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Co-design of diversified cropping systems in the Mediterranean area

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Abstract

Agriculture today faces opposing challenges: reducing its environmental impacts while feeding a growing population and adapting to climate change. Diversification of cropping systems has been proposed as a solution to address these issues and promote sustainable and resilient agricultural systems. While alternatives have been proposed by research and development, changing the agricultural systems remains a huge challenge. Engaging local actors when considering those changes is important for their successful implementation. While co-designing with stakeholders is gaining interest in the scientific community, approaches that consider varying local contexts remain uncommon. In this study, our aim was to co-design, during workshops with local stakeholders, diversification options in five case studies located in the Mediterranean countries of Algeria, France, Greece, and Spain. Prior to the co-design process, we conducted a SWOT/PESTLE analysis in each case study to analyze the local context of current and potential agricultural systems. Our hypothesis was that co-designed systems would differ between case studies, according to their environmental, social and political contexts leading to fine-tuned locally *ad hoc* systems. Options for intercropping and diversifying rotations were considered for both cereal-based systems and vine systems. Additionally, these options included adapted management practices for cereal-based systems and more innovative diversification, such as photovoltaic panels or agroforestry, for vine systems. While some of these options could serve as adaptations to climate change, they may not be sufficient to address future climate conditions. Interestingly, we did not observe significant differences among the system options designed for the various case studies, even though the local contexts were very different. Indeed, options only partially addressed the issues identified by stakeholders: primarily, economic and environmental threats. This study points to the advantage of participatory research in diverse contexts along with cross-case analyses, and to the need to consider the future of these Mediterranean regions, where crop diversification is limited by water deficit. To foster the transition next steps should consider assessing experimentally these systems with farmers to stimulate learning, while considering market possibilities.

Keywords

Participatory workshop; SWOT analysis; Vines; Cereals; Legumes; Semi-arid climate

Highlights

We combined SWOT analysis and co-design workshops to study diversification options

The approach was applied in five case studies in the Mediterranean basin

Intercropping was seen as the most promising solution in most case studies

New cereal-based rotations included legume species, or rapeseed

New systems provided a partial response to local environmental and economic threats

1. Introduction

Agricultural systems today are facing significant challenges, including the need to reduce the pollution and biodiversity loss caused by intensive conventional practices (Foley et al., 2011; Maxwell et al., 2016). They also need to adapt to climate change (Challinor et al., 2014) and navigate the increased volatility in input and product pricing caused by shocks such as the transport and logistic issues suffered during the Covid-19 crisis (Andrieu et al., 2021) and the war in Ukraine (Bentley et al., 2022). At the same time, there is a pressing need to increase agricultural production to meet the supply demands of a growing population and ensure access to a balanced diet (Ericksen et al., 2009) when food security is being threatened by climate change (Wheeler and Von Braun, 2013). Diversification has been suggested as a solution to face these issues and promote sustainable and resilient agricultural and cropping systems (Peoples et al., 2019; Reckling et al., 2023). Key for agroecology transition, diversification can be applied at different levels, from plot to farm to landscape (Wezel et al., 2020). At plot level, cropping systems can be diversified by increasing the number and diversity of cultivars and crops in the rotation (Wezel et al., 2014). At farm level, diversification can involve both the diversity of products, including livestock production, and the diversity of activity both on- and off-farm, all of which can improve economic diversification (Wezel et al., 2020). At the agricultural landscape level, diversification also involves the integration of semi-natural landscape elements, together with diversified crop mosaics (Wezel et al., 2014). Diversification options have been identified (e.g., legumes in Simon-Miquel et al., 2023 and Plaza-Bonilla et al., 2017 for Mediterranean and temperate situations; species mixtures in McAlvay et al., 2022). However, changing the agricultural systems remains a difficult challenge, in part because it can require changes at other levels in the food chain, leading to socio-technical lock-ins that limit crop diversification. For the French case, Meynard et al. (2018) showed that main obstacles were interconnected and occurred at each stage of the value chain, e.g., lack of improved variety and plant production methods, lack of information on rotations and complex new knowledge for farmers, difficulties of coordination between actors. For legumes, Magrini et al. (2016) highlighted interrelated factors that have favored cereals when compared to legumes (e.g., breeding for new varieties, public subsidies).

