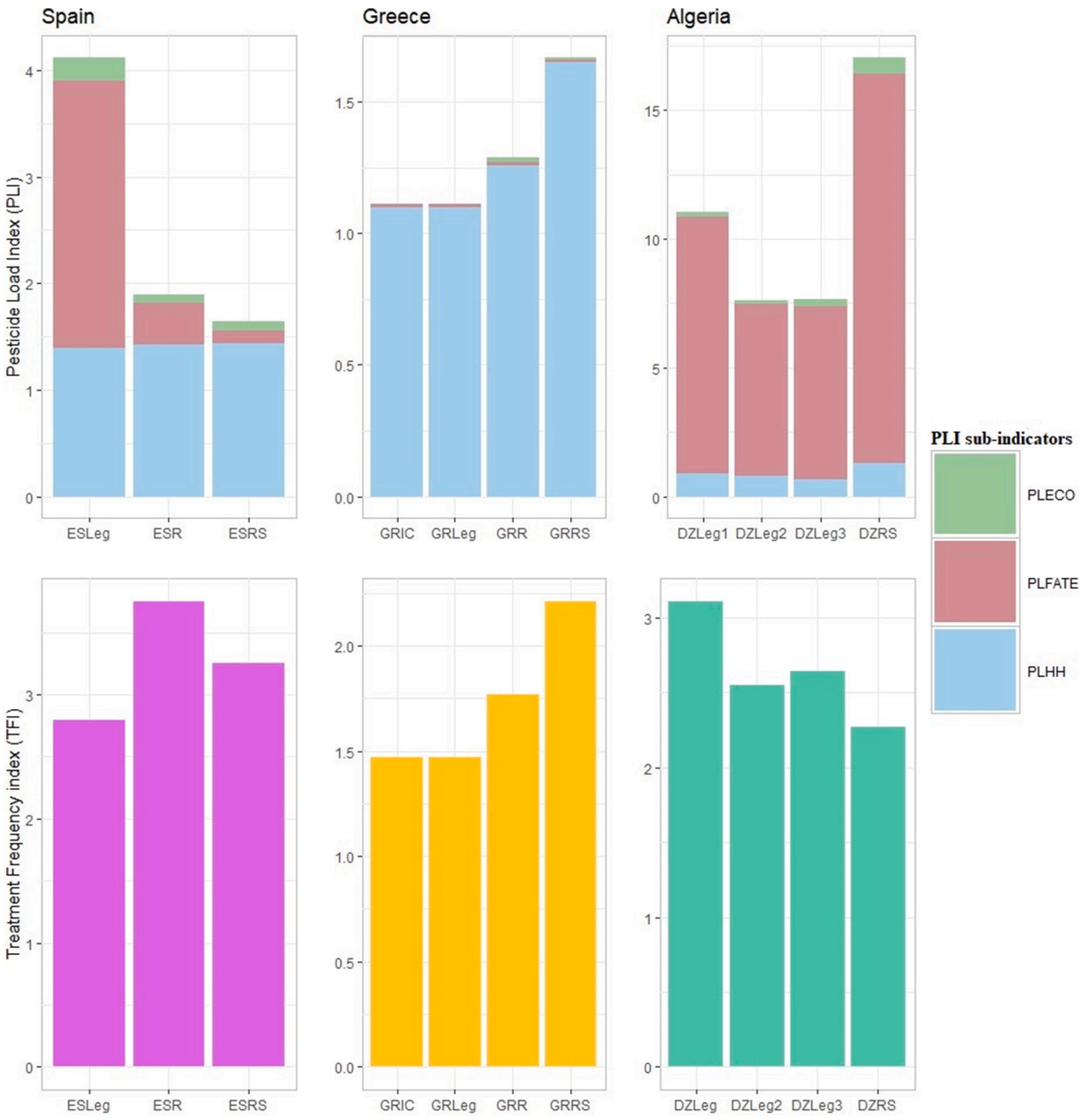

Fig. 2. Pesticide load (PL) with its three sub-indicators: PL for ecotoxicology (PLECO), PL for environmental fate (PLFATE), and PL for human health (PLHH), and treatment frequency index for the different systems; ES_{RS}: barley-soft wheat, ES_{Leg}: barley-soft wheat-pea- soft wheat, ES: barley-soft wheat-rapeseed- soft wheat, GR_{RS}: barley-soft wheat, GR_R: barley-soft wheat-rapeseed, GR_{Leg}: barley-soft wheat-pea, GR_{IC}: barley-soft wheat-vetch and barley intercropping, DZ_{RS}: barley-durum wheat, DZ_{Leg1}: chickpea-durum wheat, DZ_{Leg2}: chickpea-durum wheat-pea; DZ_{Leg3}: barley-durum wheat-chickpea.

values.

