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Stakeholders' critical perception of diversification strategies in cereal-based rotations

Ferdaous Rezgui [a,b,*], Louise Blanc [c,d], Daniel Plaza-Bonilla [c,d], Jorge Lampurlanés [c,d], Christos Dordas [e], Paschalis Papakaloudis [e], Andreas Michalitsis [e], Laure Hossard [f], Fatima Lambarraa-Lehnhardt [a], Sonoko D. Bellingrath-Kimura [a,b], Carsten Paul [a], Moritz Reckling [a,g]

[a] Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, Müncheberg 15374, Germany
[b] Thaer-Institute of Agricultural and Horticultural Sciences, Humboldt-University of Berlin, Berlin 14195, Germany
[c] Department of Agricultural and Forest Sciences and Engineering, Universitat de Lleida, Av. Rovira Roure 191, Lleida 25198, Spain
[d] Agrotecnio-CERCA Center, Av. Rovira Roure 191, Lleida 25198, Spain
[e] Laboratory of Agronomy, School of Agriculture, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece
[f] INNOVATION, Univ. Montpellier, CIRAD, INRAE, Institut Agro, Montpellier 34060, France
[g] Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), Sweden

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ABSTRACT

Agriculture has long been at the core of Mediterranean culture, resulting in multifunctional landscapes and diverse ecosystem services. In Mediterranean Europe, policy favored specialized agriculture, and reversing this trend has proven difficult. Diversification of crop rotations holds ecological benefits, yet adoption remains low. The objective of this study was to accompany Spanish and Greek stakeholders in a structured learning process beginning with the co-design of available diversification options. It continued with an ex-ante assessment of agri-environmental, social, and economic performance of these options, followed by a co-evaluation step where stakeholders rated both the assessed performances and the indicators used. These ratings were analyzed using an importance-performance matrix. Finally, the adoption likelihood of diversification was predicted using the Adoption and Diffusion Outcome Prediction (ADOPT) tool. The ex-ante assessment revealed that legumes, rapeseed, and intercropping systems generally outperformed continuous cereal cropping in the agri-environmental and social dimensions but not economically, with a profit reduction of up to 12 %. From the stakeholders' ratings, we learned that they placed the greatest importance on the economic indicators. In contrast, the agri-environmental dimension was given little importance even when energy use indicators increased by 5–42 %. Likewise, diversified systems offered notable social benefits, such as reduced workload by up to 29 %, but social aspects were ranked as less important. This divergent performance of the diversified options was translated into low adoption rates. Legume systems reached a 23–28 % adoption rate in 8–10 years, while intercropping reached 14 % in 17 years, and rapeseed systems reached only 4–5 % in 9–11 years. Economic performance emerged as the main barrier to the adoption of diversification. This study evaluated the impacts of different diversification options available to local farmers from both scientific and a local stakeholder perspective. This process can be adapted to other regions to create shared knowledge, thus enabling a wide range of actors to better understand diversification impacts. This knowledge gain affects the stakeholder's capacity to adopt diversification options and, beforehand, their willingness to do so.

1. Introduction

Agriculture is at the heart of Mediterranean cultural identity, leading to the creation of traditional multifunctional landscapes (Pinto-Correia and Vos, 2004). Nevertheless, traditional farming systems have gradually been abandoned in favor of simpler and more specialized systems aimed at increasing yields and gross margins, often at the expense of natural resources (Debolini et al., 2018; Esgalhado et al., 2021).

* Corresponding author at: Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, Müncheberg 15374, Germany.
E-mail address: Ferdaous.Rezgui@ZALF.de (F. Rezgui).

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Mediterranean farming systems in Europe are no exception to this trend, being today highly specialized and mostly oriented towards cereal-based sole-cropped systems, in short rotations (Galioto and Nino, 2023; Malek et al., 2018).

Specialized cereal cropping systems were supported by policy (e.g., common agricultural policy (CAP), the 1992 Blair House agreement, etc.), making them a popular choice amongst farmers in Europe, and they have proven challenging to reverse (Magrini et al., 2016; Zander et al., 2016). Agricultural specialization can pose environmental threats and is often coupled with intensification, undermining agricultural sustainability (Galioto and Nino, 2023). This is exacerbated by climate change, which is occurring at a faster rate in the Mediterranean region when compared to the global average (Di Bene et al., 2022; Drobinski et al., 2024).

Transitioning from current specialized cropping systems to biodiversity-based ones that deliver more ecosystem services, and focusing on local and short value chains, can help European agriculture balance production with environmental protection (Hufnagel et al., 2020; Messéan et al., 2021). The reintroduction of minor crops (e.g., legume crops) to diversify cropping systems is one way to transition to sustainable agriculture (Reckling et al., 2023; Wezel et al., 2020) that requires coordinated visions, objectives, strategies, and actions from diverse stakeholders (Pelzer et al., 2020; Zuza et al., 2024). Transitioning to diversification could entail diversifying either in time (such as rotation) or in space (such as intercropping) (Messéan et al., 2021; Wezel et al., 2020).

It has been clearly demonstrated over the last decades that farming systems with diverse species exhibit better resilience against climatic and economic shocks (Zuza et al., 2024). In a global meta-analysis on the effects of crop diversification, integrating more than 5000 findings from 85 countries, Beillouin et al. (2021) found median increases in production (14 %), biodiversity (24 %), water quality (51 %), pest and disease control (63 %), and soil quality (11 %). However, these authors caution that there was substantial variability in the results between different diversification strategies.

Changes in land use associated with crop diversification (from production to consumption and waste management) can have an impact not just on farmers but on other citizens as well (Rossi et al., 2023). In the seven-year participatory study by Prost et al. (2018), the authors demonstrated how farmers can actively participate in protecting the water quality of a water catchment for all types of citizens by rethinking their practices. Furthermore, land use decisions at any level are shaped by people's perceptions of their opportunities and constraints (Esgalhado et al., 2021). To design and assess realistic, diversified alternatives, scientists must engage with local stakeholders to integrate local-specific agroecological and socioeconomic contexts and options for stakeholder action (Pelzer et al., 2020).

In the scientific community, stakeholder participation is gaining popularity. Designing diversified farming systems in Mediterranean Europe, however, still relies on scientific research (Lago-Olveira et al., 2023; Rebolledo-Leiva et al., 2022; Simon-Miquel et al., 2023). The need for transdisciplinary and bottom-up perspectives is greater than ever for establishing scientific facts that can be used for action (Magne et al., 2024). Multi-stakeholder and multi-criteria assessment may be able to address the complexity of the diversified alternatives design and assessment process by identifying proposals that satisfy stakeholders' preferences (Ravier et al., 2015). This requires measuring their impacts on various dimensions using simple, reliable, and easily monitored indicators specific to the local context (Ravier et al., 2015). An indicator is a variable whose value is determined and compared with a reference value or range. However, little is known about how a variety of assessment indicators can be effectively used by different stakeholders in the design and assessment of cropping systems to guide their action and learning (Toffolini et al., 2016).

Exploring how stakeholders evaluate diversified options and whether and when farmers would adopt those diversified alternatives remains a research gap. Previous studies have shown that participatory and transdisciplinary agricultural research is essential for understanding on-farm realities and their impact on crop diversification uptake (Brannan et al., 2023; Rosa-Schleich et al., 2024). Addressing this gap is vital for developing practical strategies to design appropriate diversification practices for stakeholders, as their expectations can be the main driver for acceptance (Rosa-Schleich et al., 2024). According to Kuehne et al. (2017), the adoption and diffusion of new agricultural practices could be influenced by their perceived advantages, the characteristics of the targeted population, and the ease to learn the new practice.