Agriculture in the Mediterranean is particularly vulnerable to the impacts of climate change (Giorgi and Lionello, 2008), and is experiencing a progressive shift towards drier conditions (Mariotti et al., 2015). This shift is accompanied by significantly reduced precipitation throughout the region and in all seasons (Dubrovský et al., 2014). Questions are thus emerging about the capacity of current Mediterranean agricultural systems to face these impacts and adapt to new climate conditions. Historically, typical crops in the Mediterranean area have been cereals, olives, and wine grapes, crops which are thus very important to the local economies. Climate change impacts on vineyard yields at different sites in southern France have been estimated by models (e.g., Naulleau et al., 2022), and comparisons to past dry years have been provided by various stakeholders (e.g., Lereboullet et al., 2014) suggesting a potential yield loss of 7-14% by 2100 in those areas if no adaptation is made. Lionello et al. (2014) estimated higher potential yield losses (20 to 26%) by 2050 for irrigated vineyard systems in a southern Italian region (Apulia). Those estimates were larger than the potential loss for olives (8 to 19%) and wheat (1 to 4%) for the same time horizon and Italian location. At the scale of the Mediterranean region, Saadi et al. (2015) also estimated relatively low (8%) decrease in wheat yield under irrigated conditions; this decrease would reach 41% under a moderate deficit in irrigation, and up to 95% under rainfed conditions in southern and eastern regions if no other adaptation was made. Those impacts show it is crucial to study adaptations that could mitigate the threat. While irrigation, and its continuous improvement, is seen as the first line of defense for climate change adaptation in vineyards (Naulleau et al., 2021) and field crops (Marcos-Garcia et al., 2023), other approaches have been suggested. For vineyards, adaptations of plant material (e.g., variety choice), canopy and soil management, and vineyard design have been proposed in numerous studies, but adapting farm strategy (e.g., diversifying) has experienced less attention (Naulleau et al., 2021). For cereals, apart from irrigation, plant breeding for better adaptation to changes (Lopes et al., 2015) and genetic engineering for drought resistance (Wang et al., 2003) are also proposed, as well as cultivation timing and water-conserving soil management practices (Olesen et al., 2011). Changing crop species is also proposed as an adaptation, moving from crops with large inter-annual yield variability to crops with more stable yields but lower productivity (Olesen et al., 2011).

Nevertheless, many of these adaptations remain theoretical because farmers and other local stakeholders are mainly not implied in their design process, so they do not consider, test, and exploit them. One answer is to involve those actors to co-design, in workshops, new alternative systems that could help them confront their current and future issues (Jeuffroy et al., 2022). Such approaches have gained interest in the scientific community and have been applied to diverse objectives. For example they have been employed for designing arable systems with limited greenhouse gas emissions (Colnenne-David et al., 2017), for reducing pesticide use (Reau et al., 2012), for increasing fertilizer autonomy (Guillier et al., 2020), and for weed management (Queyrel et al., 2023).

In the realm of diversification, co-design approaches, relying mainly on workshops, have been used to help stakeholders consider how to use intercrops in the rotation (Salembier et al., 2023), or change rotations to introduce legume species (Notz et al., 2023; Pelzer et al., 2020), or choose specific crops (e.g., camelina in Leclère et al., 2021). Most of these studies were only conducted on one specific site, making it impossible to compare results of the co-designed options among sites and pedoclimatic contexts. In addition, they focused on only one diversification option for arable systems, thus limiting the extent of stakeholder involvement in the co-designed system. Lastly, while diagnosis is always the first step of design approach, in many studies it is limited to agronomy (sometimes including the environment), leaving most social and economic aspects out of the investigation's scope.

In this study, we aimed at co-designing, in participatory workshops, diversification options in collaboration with stakeholders from a variety of situations in different regional environments. These collaborations involved five case studies in both Northern and Southern countries of the Mediterranean region with a specific focus on two key systems of this region: vineyards and winter cereals. Drawing from a collection of existing methods, we developed a straightforward method for co-designing diversified systems. To provide clarity for a comprehensive context, we conducted a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of the current systems. Note that context is rarely considered in depth in co-design studies, where it is often limited to the technical characterization of agricultural systems (e.g., Hossard et al., 2022; Pelzer et al., 2020), which can restrict the construction of a holistic, shared diagnosis by stakeholders. Using insights gained from SWOT analysis, we engaged stakeholders in the process of co-designing alternative systems. This work addresses how far the participatory definition of local context issues orientates the co-designed alternative systems. Our main hypothesis was that co-designed systems would differ between case studies, according to their environmental, social and political (current and expected) contexts leading to fine-tuned locally *ad hoc* systems, considered as the expected outcome of this study.