The working hours for all systems were comparable (Table 2). However, the DIV required 3 % (0.3 h $ha^{-1}year^{-1}$) less work mainly due to the reduction or avoidance of some management practices for rapeseed and pea (e.g., crop protection, etc.). The worker's type remained the same in DIV, with 40 % being family members, permanent and local, and the other 60 % being workers employed temporarily during peak times. Female workers were employed, leading to a gender ratio of 0.6. As women were paid 30 % less than men, the Wage Level between Genders was 0.75. On average, farmers were around 50 years old, attended school for about 10 years, and attended around 20 hours of diversification training each year. Agricultural activity accounted for up to 85 % of the farmer's total incomes, making it their main income source.

Both GR_R and GR_{RS} were the highest systems producing protein (590 and 401 EUE ha^{-1} $year^{-1}$ respectively), followed by GR_{Leg} and GR_{IC}. The GR_{IC} had the highest NDU value (1.7) with an increase of 0.7 when compared to GR_{RS}. GR_R and GR_{Leg} both also increased by 40 % and 20 %, respectively, when compared to RS. At the crop level, all crops had values greater than one, apart from soft wheat in RS.

For the economic evaluation (Table 3), GR_R and GR_{Leg} were the systems with the highest costs (fertilization accounting for 30 %) and the lowest revenues (subsidies excluded), which generated negative gross margins (−28 and −45 EUR ha^{-1} $year^{-1}$, respectively). Only after subsidies were considered did the gross margins of GR_{Leg} and GR_R improve (+511 and 420 EUR ha^{-1} $year^{-1}$, respectively). Compared to GR_{Leg} and GR_R, GR_{RS} and GR_{IC} had the lowest costs and highest revenues (subsidies excluded). However, GR_{IC} generated four times more gross margins when compared to GR_{RS} (subsidies excluded).

Only GR_{RS} and GR_{IC} had a positive NPV (subsidies excluded).

Table 2
Social dimension indicators for the different cropping systems.

Country	Cropping System	Working Hours (h $ha^{-1}year^{-1}$)	Protein production (kg $ha^{-1}year^{-1}$)	Nutrient Density Unit
Spain	**ES_{RS}**	4.5	861.1 (683.7–1038.5)	1.0
	ES_{Leg}	3.2	926.3 (730–1122.2)	1.1
	ES_{R}	3.2	934.9 (741.3–1128.5)	1.4
Greece	**GR_{RS}**	10.0	401.5 (366.0–437.0)	1.0
	GR_{R}	9.7	590.5 (525.5–655.4)	1.5
	GR_{Leg}	9.7	387.1 (324.4–449.9)	1.3
	GR_{IC}	9.7	329.2 (300.8–357.6)	1.7
Algeria	**DZ_{RS}**	11.3	294.8 (231.1–358.4)	1.1
	DZ_{Leg1}	5.6	352.1 (272.9–431.3)	1.7
	DZ_{Leg2}	5.0	398.0 (298.0–497.9)	1.6
	DZ_{Leg3}	4.6	353.7 (266.6–440.7)	1.4

Values in brackets are the (min-max) representing the variability, calculated on the basis of CV for grain yield for the different systems; ES_{RS}: barley-soft wheat, ES_{Leg}: barley-soft wheat-pea- soft wheat, ES_{R}: barley-soft wheat-rapeseed- soft wheat, GR_{RS}: barley-soft wheat, GR_{R}: barley-soft wheat-rapeseed, GR_{Leg}: barley-soft wheat-pea, GR_{IC}: barley-soft wheat-vetch and barley intercropping, DZ_{RS}: barley-durum wheat, DZ_{Leg1}: chickpea-durum wheat, DZ_{Leg2}: chickpea-durum wheat-pea; DZ_{Leg3}: barley-durum wheat-chickpea.