For diverse case studies in the Mediterranean region, Hossard et al. (2024) demonstrated how local stakeholders co-designed new diversified options for continuous cereal cropping systems. Blanc et al. (2024) used crop modelling and participatory work to assess the performance of these diversified systems for the sole case of Spain. Using ex-ante multi-criteria assessment involving Mediterranean stakeholders in the selection of indicators, Rezgui et al. (2025) assessed diversified systems in Spain and Greece. In this study, we built on these case studies in Spain and Greece. The objectives were to i) evaluate the performance of diversified options in comparison to continuous cereal cropping through multi-criteria assessment, and then from the perspective of regional stakeholders, and ii) predict the adoption rates and time to peak adoption of the evaluated systems.

Through this work, we aim to reduce the knowledge gap regarding crop diversification in the Mediterranean: i) by providing scientific knowledge on crop diversification impact using the indicators selected by stakeholders, and ii) receiving information from local actors (e.g., farmers, researchers, agricultural companies, etc.) regarding the barriers to diversification.

2. Material and methods

2.1. General framework

This study is based on a six-step participatory approach conducted in Spain (Ebro valley region) and Greece (Thessaloniki region) from 2021 to 2024 (Fig. 1A). In the first step (diagnosis), a typology of currently practiced systems was established using data from national statistics and expert knowledge to conduct a SWOT analysis as reported by Hossard et al., (2024). The SWOT analysis of external and internal factors was used to assess farming systems in Spain and Greece, revealing that the sustainability of cereal-based systems in both countries was challenged due to economic, environmental, and social effects. The most common challenges of current systems were economic (e.g., production costs, volatile market prices, etc.) and environmental (e.g., water scarcity, pests, climate change, etc.). This step resulted in a set of farming systems that were used as reference systems against which future systems would be designed in the second step.

The co-design involved local stakeholders such as farmers, researchers, and consultants proposing new systems based on the SWOT analysis to reduce the weaknesses and confront threats revealed in the reference systems identified by Blanc et al. (2024) and Hossard et al. (2024) in workshops. The reference system (RS) in both Spain (ES) and Greece (GR) was a two-year rotation of barley and soft wheat. The diversified systems (DIV) were based on the same cereal crops as in RS. We refer to the legume systems in Spain and Greece, respectively, as ES_{Leg} and GR_{Leg}, to the rapeseed systems as ES_R and GR_R, and to the intercropping systems as GR_{IC} (Fig. 2). In the specific case of Spain, diversification of the reference system was accompanied by reduced tillage intensity and the use of pig slurry for fertilization, as this was a logical agronomic consequence for the farmers involved when growing the new crops. The details of the rotations can be found in Table A in the supplementary material.

In the third step, 10 assessment indicators (Table 1) were selected with stakeholders following the approach by Rezgui et al., (2024). In an online survey, actors ranked commonly used assessment indicators in

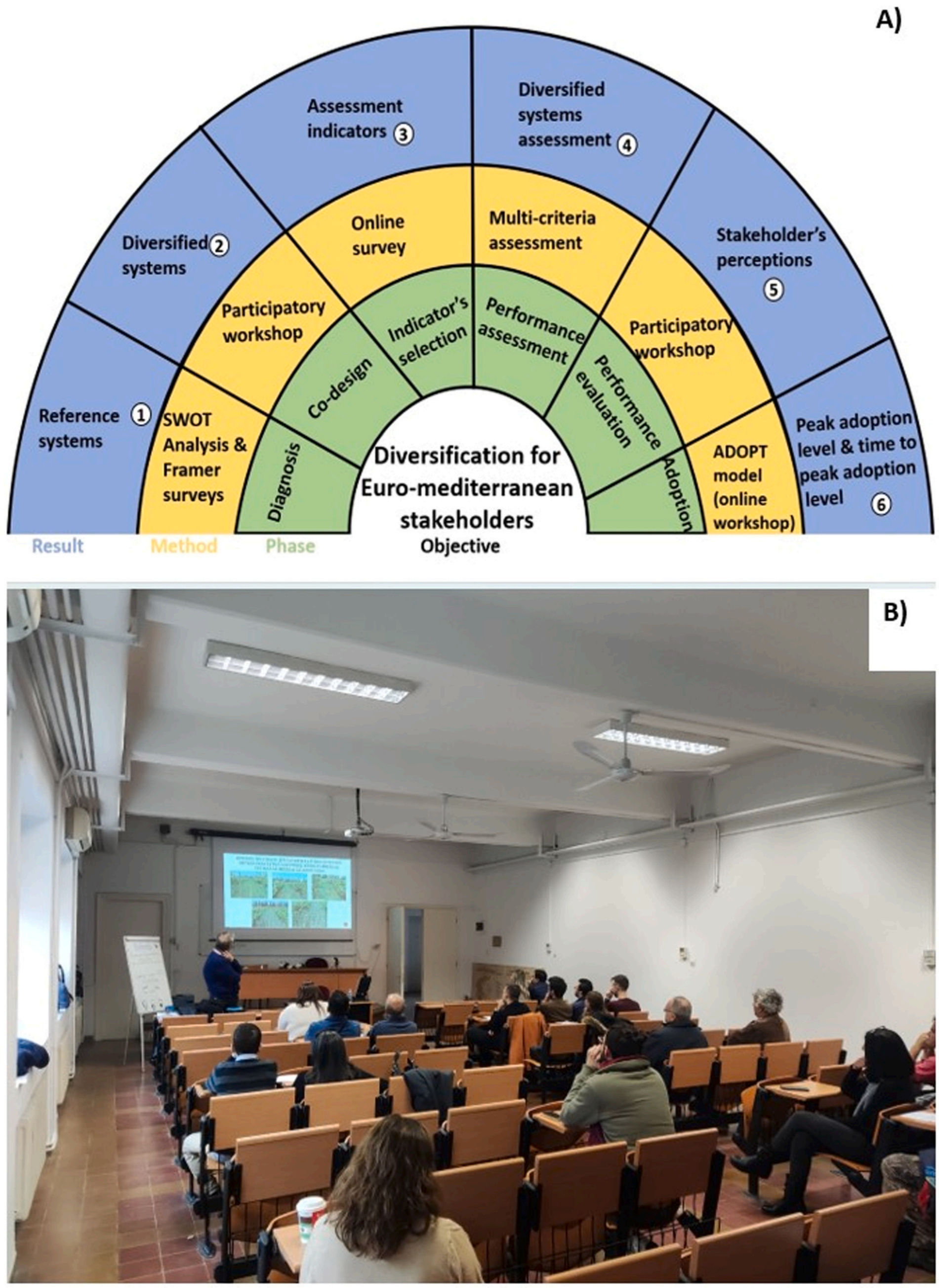

Fig. 1. Methodological steps. (A) The sixth step participatory approach process from the identification of the reference systems (RS) using SWOT analysis to the co-design of diversified options (DIV) with local stakeholders to the choice of impact assessment indicators through an online survey to the assessment of the performance of RS & DIV using ex-ante multi-criteria assessment to the evaluation of the performance by stakeholders to the ADOPT online workshop. (B) The Greek evaluation workshop (step 5) for stakeholders' perceptions (photo credit P. Papakaloudis).

the Mediterranean on a five-point Likert scale from 1 (least important) to 5 (very important). This reflects their views of what needs to be measured. In the fourth step, the ex-ante multi-criteria assessment was conducted for the RS (resulting from step 1) and DIV systems (resulting from step 2), using the 10 selected indicators from step 3. Rezgui et al. (2025) examined this in detail, with some differences in the final list of indicators when compared to this study. Consequently, this paper builds on the findings of Hossard et al. (2024), Blanc et al.((2024) and Rezgui et al. (2025), where steps 1 and 2 were reported in Hossard et al. (2024) and Blanc et al.((2024), while steps 3 and 4 were reported in Rezgui et al. (2025). This paper reports particularly the assessment results that were discussed with stakeholders in a participatory workshop (step 5, Fig. 1B) and the predictions for the adoption peak (in %) and time to adoption peak (in years) using the ADOPT (Adoption and Diffusion Outcome Prediction Tool) (Kuehne et al., 2017). ADOPT was used in a third workshop that was held online for both Spain and Greece. In this work, we will focus on the last two phases (steps 5 and 6), the stakeholders' evaluation and adoption rate predictions.