2. Material and Methods

2.1. Methods overview

In each case study, the process of designing diversified systems was performed in three steps (Figure 1): diagnosis of local agricultural systems, SWOT analysis, and co-design of diversification options. The first step involved gathering secondary data from regional statistics, surveys (ad hoc or already available), and expertise. The second and third steps were carried out in a participatory workshop in each case study, lasting approximately 4 hours. In each case study, the workshops involved diverse groups of local stakeholders, including farmers, representatives from extension services, regional administration services, irrigation water managing companies, a seed producing company (one case study), dealers, and researchers (both external and internal to the project) (Table 1). Stakeholders were selected based on their expertise in agricultural systems, current issues, and ability to envision and/or advocate for innovative solutions.

	Objective	Method
Step 1	Diagnosis (farm typology)	Surveys of actors and farmers; data analysis
Step 2	SWOT analysis	Workshop; Lab work
Step 3	Co-design diversification options	Workshop

Figure 1. Overview of the overall approach in 3 main steps.

Table 1. Participants in case study's workshops (CER: Cereal-based system; VIN: Vineyard system).

Country	Algeria	France	Greece	Spain
System	CER	VIN	CER & VIN	CER
Farmers*	7	1	2	4
Extension services**	-	2	-	-
Private consultant/dealer	1	-	-	1
Seed producing company	-	-	1	-
Regional administration	7	-	-	1
Irrigation water management company	1	-	-	1
Agricultural engineering students	2	2	2***	2
Researchers (external)	2	4	1	1
Researchers (internal)	3	4	4	3
TOTAL	19	13	10	13

*Some farmers have two roles (i.e., farmer and working in regional administrations or as researchers); **Both public and private; *** refers to the participation of two students, future farmers who are also sons of farmers.

2.2. Case studies

The approach was applied on five case studies, located in four Mediterranean countries: Algeria (region of Setif), France (region of Hérault), Greece (region of Thessaloniki), and Spain (region of Ebro valley) (Figure 2). Here, we considered case studies as geographical areas where predominant and alternative cropping systems were defined, and on which stakeholders can take actions. The most representative crops of the regions were investigated: cereal-based systems in Algeria, Greece and Spain, and vineyards in Greece and France (Figure 2). They all exist in a Mediterranean-type climate, characterized by frequent droughts in the summer. They present a gradient of soils and rainfall, which are variable within case studies and between case studies (Table 2).

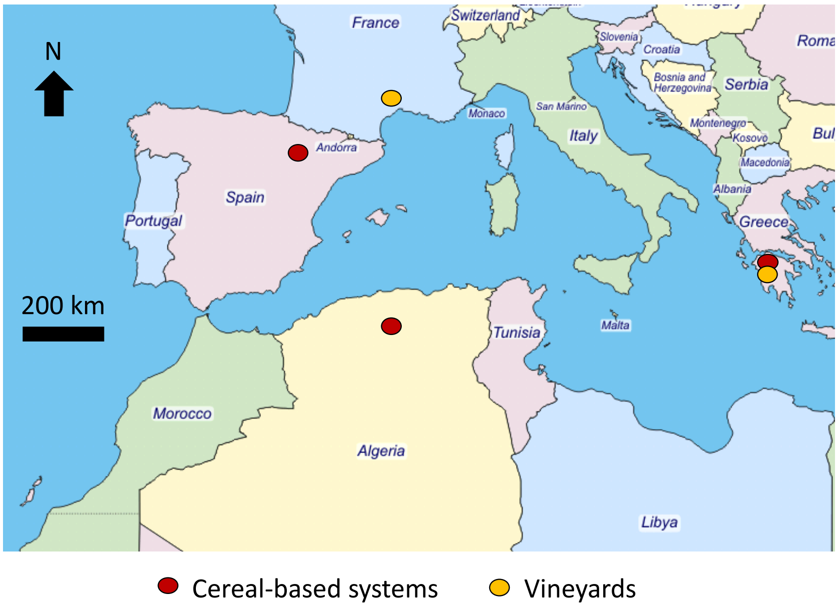

Figure 2. Location of the five case studies.

Table 2. Main characteristics of the case studies in terms of climate, agricultural systems, and soils.