However, the NPV of GR_{RS} was still four times higher than that of the intercropping.

3.3. Farming systems performance in the Setif region, Algeria

The NUE values for all three DIV were higher than those of RS (Table 1). DZ_{Leg2} was the only system with NUE (kg N crop (kg N fertilizer)$^{-1}$ ha^{-1}) value of 1, followed by DZ_{Leg3} and DZ_{Leg1} with values of 0.9 and 0.7, respectively. PUE was the highest for DZ_{RS} (+16 % compared to DZ_{Leg1} and DZ_{Leg2}, and +10 % compared to DZ_{Leg3}). WUE was the highest for RS with 8.1 EUR ha^{-1} $year^{-1}$(+11 % compared to DZ_{Leg1}; +6 % compared to DZ_{Leg2}, and +7 % compared to DZ_{Leg3}). For EUE, all DIV systems had higher values compared to DZ_{RS}. In low-yielding years, DIV systems would still have as high EUE values as those DZ_{RS} in high-yielding years.

All cropping systems had the major share of energy inputs coming from non-renewable resources (+80 %). The RS had the lowest TFI value (2.27), followed by DZ_{Leg2} and DZ_{Leg3}, whereas DZ_{Leg1} had the highest value (3.11). Wheat had the highest TFI amongst all crops with a value of 3. In contrast to TFI, the highest PLI was found in RS (17), followed by DZ_{Leg1}, DZ_{Leg3} and DZ_{Leg2}, respectively. Across all systems, PLFATE was the highest contributor to the PL (Fig. 2).

Working hours decreased on average by 50 % in DIV (from 11 to ~ 5.5 h $ha^{-1}year^{-1}$) (Table 2). Over 86 % of all workers were temporary, hired during peak work periods. The cereal-based system depended exclusively on male workers from the region. Farmers in the region were on average 52 years old and attended school for an average of 14.5 years. Despite the lack of training on diversification, some farmers allowed research institutions' experiments on their farms. However, it remained unclear what impact these experiments had on improving farmers' knowledge. Farming accounted for 70 % of farmers' income. The DZ_{Leg2} ranked as the highest protein producer, followed by DZ_{Leg3}, DZ_{Leg1}, and DZ_{RS}. NDU showed the higher efficiency of the diversified systems (DZ_{DIV}), on average, to satisfy the daily fiber and protein demand for human nutrition, with a value of 1.4 compared to RS with an NDU of 1.

RS had the highest production costs (687 EUR ha^{-1} $year^{-1}$), followed by DZ_{Leg2}, DZ_{Leg1}, and DZ_{Leg3} (Table 3). Fertilization and pest treatment operations accounted for 54 % of RS's costs. Besides synthetic inputs, seeds constituted the biggest part of the production cost in DIV. DZ_{Leg2} was the highest revenue-generating system (+874 EUR ha^{-1} $year^{-1}$ compared to RS). The gross margins were the highest for DZ_{Leg2}, followed by DZ_{Leg3} and DZ_{Leg1}, while it was negative for DZ_{RS} (−21 EUR ha^{-1} $year^{-1}$).

4. Discussion

4.1. Agri-environmental performance

Legumes and rapeseed improved resource use efficiencies (NUE and EUE) when incorporated into cereal-based rotations (Table 1). Compared to RS, DIV required less N fertilization, mainly due to legumes' nitrogen fixation capacity. Hence, DIV had higher NUE values (increased yields and reduced fertilization needs). In accordance with other studies, legumes added to cereals either within rotations or as intercropping have been shown to beneficially improve NUE (Kherif

Table 3
Economic indices (EUR ha^{-1} $year^{-1}$) for the different case studies.