2.2. Data collection and analysis

2.2.1. Stakeholders' evaluation workshop

The Spanish workshop was hosted at the University of Lleida, while the Greek one was held at the farm of the University of Thessaloniki. Invitations were sent to stakeholders who had already collaborated, either closely or remotely, with the university or the research team and

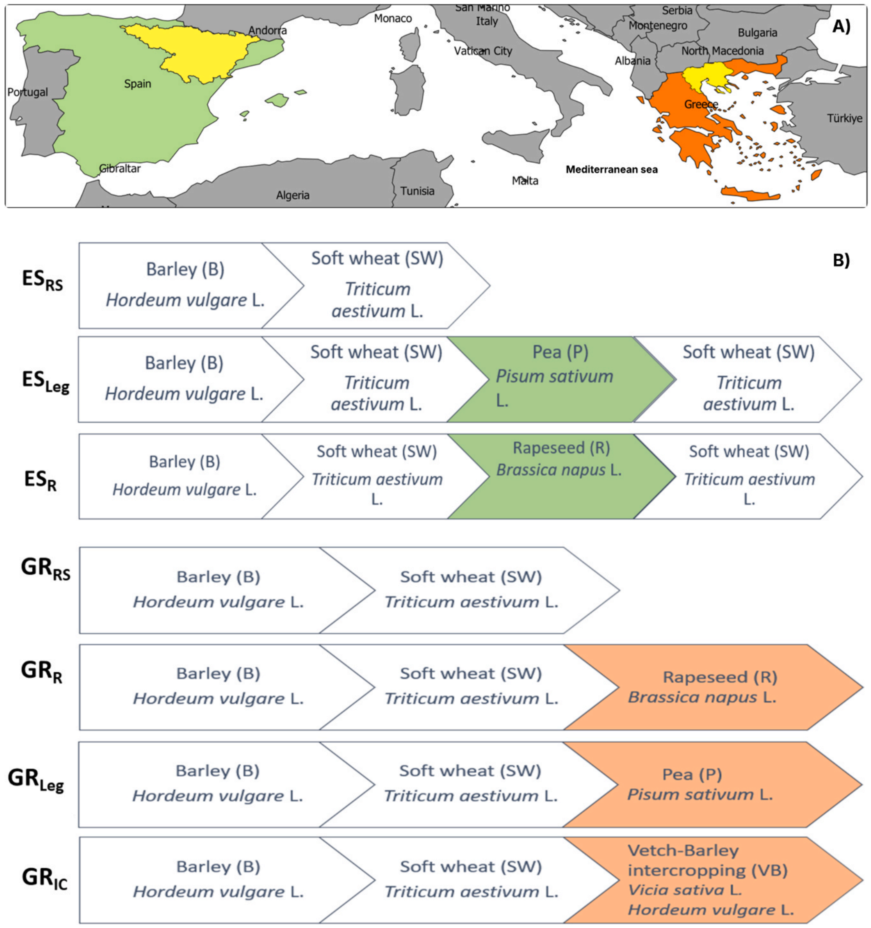

Fig. 2. Studied regions and assessed farming systems. (A) Localization of the study regions (in yellow), both in Spain (Ebro valley region, ES) and in Greece (Thessaloniki region, GR). (B) The assessed farming systems (continuous cereals and diversified systems).

Table 1
The ten participatory-selected indicators used for the performance assessment of the arable crops.

Dimension	Indicator	Acronym	Description	Unit	Reference
Agri-environmental	Energy Use Efficiency	EUE	Ratio between the output energy to the input energy	-	Zahedi et al. (2015)
	Non-renewable energy input	NRE	Amount of non-renewable energy coming from inputs (synthetic fertilizers, pesticides, fuel)	GJ ha^{-1} yr^{-1}	
	Renewable energy input	RE	Amount of renewable energy coming from inputs (water, seeds, human work, and organic fertilizers)		
	Treatment Frequency Index	TFI	Product dose used by the farmer divided by the reference dose as recommended by the manufacturer	-	Hossard et al. (2014)
	Pesticide Load Index	PLI	Amount of the active ingredient (kg ha-1 yr-1) multiplied by the Pesticide Load points per kg of active ingredient (toxicity to non-target organisms)	Pesticide Load points ha-1 yr^{-1}	Kudsk et al. (2018)
Social	Grain quality	GQ	Protein production coming from grain rotation outputs as a way of contributing to human nutrition	kg protein ha^{-1} yr^{-1}	Costa et al. (2021)
	Workload	WL	Average of worked hours per crop	h ha^{-1} yr^{-1}	Popovic et al. (2018)
Economic	Grain yield	GY	Grain yield	kg ha^{-1} yr^{-1}	
	Economic profit	P	Annual net income		Yang et al. (2019)
	Economic cost	C	Annual total costs	€ ha^{-1} yr^{-1}	

who were present at the co-design workshop (step 2). As the focus of this study was on diversifying cereal rotations, the invited stakeholders, including farmers, were chosen fundamentally based on their expertise in cereal cropping. The total number of participants in both Greece and Spain was 42 (Table B, supplementary material). In Greece, 32 stakeholders participated, of which 16 were agricultural students (many of whom were farmers' sons and future farmers themselves) and 12 were farmers, while 4 were researchers. The participants in Spain were mainly farmers and researchers, but four of them identified themselves as both farmers and researchers or engineers and consultants. During this evaluation workshop, the local stakeholders assessed the performance of the co-designed systems based on the ex-ante assessment (step 4). The workshops were structured around, **i) indicator's importance ranking**: each stakeholder ranked individually the importance of all agri-environmental, social and economic indicators on a scale of 1 (least important) to 5 (most important), **ii) summary of the co-design workshop output**: researchers reminded the description (rotation, management practices, etc.) of the reference and the co-designed systems (Table A, supplementary material), **iii) presentation of the agricultural systems' performance**, i.e. the ex-ante assessment of the considered systems using the selected indicators (Table 1). Using the pre-selected indicators, the performance of the RS and DIV systems was calculated. These indicators were from the three dimensions of sustainability, namely: the agri-environmental, social, and economic dimensions. The impact indicators were calculated for each crop per ha and year. To represent the full rotation, each indicator was averaged over the rotation duration. To compare yields, we converted them all (Table C, supplementary material) to cereal units (CU). One CU is equivalent to one kg of barley, based on the conversion coefficients as calculated by Brankatschk and Finkbeiner (2014) in terms of the nutritional value (metabolizable energy), and **iv) performance rating**: stakeholders rated individually each indicator's performance on a three-point scale from 1 (unsatisfactory) to 3 (satisfactory). The difference in scale between the indicator's importance and performance (five-point versus three-point scale) is due to the nature of each attribute. Indicator importance depends on stakeholders' backgrounds and preferences, making it more subject to variation; performance, however, is based on the same ex-ante assessment shown to all stakeholders, making it less prone to variation.