Country	Region	Size (km^2)	Climate			Agricultural systems	Acreages of main crops (km^2)		Soils	References
			Air tempera-ture (°C)	Rainfall ($mm.y^{-1}$)	PET ($mm.y^{-1}$)		Cereals	Vine-yards		
Algeria	Setif	6 504	15 vs 11 (North, South)	450 vs. 250 (North, South)	775	Cereals and livestock	1 570	-	Clay to clay loam Deep vs. shallow (North, South)	Benniou and Brinis, 2006; Bouregaa, 2023; InfoClimat, 2022
France	Hérault	6 100	14-15	600-650	990	Vineyards	-	790	Deep, alluvial soils on plains Shallow to middle depth, shale or clay-limestone in foothills	ADEME, 2011; DRAAF Occitanie, 2022; Naulleau et al., 2022; Observatoire viticole, 2014
Greece	Thessaloniki	39 000	16	400	920	Cereals and vineyards	13 600	1 300	Loam Medium to deep soil	Antonopoulos and Antonopoulos, 2017; Papastylianou et al., 2021
Spain	Ebro valley	85 500	13-16	300-450 vs. 800 (central, mountaino us areas)	1 000	Mainly cereals in the rainfed areas and livestock	14 900	-	Calcareous, with fine-grained sediments Medium soil depth	Badía et al., 2011; Cuadrat, 1999; ESYRCE, 2020; Herrero and Snyder, 1997

PET: Potential evapotranspiration

2.3. Diagnosis of current agricultural and cropping systems

The objective of this step was to analyze the current cropping and farming systems, identify the main systems and select the ones to be included in the co-design step. Methods for the diagnosis differed among the case studies and depended on certain conditions: (1) availability of secondary data and/or national statistics, and (2) accessibility to farmers and other stakeholders (this part of the work was performed during the lock-downs due to the Covid-19 crisis).

For the Algerian and French case studies, previous farm typologies were mobilized to characterize the current agricultural systems. In Algeria, we used a diagnosis of the Setif area performed in 2014 and actualized in 2018 (Benniou et al., 2014; Lupinko, 2018). In France, we used a diagnosis of a watershed (45 km^2, 1,200 ha of grapevines) located north of the town of Beziers, where 26 winegrowers were surveyed to build a farm typology leading to four main farm types (Hossard et al., 2022).

For the Greek and Spanish case studies, data from national statistics and expert knowledge were used to identify the main agricultural systems for SWOT analysis and co-design. We should note that the definition of main cropping systems (the main rotation/crop for locally predominant farm types) was presented, discussed, and updated, when necessary, all with stakeholder participation in the first step of the co-design workshop.

2.4. SWOT construction and analysis

To analyze the context and the internal and external forces driving the agricultural systems in each case study, we built a SWOT matrix in collaboration with local stakeholders. The SWOT was built on a unique cropping system in France and on different types of agricultural systems in Algeria, Spain, and Greece. In Greece, a general SWOT was built on the regional agriculture and then specifically adjusted for vineyard or cereal-based systems. For the sake of clarity, we only present the SWOT elements related to the cropping systems for which diversified alternatives were co-designed.

The SWOT approach facilitates the strategic analysis through a comprehensive diagnosis of the entire system, including external and internal factors, and leads to the development of the SWOT matrix. This matrix provides an overview of the opportunities and threats presented by the internal and external environment of the system (Lambarraa-Lehnhardt and Lmouden, 2022; Nazari et al., 2018). This list of factors can be used to describe the current (corresponding to the SW sections of the framework) and possibly future (OT) trends of both internal and external environments participating in the shape and content of the studied system (Yavuz and Baycan, 2013). The SWOT analysis thus allowed us to conduct a situational evaluation (Wickramasinghe and Takano, 2009)

Based on the presentation and discussion of the main agricultural systems, a SWOT was built during the workshop with all stakeholders (Table 1). The identification of the elements of the four quadrants was first realized by each participant individually for all case studies except Spain, where it was directly performed by groups of two or three stakeholders. In all case studies except Spain, this individual work was followed by small, one-to-one discussion groups which produced an internal, initial ranking of all elements. In all case studies, the elements were combined in a common SWOT matrix, which was then collectively discussed.

After the workshops, all factors from the SWOT matrixes were analyzed using the PESTLE framework (Srdjevic et al., 2012) to highlight the main themes that were spotted in each case study, with the objective of comparing the situations in the different case studies. PESTLE considers Political, Economic, Social, Technological, Legal, and Environmental classes to categorize sets of factors and facilitate their analysis and comparison. Note that a unique factor could correspond to more than one element of the PESTLE framework. To facilitate the comparison and analysis of the diversity of factors (Supp Mat 1A), we inductively built a classification according to their main themes. 13 specific themes (i.e., specific to one PESTLE class) were identified: Infrastructures and Political choices (for Political factors); Credit, Diversification of activities, Investment, Market, Productivity and Financial resources (for Economic factors); Social resources (for Social factors); Technological resources (for Technological resources); Regulations (for Legal resources); Climate change and Environmental resources (for Environmental factors). Themes, crossing PESTLE classes, concerned: Collective organization (Economic, Social, and/or Technological), Infrastructures (Political and Technological), Investments (Economic and Technological), Labor (Economic, Social, and/or Technological), Resources (Economic, Social, Technological, and/or Environmental), and Subsidies (Economic and Legal). The PESTLE framework has been used in the business and management sectors to monitor the macro-environmental factors that have an impact on the studied system environment (Widya Yudha et al., 2018).