Country	Cropping System	Costs	Revenues (subsidies excluded)	Gross margin (Subsidies excluded)	Subsidies	Gross margin (Subsidies included)	Net Present Value (5 %; subsidies excluded)	Net Present Value (5 %; subsidies included)
Spain	**ES_{RS}**	445	1249 (992–1507)	805 (547–1062)	230	1034 (777–1292)	151 (100–202)	197 (146–248)
	ES_{Leg}	304	1180 (935–1425)	876 (58–1122)	252	1128 (883–1374)	147 (102–192)	193 (148–238)
	ES_{R}	356	1149 (914–1383)	793 (121–1027)	233	1026 (791–1260)	148 (102–194)	194 (149–240)
Greece	**GR_{RS}**	696	745 (679–811)	49 (-17–115)	420	469 (403–535)	8 (4–14)	28.0 (23.4–32.2)
	GR_{R}	753	725 (654–796)	−28 (-99–43)	420	392 (321–463)	−3.32 (-8–1.25)	25.0 (20.0–29.0)
	GR_{Leg}	712	667 (573–762)	−45 (-139–49)	511	466 (372–560)	−4 (−9.0–1.4)	27.0 (21.4–32.0)
	GR_{IC}	636	822 (736–874)	186 (101–239)	511	697 (612–750)	2.17 (−2.34–11.8)	32.1 (27.6–41.7)
Algeria	**DZ_{RS}**	687	666 (522–810)	−21 (−164)-123)	N/A	N/A	31	N/A
	DZ_{Leg1}	582	1059 (810–1309)	477 (228–726)	N/A	N/A	51	N/A
	DZ_{Leg2}	625	1540 (1133–1948)	916 (509–1323)	N/A	N/A	51	N/A
	DZ_{Leg3}	580	1227 (905–1548)	647 (325–968)	N/A	N/A	38	N/A

Values in brackets are the (min-max) representing the variability, calculated on the basis of CV for grain yield for the different systems; ES_{RS}: barley-soft wheat, ES_{Leg}: barley-soft wheat-pea- soft wheat, ES_{R}: barley-soft wheat-rapeseed- soft wheat, GR_{RS}: barley-soft wheat, GR_{R}: barley-soft wheat-rapeseed, GR_{Leg}: barley-soft wheat-pea, GR_{IC}: barley-soft wheat-vetch and barley intercropping, DZ_{RS}: barley-durum wheat, DZ_{Leg1}: chickpea-durum wheat, DZ_{Leg2}: chickpea-durum wheat-pea; DZ_{Leg3}: barley-durum wheat-chickpea.

et al., 2023; Simon-Miquel et al., 2024).

The Ebro valley in Spain, where intensive swine and poultry production is often linked to cereal systems (Hossard et al., 2024) is characterized by abundant N availability from livestock manure. This requires appropriate management to limit environmental risks of N surpluses (e.g., groundwater contamination). In this specific case, we showed that reducing N mineral fertilization and substituting it with swine slurry (as an appropriate management way) leads to NUE improvements while increasing yields in DIV. Additionally, soil management practices were reduced in DIV, tending towards soil-conserving systems (Spain). Thus, fuel consumption decreased as did energy inputs, while the increase in yields led to a rise in energy output, explaining the higher EUE in DIV. The mean EUE for DIV (7 for Spain and Greece and 5 for Algeria) falls within the range of other EUE for cereal-legume systems with a value of 10 (Meena et al., 2021; Nassi O Di Nasso et al., 2011).

RS outperformed DIV in PUE and WUE (Table 1). In other studies, however, diversification was found to improve resource use efficiency (PUE) and Water quality (An et al., 2023; Rodrigues et al., 2024). For Spain, PUE values can be explained by the increased use of swine slurry (two times the RS amount, thus twice as much P), while yields did not double despite increasing with diversification. Unlike synthetic fertilizers, swine slurry contains different ratios of nutrients than those required by crops. It is challenging to use swine slurry to introduce N as the main nutrient without accumulating P or to introduce P as the main nutrient without limiting N (P is in a higher proportion than N in swine slurry) (Zhang et al., 2021). The combination of low P input and high yields resulted in higher PUE values in Spain than in Greece and Algeria. In these last two case studies, the combination of low yields and reduced P fertilization for legumes and rapeseed resulted in a lower average PUE in DIV than in RS. Low WUE values for legumes and rapeseed (due to lower yields than cereals) can explain lower WUE in DIV of all countries. The pesticide use indicators (TFI and PLI) are lower for DIV than for RS in Greece, but not in Spain and Algeria. However, the PLI for Algerian DIV is still lower than that for RS, the same as in Greece(Fig. 2). Pest infestations and disease incidence may decrease throughout the season due to the introduction of different crop families, thus lowering the need for pesticides. This is in line with Guinet et al. (2023), where cereal legume mixtures were found to use fewer pesticides. While Spanish rapeseed remains the most heavily treated crop in this study, Greek rapeseed receives no pesticides other than one herbicide. Greek legumes have not been treated with any pesticides as no pest damage was detected, hence, grain yields remained stable (Hossard et al., 2024). In Algeria, TFI of DZ_{RS} was lower than that of DZ_{Leg}. This may be explained by data source quality (farmer surveys). Farmers reported higher pesticide quantities in DIV cereals than in RS, likely due to not considering the effect of legume integration. In the same region and with similar crops, Zemmouri et al. (2022) reported lower TFI values for barley-pea intercrops than for continuous barley or pea cropping systems.