2.2.2. *Importance performance matrix*

The data coming from the ranking of the indicators was used to conduct an importance-performance matrix that measures the satisfaction of stakeholders towards the assessed farming systems (Phadermrod et al., 2019). Since stakeholders' satisfaction is driven by their perceptions, it involves two components of the system's attributes: the importance of the indicator to the stakeholder and the performance of the system in providing that impact. The intersection of the medians of these two attributes creates a two-dimensional system of coordinates, where importance is represented on the y-axis and performance on the x-axis. The distribution of each indicator for each system is identified as a major or minor strength or weakness based on its location on the matrix and is described as follows: i) Quadrant 1 (Q1) contains the system's highly performing variables that are perceived by the stakeholders as the most important, ii) Quadrant 2 (Q2) contains variables that are perceived to be very important to stakeholders, but performance levels are fairly low, iii) Quadrant 3 (Q3) contains variables of low importance and low performance, iv) Quadrant 4 (Q4) contains variables that stakeholders perceive as of low importance, but the system appears to provide high performance. Variables within a quadrant were not compared to each other and were considered homogeneous, but rather, the variables in one quadrant were compared to the variables in another quadrant.

2.2.3. *Adoption rate, adoption peak, and time to peak adoption prediction*

The Adoption and Diffusion Outcome Prediction Tool (ADOPT) was used to predict the adoption of the diversification practices and their respective time to adoption peak (Kuehne et al., 2017) through two online workshops with Spanish and Greek stakeholders. These stakeholders were both researchers and farmers, and experts in each of the regions. In particular, they are experts in the dynamics and context of cereal production (i.e., pedoclimatic conditions, frequently used species and varieties, agricultural input companies, market outlets, etc.). ADOPT builds on the diffusion of innovations' theory, predicting farmer adoption by accounting for both the practice and population-specific factors, known to be important to adoption outcomes (De Oca Munguia and Llewellyn, 2020). ADOPT considers 22 variables classified under four categories: i) the practice's characteristics (e.g., costs, profits, etc.) influencing its advantage, ii) the characteristics of the population (e.g., existing knowledge, awareness, etc.) influencing their perceptions of the practices, iii) the ease and speed of learning the practice, and iv) the factors influencing potential adopters' ability to learn (e.g. environmental motivation, risk orientation, etc.).The complete list of the 22 variables is shown in Table D in the supplementary material.

Each variable is related to a question to which the answer is on a scale of five-to-seven-degree responses. For instance, the variable "Relative upfront cost of the project" under the category "practice's characteristics" is associated with the question "What is the size of the up-front cost of the investment?" which entails a five-degree response ranging from "very large initial investment" to "no initial investment required". In fact, ADOPT generates quantitative predictions that complement other data derived from simulation models, farm surveys, etc. The results of the ex-ante multicriteria assessment (step 4) were used as inputs to the model. For example, for the same variable "Relative upfront cost of the project", the stakeholders were shown the economic costs (C) and were asked to discuss among themselves to come up with one response for this variable. The other ADOPT variables that did not match the ex-ante indicators were either based on national statistical data (e.g., management horizon) or simply discussed by the stakeholders (e.g., farmer group involvement), as they were field/farmer community experts. These responses, as given by the stakeholders, will constitute the baseline scenario of the model.

Based on variations, either an increase or decrease in the response degree of the variables from the baseline (the responses given during the workshop), ADOPT generates two scenarios: i) an optimistic scenario, i.e., assuming the next highest possible response degree. For example, assuming the stakeholders answered to the "relative upfront cost of the project" by "moderate initial investment", an optimistic scenario would be "minor initial investment". ii) pessimistic scenario, i.e., assuming the next lowest possible response degree. Using the " relative upfront cost of the project " example again, a pessimistic scenario would be "large initial investment".

For all systems, we explore how these two scenarios affect the adoption rate (percent of farmers adopting a practice at a given time since its introduction), the adoption peak (maximum adoption rate), and the time to peak adoption (time to reach the adoption peak since the introduction of the new practice in years).

3. Results

3.1. *The performance results of the diversified systems*

3.1.1. *Ex-ante multi-criteria assessment*

Across both case studies, DIV systems often outperformed the RS, but not for all indicators and not in both countries (Table 2). Generally, DIV systems outperformed RS in terms of energy indicators (e.g., EUE, NRE, etc.). In Spain, ES_{Leg} and ES_{R} had higher EUE values than ES_{RS}, with ES_{Leg} having the highest value of 8.8. The higher EUE values for DIV when compared to the RS can be attributed to the reduced tillage intensity and the use of pig slurry for fertilization, which decreased both the fuel consumption for machinery and the total energy from fertilizer input (organic fertilizers have a lower energy equivalent than mineral fertilizers). In Greece, 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). Legumes generally required fewer management interventions than cereals (e.g., fuel consumption, fertilizer, and pesticides), which represent the majority of non-renewable energy, explaining the lower NRE for ES_{Leg}, GR_{Leg}, and GR_{IC}. In fact, the ES_{Leg} was the system with the largest share of renewable energy input (61 %). while the rapeseed systems in both Spain and Greece had a greater share of nonrenewable energy input (77 % and 86 %, respectively). Compared with Greek systems, Spanish systems had the highest pesticide use (higher TFI) and the highest toxicity to non-target organisms (higher PLI). The TFI was highest for ES_{R} and lowest for ES_{Leg} when compared to ES_{RS} (+15 % and −14 %, respectively), with rapeseed having the highest TFI (6), and cereals the lowest (3). The PLI was lower for ES_{R}, with a value of 2, but it was the highest for ES_{Leg} with a value of 4. In Greece, RS had the highest TFI (2.21) and PLI (1.67), followed by GR_{R} (TFI= 1.77, PLI=1.29). The legume systems (GR_{Leg} and GR_{IC}) tied for TFI at 1.47 and PLI at 1.11, with cereals having the highest TFI (2), while

Table 2
Performance results for the diversified systems using the impact assessment indicators.

Dimension	Case study	Ebro valley-Spain			Thessaloniki-Greece			
Agri-environmental	**Indicator/Cropping system**	**ES_{RS}**	**ES_{Leg}**	**ES_{R}**	**GR_{RS}**	**GR_{R}**	**GR_{Leg}**	**GR_{IC}**
	Energy Use Efficiency (EUE)	4.9	8.8	7.6	5.7	6.3	6.5	5.7
	Non-Renewable Energy (NRE) (GJ)	14.7	4.5	7.0	6.9	8.6	5.4	5.2
	Renewable Energy (RE) (GJ)	6.4	7.0	5.8	2.1	1.4	2.2	2.3
	Treatment Frequency Index (TFI)	3.3	2.8	3.8	2.2	1.8	1.5	1.5
	Pesticide Load Index (PLI) (Pesticide Load points ha^{-1} yr^{-1})	1.6	4.1	1.9	1.7	1.3	1.1	1.1
Social	Grain Quality (GQ) (kg $ha^{-1}yr^{-1}$)	861	926	935	402	591	387	329
	Workload (WL) (h $ha^{-1}yr^{-1}$)	4.5	3.2	3.2	10.0	9.7	9.7	9.7
Economic	Grain Yield (GY) (t CU $ha^{-1}yr^{-1}$)	7.2	6.2	6.3	3.3	3.5	2.8	2.5
	Costs (€ ha^{-1} yr^{-1})	445	304	356	696	753	712	636
	Profits, subsidies excluded (P) (€ ha-1 yr-1)	805	876	793	49	-28	-45	186

rapeseed had the lowest (0.88). Agri-environmental performance was better for legume systems (ES_{Leg}, GR_{Leg}, and GR_{Ic}) compared to those with rapeseed.

For the social dimension, Spanish DIV had higher protein production (Table 2) and lower working hours per hectare (-29 %) compared to RS, since some management practices (e.g., fertilization, phytosanitary treatment, etc.) were reduced. In Greece, the difference was marginal since other limiting factors existed, such as the choice of a low-input RS system. Low-input systems consequently require limited management practices, resulting in reduced workloads. Greece also had a lower protein production (grain quality) for the legume systems, while its workload was lower than that of RS (-9 %). Except for GR_R, DIV yields for both countries (based on cereal units) were decreasing in comparison to RS. The decrease ranged from −12 % to −25 %. Economically, ES_{Leg} and GR_{IC} were the only systems to have lower costs (C of ES_{Leg}= 304 € ha^{-1} yr^{-1}, C of GR_{IC}=636 € ha^{-1} yr^{-1}) with higher profits (P of ES_{Leg}= 876 € ha^{-1} yr^{-1}, P of GR_{IC}=186 € ha^{-1} yr^{-1}) than RS (C of ES_{RS} =445 € ha^{-1} $yr^{-1}$and P of ES_{RS} =805 € ha^{-1} yr^{-1}, C of GR_{RS} =696 € ha^{-1} yr^{-1} and P of GR_{RS} =49 € ha^{-1} yr^{-1}), the remaining systems underperformed RS in either cost or profit. Furthermore, when subsidies are excluded, GR_R and GR_{Leg} have negative gross margins (-10 % and −12 %, respectively) when compared to GR_{RS}.

3.1.2. Importance performance matrix

The intersection of the median importance and median performance was 2.3 and 3.5 for Spain, and 1.7 and 3.7 for Greece (Figs. 3–4), respectively. The economic indicators (grain yield, profit, and cost) were identified as highly important by Spanish and Greek stakeholders. For Spain, only the yield and profit of RS (GY_{RS} and P_{RS}) were considered to be well performing (Fig. 3, Q1), which is in line with the performance results (Table 2). Spanish stakeholders did not seem to accord a large difference in performance between DIV and RS, although ES_{RS} did seem to do better in terms of yields, profits, and costs (Fig. 3, Q2). The GR_R delivered the highest economic performance for stakeholders despite its higher costs and lower profits than those of RS (Fig. 4, Q1). Intercropping, the only system that generated positive returns (Table 2), wasn't considered more performant than the others by stakeholders.

In terms of social indicators, both countries showed similar trends, with stakeholders placing a higher priority on workload (WL) than on grain quality (GQ). The Spanish DIV systems have shorter working hours

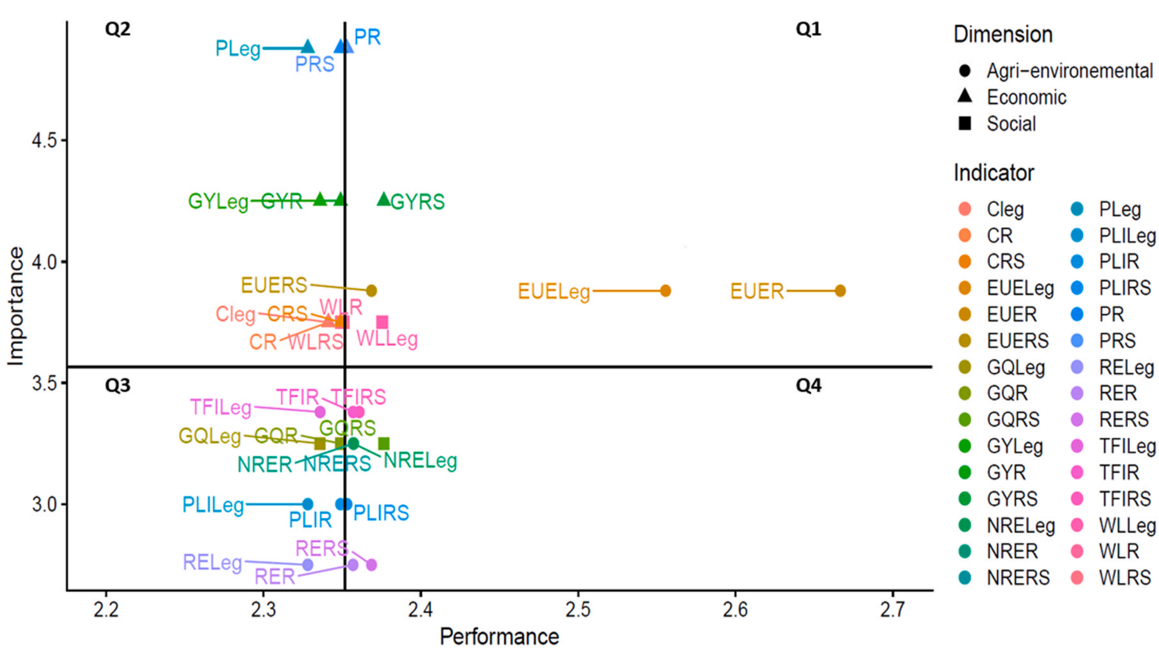

Fig. 3. Spanish importance performance matrix showing the distribution of the average scores as rated by the stakeholders for the importance (scale - 1- 5) and performance (scale 1–3) of the reference system (RS), the rapeseed system (R), and the legume system (Leg). The indicators were Energy Use Efficiency (EUE_{RS}; EUE_R and EUE_{Leg}), Nonrenewable Energy (NRE_{RS}; NRE_R and NRE_{Leg}), Renewable Energy (RE_{RS}; RE_R and RE_{Leg}), Treatment Frequency Index (TFI_{RS};TFI_R and TFI_{Leg}), Pesticide Load Index (PLI_{RS}; PLI_R and PLI_{Leg}), Grain Quality (GQ_{RS}; GQ_R and GQ_{Leg}), Workload (WL_{RS}; WL_R and WL_{Leg}), Grain Yield (GY_{RS};GY_R and GY_{Leg}), Profits (P_{RS}; P_R and P_{Leg}) and Costs (C_{RS}; C_R; C_{Leg}).

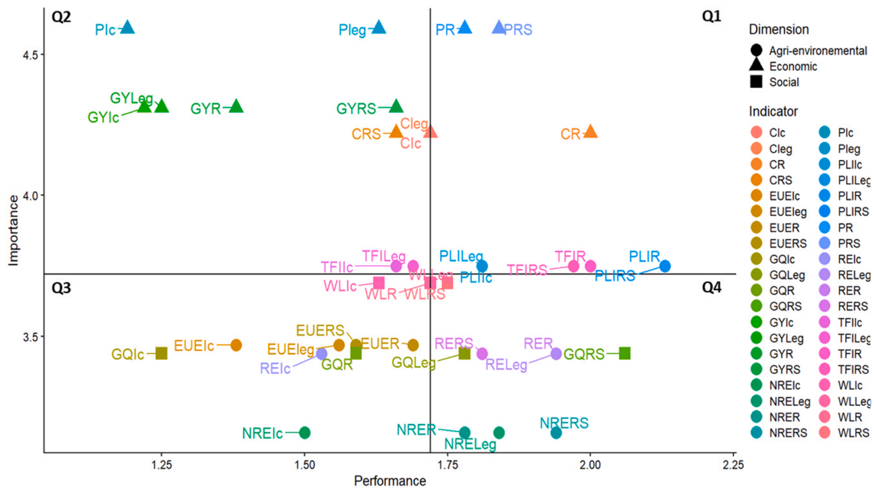

Fig. 4. Greek importance-performance matrix showing the distribution of the average scores as rated by the stakeholders for the importance (scale - 1- 5) and performance (scale 1–3) of the reference system (RS), the rapeseed system (R), the legume system (Leg), and the cereal-legume intercropping system (IC). The indicators were Energy Use Efficiency (EUE_{RS}; EUE_{R}; EUE_{Leg} and EUE_{Ic}), Nonrenewable Energy (NRE_{RS}; NRE_{R}; NRE_{Leg} and NRE_{Ic}), Renewable Energy (RE_{RS}; RE_{R}; RE_{Leg} and RE_{Ic}), Treatment Frequency Index (TFI_{RS};TFI_{R}; TFI_{Leg} and TFI_{Ic}), Pesticide Load Index (PLI_{RS}; PLI_{R}; PLI_{Leg} and PLI_{Ic}), Grain Quality (GQ_{RS}; GQ_{R}; GQ_{Leg} and GQ_{Lc}), Workload (WL_{RS}; WL_{R}; WL_{Leg} and WL_{Ic}), Grain Yield (GY_{RS};GY_{R}; GY_{Leg} and GY_{Ic}), Profits (P_{RS}; P_{R}; P_{Leg} and P_{Ic}) and Costs (C_{RS}; C_{R}; C_{Leg} and C_{Ic}).

than RS (Table 2), which translates into a better performance in stakeholders' rankings in terms of workloads. The opposite was observed in Greece, where RS performed better in terms of workload, according to stakeholders. Grain quality performance was rated high for both RS in both countries, unlike the case for DIV systems with protein-rich crops (rapeseed and peas). Only GR_{Leg} was in the high-performance quadrant (Q4), but it was still not ranked as high as the RS.