4.2. Social performance

In all countries, DIV required fewer working hours than RS (Table 2) due to the reduction in management practices. In Spain, the reduction was around 30 %, while in Algeria around 50 %. Due to other production limiting factors, the difference in WH between Greek DIV and Greek RS was marginal as GR_{RS} was already a low-input system.

Furthermore, DIV had a higher protein production than RS (except for Greek legume and intercropping systems). The combination of protein-rich crops (e.g., pea, rapeseed) and higher cereal yields in DIV led to more protein per system. Simon-Miquel et al. (2023) reported similar results on increasing protein production through legume integration in continuous cropping systems under Mediterranean climate. Currently, wheat provides a fifth of human daily protein and energy intake (Royo et al., 2017). In this study, we found that cereals grown in DIV and intercropping produced higher protein levels than those grown in continuous cropping systems (Table 2). Our study emphasizes the importance of rotating cereals with other species to improve their quality as staple foods. All the systems had an NDU value equal to or greater than 1, indicating the capacity to satisfy human daily nutrient intake, and similar to the reported results by Costa et al. (2021).

In Greece and Algeria, most workers are temporarily hired during peak times (e.g., during summer harvest). It is increasingly difficult to find workers (Hossard et al., 2024) as farms with similar crop vocations compete for already low available agricultural workers. This can be attributed to the aging of farming populations and the lack of interest in this economic sector among the younger generation. Most of whom migrate from the countryside to cities because of negative societal perceptions of living and working conditions (Quintas-Soriano et al., 2022). Diversification is often eased by education and training opportunities (Hossard et al., 2024), which are present in all countries despite the differences in time devoted to each training type. Nevertheless, the Mediterranean region can still benefit from the traditional knowledge of its rural population (Ruiz et al., 2020; Zagaria et al., 2023). A knowledge that has been in decline in recent decades along with the value of ancestral resilient crops due to the transition to an industrial diet, based on imported processed products. This has caused a shift away from the traditional Mediterranean diet, causing or accentuating major public health problems (e.g. diabetes, cancer, etc.) (Bach-Faig et al., 2011).

4.3. Economic performance

Both in Spain and Algeria, DIV had lower operational costs than RS (Table 3), again due to the decrease in management practices intensity. The synthetic inputs accounted for one-third of the Spanish and half of the Algerian costs in RS, mainly fertilization products. The substitution of mineral fertilization with organic amendments in Spain reduced cereal costs as advocated by Musto et al. (2023) by almost a third.

In legume DIV systems, peas had lower yield compared to cereals, which was compensated for by their higher selling price, leading to higher gross margins. Rebolledo-Leiva et al. (2022) reported in similar rotations with legumes generally increasing gross margins due to the increase in yields, and the reduction in both agrochemical consumption and mineral fertilization. While all Algerian DIV were more profitable than RS, DZ_{Leg2}, with two legumes, was the most profitable, mainly due to the high chickpea selling prices (Hossard et al., 2024). Similarly, Lago-Olveira et al. (2023) found that incorporating chickpea led to a considerable increase in gross margins due to the lower cost of cultivation and its higher market price compared to wheat.