Similarly, the perceptions of agri-environmental indicators were similar in both countries. They were ranked in average as the least important indicators compared to the social and economic indicators. However, there was a divergence within the agri-environmental dimension itself among both countries: in Spain, only energy efficiency (EUE) was considered important, while in Greece, both pesticide indicators (PLI and TFI) were. There was a greater difference between systems in terms of performance ranking. In Spain, DIV systems were perceived to be more energy-efficient than RS. A net performance difference was observed in Greece for pesticide use, with the legume systems (either in rotation or in intercropping) outperforming GR_{RS}.

3.2. Potential adoption of diversified systems

3.2.1. Adoption rate, adoption peak, and time to peak adoption

Legume systems had a higher predicted adoption peak (from 23 % to 28 %) in a shorter time (from 8 to 10 years) compared to rapeseed

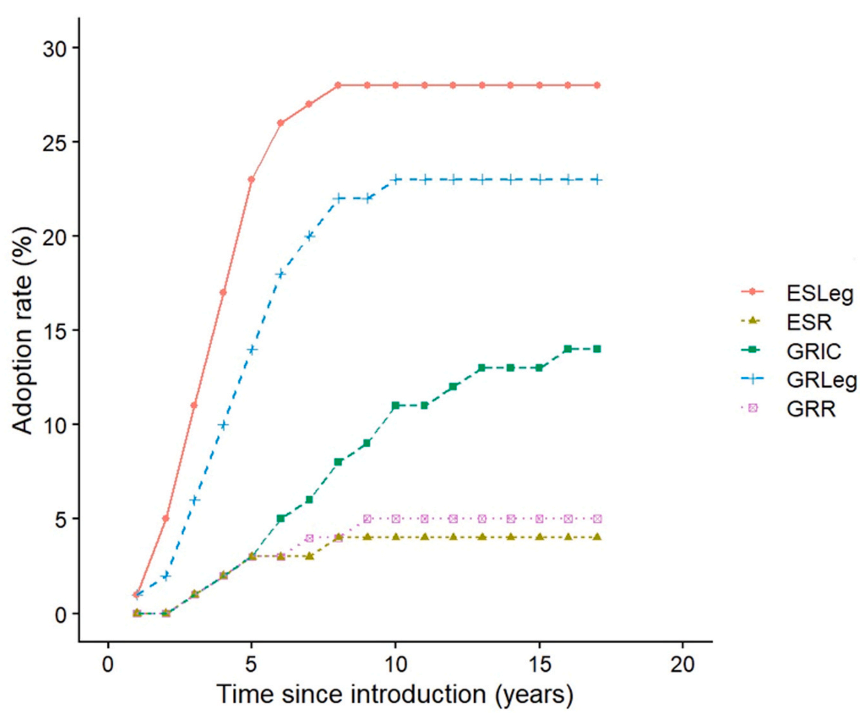

Fig. 5. Adoption rate (%) and time (years) for the different diversified systems. ES_{Leg}: barley-wheat-pea-wheat, ES_{R}: barley-wheat-rapeseed-wheat, GR_{IC}: barley-wheat-vetch and barley intercropping, GR_{Leg}: barley-wheat-pea, and GR_{R}: barley-wheat-rapeseed.

systems, which had a lower predicted adoption peak and were expected to take longer to reach those peaks. Meanwhile, the intercropping system was positioned in the middle with a lower adoption peak than legume systems, but a higher adoption peak than rapeseed systems. The Spanish legume system was expected to reach the highest adoption peak and fastest (28 % of the farmer population in the Ebro valley in 8 years). The Spanish rapeseed system was predicted to be the least adopted (adoption peak of 4 %). In Greece, the intercropping system was expected to be the slowest (17 years) to reach its adoption peak (14 %).

3.2.2. *Variance in adoption peak levels and years to adoption peak*

The adoption rate was most affected by the variable "profit benefits in the years that are used", while the time to peak adoption was most affected by the variable "relevant existing skills and knowledge". The results of these variables are shown in Table 3, while the remainder of the variables are shown in Fig. A and Fig. B in the supplementary material.

The adoption peak nearly doubled for all systems for the optimistic scenario, while occurring faster (nearly a year earlier) when compared to the baseline scenario. In fact, the same trend was observed as in the baseline scenario, where legume systems were the most probable to reach the adoption peak, followed by intercropping and rapeseed systems. Despite higher profits and better existing knowledge assumptions in the optimistic scenario, the highest adoption peak was around 50 %. Under the pessimistic scenario, the adoption peak nearly halved for all systems while occurring at a slower pace (nearly a year later). Similar conclusions apply to the optimistic scenario where legume systems appear to be the most likely to be adopted.

Regardless of the scenario, the other variables that most affected the adoption peak were the profit in the future, the time to environmental cost benefits, risk exposure, and the ease and convenience of the diversification practice. In Greece, upfront costs were also a factor that greatly affected adoption (Fig. A, supplementary material). Among the other variables that affected the time to peak adoption, complexity of the practice and its trialability (easiness to try) were the most important (Fig. B, supplementary material).

4. Discussion

4.1. *The performance results of the diversified systems*

4.1.1. *Ex-ante multi-criteria assessment*

Integrating legumes and rapeseed into cereal-based rotations improved energy efficiency (Table 2). DIV systems had a mean EUE of 7, in line with other cereal-legume system studies (Meena et al., 2021; Nassi O Di Nasso et al., 2011). Pesticide use indicators (TFI and PLI) for DIV were generally lower than those for RS in Greece, but not in Spain. Pest infestations and disease incidence may decrease as a result of the introduction of different crop families, decreasing pesticide use, as reported by Guinet et al. (2023).

Due to reduced management practices, DIV required fewer working hours than RS in both countries. A similar conclusion was reached in the study of Dardonville et al. (2022), where biodiversity-based systems were found to have lower workloads than conventional systems. The DIV systems with protein-rich crops (pea and rapeseed) produced more protein than RS (except for Greek legume and intercropping systems). Despite legumes being naturally rich in proteins, the Greek legume and intercropping systems were the exception due to low legume yields. Similarly, Simon-Miquel et al. (2024) found legume integration to increase protein production in continuous cropping systems under Mediterranean conditions. The general idea that adding legumes to a rotation will automatically increase protein production (compared to a pure cereal rotation) is paradoxical, especially when legumes are proven to produce lower yields and have higher yield variability than cereals (Cernay et al., 2015).