For Greece, two DIV had higher costs than RS (Table 3). Chemical inputs for GR_R and high seed prices for peas in GR_{Leg} were the main reasons for this. In contrast to what was discussed above about legumes resulting in higher gross margins, GR_R and GR_{Leg} had very low and negative gross margins when subsidies were excluded. This is common in Greece, where it has been reported previously that cereals in the Thessaloniki region have negative gross margins per hectare (Tziolas and Bournaris, 2019). This is the result of low yields due to other production factors like climate conditions. It is only when subsidies are considered that these systems prove to be economically profitable. In light of these limitations, Greek farmers favor low-input cropping systems (e.g., low pesticide rate) since additional inputs to systems already known for low returns aren't economically worthwhile (Preissel et al., 2015). Incorporating legumes and rapeseeds into cereal-based rotations could decrease costs on average, but it still did not generate higher returns without subsidies being considered in the European systems, similar to other studies (Notz et al., 2023; Tziolas and Bournaris, 2019).

4.4. Implications for management and policy

This study assessed diversified systems that were designed in a participatory approach with local stakeholders in each of the studied

countries (See more details in Hossard et al. (2024)). The participation of different stakeholders through the selection of impact indicators assured the relevance and reliability of the performance assessment to the particular Mediterranean context.

In this study, we provided knowledge to local stakeholders regarding whether the systems they designed would be able to solve the mentioned challenges in Hossard et al. (2024). For Algerian stakeholders, they sought for systems that would reduce costs and ensure more efficient water use. We have shown that the designed systems had lower costs compared to the RS. On the other hand, we found that the RS is efficient regarding WUE. In Greece, DIV were not designed specifically to respond to observed struggles, but rather to reduce pollution threats. Apart from pesticide use indicators, which prove that Greek DIV required less pesticides, this study cannot fully answer the question of pollution. More comprehensive studies are needed to evaluate other impact categories (e.g., gas emissions, carbon footprint, etc.). Spanish systems were designed to better valorize the organic swine slurry available, while decreasing synthetic N fertilization to comply with regulations. We have shown that such aspirations could be achieved by diversifying with grain legumes and rapeseeds. These rotations as part of diversification can only mitigate some of the challenges the Mediterranean region faces. Nonetheless, diversification provides benefits compared to what is currently practiced. The rotations with legumes performed slightly better than those with rapeseed (Spain and Greece), but there was no difference in performance between rotations with one or two legumes (case of Algeria). Intercropping outperformed all other systems in Greece. This is a traditional farming practice that is regaining recognition, especially in low-input crops such as those grown in Greece (Pankou et al., 2021). Stomph et al. (2020) emphasized the importance of using meaningful and acceptable metrics to compare intercrop performance with sole crops in relation to agricultural sustainability aspects. In this study, we showed that intercropping is an agri-environmentally, socially and economically attractive option available to Greek farmers. Intercropping outperformed continuous cereal cropping, legumes, and rapeseed systems on all economic indicators. In terms of the agri-environmental and social dimensions, only water use efficiency and protein production were lower than the other systems. Improved selection of varieties and more suited species combinations could be used to increase these indicators (water and protein).

With the Mediterranean Basin, a climate change hotspot, experiencing increased warming and drought at rates faster than the global average, some of the selected crops by stakeholders may not be suitable for rotations in the future. According to Zagaria et al. (2023), rainfed wheat is one of the crops that could be substituted with permanent crops (e.g., pistachios or dates) in some regions (e.g., Greece, Morocco, etc.). When irrigation water is available, more opportunities for diversification are provided. The limited water resources in the basin, however, make irrigation one of the limiting factors for diversification (Hossard et al., 2024).

Finally, a collaborative effort between policymakers, farmers, and scientists is still required to co-design sensible rotations. Current policies, such as the 2023–2027 CAP crop rotation requirements, need local fine-tuning given the large variability of systems and conditions in Europe. Moreover, less than 10 ha farms (case of Greece) are exempted from such requirements. Furthermore, the new eco-schemes within the CAP could have been more effective if they covered the entire agricultural area by targeting crop diversification and non-productive agro-ecological infrastructures to promote diversification (Guyomard et al., 2023). It is difficult, however, to reorient subsidies toward more environmental concerns when farm income is strongly reliant on subsidies (Tziolas and Bournaris, 2019). This underscores the need for long-term market-based incentives, risk-mitigation mechanisms (e.g., specialized insurance schemes or guaranteed price mechanisms for early diversification adopters), and premium price schemes for diversified crops. Enhancing market access through value chain integration (Weituschat et al., 2023), Cooperative models may also help increase the attractiveness of diversification to farmers. Although society is increasingly concerned about environmental issues, there is a lack of awareness about crop diversification products, and where to buy them (Zabala et al., 2023). Therefore, establishing certification or eco-labeling initiatives for produced crops from diversified systems could increase consumer awareness of such products.