In Spain, DIV systems had lower operational costs than RS, again because of a lower intensity of management practices. In legume systems, peas had a lower yield than cereals, which was compensated for by a higher selling price, leading to higher profit margins. Similarly, Rebolledo-Leiva et al. (2022) reported that rotations with legumes generally increased gross margins. In Greece, GR_R and GR_{Leg} had higher costs than RS. Contrary to what has been discussed above about legumes resulting in higher profits, GR_{Leg} actually had low profits when subsidies were excluded. This is the result of low yields due to other production factors, like climate conditions. Due to these limitations, Greek farmers favor low-input cropping systems (e.g., low pesticide rates), since additional inputs to low-return systems aren't economically worthwhile. This strategy has also been documented in other European countries, such as in northern Germany (Preissel et al., 2015). In accordance with other cases across Europe (Notz et al., 2023), the incorporation of legumes and rapeseed into cereal rotations could reduce costs on average, but it does not generate higher returns without subsidies.

4.1.2. *Importance performance matrix*

Stakeholders considered the economic indicators (grain yield, profit, and cost) as highly important, but diversification was not perceived as economically viable. While suggested that economic factors might not be as important as previously discussed in literature but are a consequence of not involving farmers in research, we found that this was still true for Mediterranean stakeholders. In Spain and Greece, where the legume and intercropping systems had higher profits and lower costs than the RS, stakeholders still viewed them as a low-performing system (Fig. 3 & 4). Even though these conclusions were specific to Spain and Greece, both countries could be considered representative of Mediterranean Europe (Rezgui et al., 2025). Therefore, our results are likely representative of other cereal-growing countries in Europe. However, this may not be entirely accurate for other Mediterranean countries (e.g., MENA regions). The study of Rezgui et al. (2023) investigating the adoption of agroforestry as a diversification strategy in Mediterranean Africa has found that the economic factor also played an important role. A review by Brannan et al. (2023) reported mixed findings for the impact of economic factors on crop diversification in Europe. On the one hand, it was found that economic factors could be a barrier to legume growing (Zander et al., 2016). On the other hand, Morel et al. (2020) found the profitability of diversification strategies in Europe not to be a barrier. One reason for this might be the significant differences in economic performance within European countries due to the size of the trained farm population, among other factors (Giannakis and Bruggeman, 2015).

In our case, stakeholders might, however, have expected even higher

Table 3
Adoption peak and time to peak adoption variance when considering two scenarios for the two most influential variables: profit benefits in the years that are used, and relevant existing skills and knowledge.

Diversified system	Adoption peak (%)			Time to peak adoption (years)		
	Baseline	Optimistic scenario	Pessimistic scenario	Baseline	Optimistic scenario	Pessimistic scenario
ES_{Leg}	28	51	13	7.9	6.4	9.4
ES_R	4	8	2	8.9	7.4	10.4
GR_R	5	9	3	10.5	9.2	11.8
GR_{Leg}	23	40	12	10	8.7	11.3
GR_{IC}	14	26	7	16.6	15.3	17.9

returns, especially since new management practices were employed. This could explain the differences between actual performance values (Table 2) and stakeholder ratings (Fig. 3 & Fig. 4). Economic profitability (directly related to yield, variable in its turn due to uncontrollable factors like weather conditions) may not reflect in this short term the positive return legumes can provide in the long run (Blanc et al., 2024). For higher yields with less variability, an ecological process (e.g., the build-up of a carbon soil pool) must take place over time. Unfortunately, such changes cannot be detected at the end of a three-to-four-year rotation sequence. This is in line with the findings of Rosa-Schleich et al., (2019), where it was stressed that short-term costs may be too high for farmers compared to the long-term ecological benefits, leading to increased yields. Grain yields (in CU) of almost all DIV systems were lower than RS. When grown under rainfed Mediterranean conditions, legume crops tend to have lower and more variable yields than cereal crops (Cernay et al., 2015; Simon-Miquel et al., 2024), and if there is a yield increase, it is minimal since other factors, such as water availability, limit larger yields (Preissel et al., 2015). Regardless of the growing environment, legumes tend to have a higher yield variability than most other crops, including cereals (Cernay et al., 2015; Reckling et al., 2016).

Considering the Spanish workshop was conducted in 2022, the high importance attributed to EUE might be related to the rising fuel and energy prices at the time, caused by the ongoing war in Ukraine. The Greek stakeholders have placed great emphasis on pesticide use as the most important agri-environmental indicator, reflecting their stated desire to design pollution-reduced systems during the co-design workshop (Hossard et al., 2024).

Similarly, social indicators were considered less important, while they were mostly regarded as highly performing. On average, the importance and performance of workload (WL) were ranked higher than that of grain quality. The long working days and physically demanding tasks of agriculture have no doubt a negative effect on the mental health of farmers and or workers, and any reduction in this time may improve work satisfaction (Schanz et al., 2023), which is probably why stakeholders consider the indicator important. The difference in workload between DIV and RS (1.3 h and 0.3 h per year in Spain and Greece, respectively) may not have been large enough to be considered performant by the stakeholders, thus explaining their low rankings. Despite increases in grain quality with diversification, the indicator is not of high importance to stakeholders due to the lack of a clear economic outcome, even though cereals could be sold at a higher price depending on whether they are intended for food (higher protein content) or feed, as is the case in France. Based on crop modelling simulations, Blanc et al. (2024) evaluated how selling cereals based on their protein content affected income and found barely an improvement in the case of Spain (protein content is currently not considered when pricing cereals), along with a lack of confidence among the stakeholders that protein content would improve economic returns.

4.2. Adoption of diversified systems

4.2.1. Regional context impact

In both countries, DIV systems with legumes were more likely to be adopted than rapeseed-supported systems (Fig. 5). The Ebro valley is home to half of Spain's swine livestock. The potential for producing peas and rapeseed for animal feed could have stimulated interest in adopting these crops, considering the increasing market demand for locally produced protein crops. The low predicted adoption level for rapeseed systems may be due to their high pesticide demand, lower and more variable yields that result in lower economic returns. In fact, rapeseed cultivation becomes less suitable for dry areas such as the Mediterranean region, due to increasing climate change (Jaime et al., 2018).

Due to production-limiting factors such as climate conditions, Greek systems are already of low return. Thus, Greek farmers favor low-input systems (e.g., low pesticide use, low fertilization) as it is not an economically worthwhile investment (Preissel et al., 2015). In this study, neither rapeseed nor legume systems are profitable in Greece, and neither system can be sustained without CAP subsidies. Thus, the co-designed diversified alternatives, supposedly a more sustainable choice economically, are of a lower economic profit than the continuous cereal systems currently practiced in the region, explaining their low adoption rates. In fact, economic viability is one of the key factors affecting large-scale adoption or non-adoption of a given practice (Kuehne et al., 2017; Lamichhane, 2023). In Greece, the recession further complicated the situation (Hossard et al., 2024). While intercropping offers better economic performance than both legume and rapeseed systems, its adoption rate is lower than that of the legume-supported systems due to its higher technical complexity. Greek stakeholders expressed their concerns about the segregation of seeds at harvest as a hurdle to adopting this system, and the ex-ante assessment did not actually account for the cost of such an operation. Hence, large-scale adoption of diversified cropping practices requires support by technological advances (Lamichhane, 2023).

4.2.2. Age impact

Farmers' ages can also have an impact on the adoption of new practices, as younger farmers may inherit the practices from the previous generation, or they may be more open-minded toward adopting new practices. In the study of Topp et al. (2024) in the Mediterranean, it was found that innovation (no-till and reduced tillage) is negatively associated with age, suggesting that older respondents value traditions more than new practices.