Other policies should also target agri-food trade, food waste, and diets (Guyomard et al., 2023). For instance, reviving the Mediterranean diet, listed in 2010 by UNESCO as part of humanity's intangible cultural heritage (Bach-Faig et al., 2011), could promote diversification by cultivating crops suited to the Mediterranean climate and territory.

4.5. Potential methodological limits

Performance assessment studies are highly dependent on data availability, the methodology used and the assumptions underlying the calculations. Despite our efforts to select indicators with local stakeholders to ensure better transfer of assessment outcomes, we acknowledge that data availability was a challenge in this study. In fact, data shortages prevented the computation of certain social indicators for Spain (human capital impact category).

The imbalance between the sustainability dimensions when it comes to the number of indicators (fewer indicators in the social dimension) could influence the results of the assessment by changing perceptions about what is crucial to sustainable development (Rodriguez et al., 2021). Moreover, some impact indicators might overlook some important aspects of a system's performance. As an example, NUE was reported to fail in detecting sites with inherently low N recovery efficiency and high loss risk, highlighting the weakness of ignoring soil N supply (Tamagno et al., 2024). Furthermore, the need to exclude potentially relevant indicators limits our study's ability to make generalized statements about the systems' performance for individual sustainability dimensions or sustainability as a whole. Without thresholds, it may be difficult to determine whether a sustainability target (i.e., ONU's SDGs) has been achieved or not. Taking into account the farming system and context, stakeholders should join the discussion on thresholds for developing indicators (Chopin et al., 2021) that can be used to provide information on sustainability. Considering data variability using yield variation over the last 20 years was important, but it did not account for future scenarios with current temperatures rising faster than expected.

5. Conclusion

In the Mediterranean region, cereals have historically been a strategic, traditional crop. Currently, they are generally grown as continuous crops in cereal systems. We have shown that context-dependent diversification practices could be a way to enhance some aspects of their performance. By assessing the agri-environmental, social, and economic performance of diversified systems (including legumes, rapeseed, and intercropping) in Spain, Greece and Algeria, we conclude that these systems can outperform continuous cereal cropping mainly in nitrogen and energy use efficiencies and nutrient quality. Economically, continuous cropping often generates higher revenues than diversified options when subsidies are excluded, which requires policy intervention to encourage diversification practices more effectively. This study presents a complementary view of practical options available to farmers across the Mediterranean in solving current issues. The assessment indicators and systems were designed in collaboration with stakeholders in a participatory approach, which was a particular strength that could be applied more frequently in impact assessment studies in agriculture.

CRediT authorship contribution statement

Ferdaous Rezgui: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Fatima Lambarraa-Lehnhardt:** Writing – review & editing, Validation,

Supervision, Methodology, Conceptualization. **Louise Blanc:** Writing – review & editing, Validation, Investigation. **Daniel Plaza-Bonilla:** Writing – review & editing, Validation, Investigation. **Jorge Lampurlanés:** Writing – review & editing, Validation, Investigation. **Christos Dordas:** Writing – review & editing, Validation, Investigation. **Paschalis Papakaloudis:** Writing – review & editing, Validation, Investigation. **Andreas Michalitsis:** Writing – review & editing, Validation, Investigation. **Mourad Latati:** Writing – review & editing, Validation, Investigation. **Amina Raggas:** Writing – review & editing, Validation, Investigation. **Sonoko D. Bellingrath-Kimura:** Writing – review & editing, Supervision. **Carsten Paul:** Writing – review & editing, Validation, Supervision. **Moritz Reckling:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.127040.

Data availability

Data will be made available on request.

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