4.2.3. Risk impact and adoption policies

The risk attitude of farmers is crucial for the successful implementation of diversification practices (Rosa-Schleich et al., 2024). In this regard, and during the ADOPT workshop session, Greek stakeholders confessed their concerns about the high variability in rapeseed yields. Hence, they prefer a modest but constant income over a highly fluctuating income. Furthermore, the market for rapeseed and pea might be underdeveloped, compared to wheat and barley, where there are already factories and breweries using these cereals as raw materials for food. Thus, this study demonstrates farmers' concerns about taking risks when adopting new crops that may lead to a loss of income. This may serve as an incentive for policymakers to implement targeted subsidies, for example, risk-mitigation programs (e.g., insurance schemes or guaranteed price mechanisms for early adopters), so farmers can transition to diversified systems without suffering immediate losses. In Europe, farmers' decisions are strongly influenced by the CAP (Esgalhado et al., 2021). In Mediterranean Europe, diversification practices are funded based on the problem size (area covered by the targeted crops, nutrient leaching, biodiversity losses, and soil erosion), but the practices promoted are marginally effective. For example, mandatory measures dealing with crop rotation (e.g., Good Agricultural And Environmental Condition 7 (GAEC 7), which translates to "preserve the soil potential through crop rotation") include a number of exemptions, while voluntary measures addressing further diversification practices (ECO schemes and AEC measures) focus mainly on improving spatial diversification rather than crop rotations (Galioto and Nino, 2023). As was demonstrated in this study, diversified rotations can hold environmental benefits; policymakers could consider targeting crop rotation within the CAP instead of focusing on the spatial diversification. Moreover, the CAP crop rotation requirements for 2023–2027 exclude farms with less than 10 ha (Guyomard et al., 2023). In Greece, the average UAA is 7 ha (Table B, supplementary material), thus signaling to policymakers that local fine-tuning is needed since Europe has a wide variety of systems and conditions. Diversification practices perceived by farmers as less performant than current systems, such is the case of legume integration in Greece, would require market-driven approaches such as agri-environmental incentives. In this regard, the study of Colombo et al. (2020) is an example of how researchers can contribute to diversification by addressing agronomic issues, developing niches for the commercialization of new crops, and removing technological and regulatory barriers at the value-chain level. The economic attractiveness of diversification can also be enhanced by consumer-driven demand for sustainably grown crops, such as certification with eco-labels.

4.3. Methodological strengths and limits

In this study, we employed an integrative (several diversified systems and indicators) and simple (mean values of indicators) approach to identify whether co-designed systems would be a viable alternative to current practices. The study was characterized by a mutual learning process. The importance of this was already emphasized in other participatory studies conducted around the world (Andrieu et al., 2019; Quinio et al., 2022). In this process, two types of knowledge were important: i) the local knowledge brought forward by regional stakeholders, which involved an in-depth understanding of the local socio-economic environment, and suitable, real field management practices; ii) the scientific knowledge of the researchers, mainly dealing with the organization and facilitation of the workshops and the ex-ante assessment of the diversified rotations proposed. The repeated and sustained interactions between stakeholders and researchers led to the improvement of trust, as can be seen, for example, in the second Spanish workshop, where most of the stakeholders returned from the first workshop (Blanc et al., 2024).

By using an iterative process, we attempted to create evidence-based knowledge, which is crucial for ensuring the sustainability of diversification practices (Lamichhane, 2023). Sustainability, however, is not a static concept, as there are always changes regarding our understanding of the relationship between human activities and the environment, social and economic dimensions, as well as changing expectations from society (Perrin et al., 2023). Thus, knowledge needs to evolve to keep pace with the evolving concept of sustainability. In this regard, the advantage of our study is that it can be used in the future even if the definition of sustainability changes. Stakeholder perceptions are what change over time, which could affect the results of the approach but not the approach itself.

The results of this study were based on a comprehensive set of impact indicators used in the ex-ante assessment. These indicators may not reflect all the challenges the Mediterranean region faces nor all system variations, since average values were used. However, the use of average value simplified sharing data of varying natures and origins and facilitated discussions between stakeholders in a limited timeframe. Keeping with indicators, their importance ranking was self-rated by stakeholders, which may lead to low discrimination power since they tend to consider all attributes equally important (Gustafsson and Johnson, 2004), as was the case in this study.

Moreover, this study is limited by the number of participants (42), which may be considered as not representative, especially for Spain when compared to Greece (a larger study region, more farms, but fewer participants). The size may affect the significance of the importance-performance results in both countries, even though in the case of Greece, the participants' size was larger and more diverse, mainly in terms of gender. The number of participants in this study is still comparable to other participatory-based studies in the Mediterranean, despite their rarity, such as the study of Di Bene et al. (2022) with 50 participants. This limitation may reflect the fact that participatory research is still developing in both regions, and reaching a larger number of stakeholders may take time. The selection of participants in the evaluation workshop (step 5) was influenced by two factors: i) our desire to continue with the stakeholders who attended the first workshop (step 2); ii) the expertise of those stakeholders in cereal agricultural systems, since the main focus of this paper was cereal system diversification. Thus, in this study, the lower number of women may have an impact on results because women may be more open to adopting certain practices and conserving nature on farms(Druschke and Secchi, 2014). However, the lower number can be attributed to the simple fact that rural demographics are still influenced by the masculinization of depopulated areas (Topp et al., 2024).

Predicting the adoption level by using a tool rather than directly asking the stakeholder group during the workshop, when they evaluated the performance of the systems previously designed, may be perceived as a limitation, but it was a deliberate choice. This is because the model offers a better understanding of the reasons behind the adoption rather than merely quantifying the rates. Although our predictions were not explicitly compared to other adoption studies, experts have confirmed that they are in line with current European adoption levels of legumes. The lack of comparison is due either to the rarity of such studies in the Mediterranean area and Europe or to other innovation types, such as in the study of Parra-López et al. (2025), where adoption was predicted for digital traceability in the olive sector in Spain. Despite this, ADOPT was and is still used across many agricultural contexts in North America, South Asia, and Oceania with valid predictions (Kenny and Drysdale, 2019; Natcher et al., 2021; Ochieng et al., 2022).

5. Conclusion

Our study found that context-dependent diversification options outperformed continuous cereal systems in agri-environmental and social aspects, but not economically, with notable differences between Spain and Greece. Additionally, we found that stakeholders emphasize economic aspects over social or agri-environmental ones. Furthermore, the predicted adoption levels of diversified systems are low. This demonstrates that social and environmental benefits alone are insufficient to drive adoption when diversification does not bring immediate and sufficient financial gains.

We conclude that involving participatory and iterative approaches was essential for bridging the gap between scientific knowledge and on-farm reality, particularly in the context of crop diversification. Diversification's impact can only be understood through scientific knowledge (ex-ante assessment), especially when the proposed diversified systems are not yet widely practiced. Local knowledge is brought up by the stakeholders when designing diversified systems that are context-specific and are aligned with the economic, social, and environmental dynamics of each region. This co-creation of knowledge is essential for supporting farmers, researchers, advisers, policy makers, and other actors in their quest to make informed decisions on crop diversification.

CRediT authorship contribution statement

Ferdaous Rezgui: conceptualization, methodology, formal analysis, validation, writing-original draft, investigation and visualization. **Louise Blanc:** validation, investigation, writing-review and editing. **Daniel Plaza-Bonilla:** validation, investigation, writing-review and editing. **Jorge Lampurlanés:** validation, investigation, writing-review and editing. **Christos Dordas:** validation, investigation, writing-review and editing. **Paschalis Papakaloudis:** validation, investigation, writing-review and editing. **Andreas Michalitsis:** validation, investigation, writing-review and editing. **Fatima Lambarraa-Lehnhardt:** conceptualization, validation, writing- review and editing and supervision. **Laure Hossard:** conceptualization, methodology and writing-review and editing. **Sonoko D. Bellingrath-Kimura:** supervision and writing-review and editing. **Carsten Paul:** validation, supervision, and writing-review and editing. **Moritz Reckling:** conceptualizing, validation, resources, writing-review and editing, supervision, funding acquisition.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2026.128000.

Data availability

Data will be made available on request.

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