2.5. Co-design of diversified systems

The co-design of diversified systems was conducted with local stakeholders after building the SWOT matrix. While project researchers encouraged stakeholders to link the new systems co-designed with the different part of the SWOT (e.g., reducing a weakness, facing a threat), this was often not explicitly done. Those links were reframed by the research team when analyzing the results of the workshops. The co-designing took place in two steps. First, each participant was asked to propose diversification options that he/she had tested him/herself (successfully or not) or heard/thought about. Second, there was a collective discussion where some of the previously cited options were selected to construct a minimum of three alternative systems. The discussion was organized as follows. First, the researchers recalled the different options cited. Second, stakeholders were asked to choose the ones they evaluated as the most promising, either alone or in combination. For each of these choices, stakeholders were asked for details of the system, e.g., crop sequence composition for cereal-based systems, and if this system would be imaginable for all or specific farm types. The level of detail (i.e., how far the system was described in terms of its management practices, e.g., tillage, fertilization, sowing) of each system varied among case studies, depending on the participants and their proposals.

Diversification options were analyzed according to the intensity of changes they involve. Intensity was assessed according to the Efficiency-Substitution-Redesign framework of Hill and MacRae (1996). We considered that alternative systems would be classified in the "efficiency" class if they were limited to resources optimization (e.g., light), in the "substitution" class if they did not change the overall crop management (e.g., replacing one crop by another, in case of "similar" crop, i.e., replacing a cereal by another), and in the "redesign" class if they significantly changed management (e.g., introducing new crops with other management (e.g., legumes, forage crops), extending crop sequences for cereal-based systems, replacing wines by other crops for vineyard system).

3. Results

3.1. Description of the current agricultural systems

For cereal-based systems, the reference rotation was a 2-year rotation of winter wheat (*Triticum durum* in Algeria and Greece, *Triticum aestivum* in Spain)-winter barley (*Hordeum vulgare* L), in the three case studies (Algeria, Greece, and Spain). Therefore, the main crops were a unique botanical family (*Poaceae)*, cultivated for grain production. These crops were mostly rainfed, with supplementary irrigation if needed and available—which might not be the case every year—in Spain and for one farm type in Algeria that was located in the driest area.

In Algeria, this 2-year rotation was typical for two out of the three farm types: mixed farms with ovine and bovine livestock, located in dry areas (250 mm rainfall per year); and mixed farms with only ovine livestock, located in wetter areas (417 mm rainfall per year). Stakeholders decided to focus on those two farm types because they are the most at risk due to their size (small and medium farms, 5 to 10 ha). The third farm type involves larger areas (50 ha), a larger workforce and more capital.

In Spain, the 2-year rotation was predominant in areas receiving about 300-400 mm of rainfall and having 900-1000 mm potential evapotranspiration per year. This rotation is typical for mixed farms with swine production that requires land for slurry management. These farms use intensive tillage practices, mineral nitrogen fertilization, and irrigation if possible (water is often unavailable during summers). This was one of the systems and farm types chosen by stakeholders for co-design.

In Greece, the 2-year rotation was predominant in cereal-based farms with dry conditions. The farmers used conventional tillage and both crops were sown during autumn as winter crops. The system was based on using fertilizers with N and P, and herbicides. Normally the farmers did not use other pesticides because pest damages did not significantly reduce grain yield.

For vineyard systems in the two case studies (France and Greece), the reference was cultivating vines only, using tillage (and some herbicides) in the rows to reduce weed pressure, leading to bare soil most of the time. Typical vineyards were in areas subject to low rainfall averages: 600 mm per year in the French case and 450 mm in the Greek study. In France, this system was typical of farms selling their product to cooperative wineries, employing relatively intensive practices to obtain yields close to the maximum authorized by their label (Protected Geographic Information in particular) (Naulleau et al., 2022). This farm type was predominant (65% of cultivated areas) in the region, mostly rainfed (Hossard et al., 2022). Stakeholders drew on this farm type for designing diversification options. In Greece, the farms were rainfed. Some of them were situated on marginal soils and in hilly areas.

3.2. SWOT analyses

Overall, the profiles of the SWOT analyses differed among the case studies and types of production (Figure 3). However, all the profiles ranked economic factors first when considering factors for the entire SWOT matrix. The economic factors were particularly predominant in the French vineyard case study, where they represented half of the total factors. For the two Greek case studies, social and technological factors were almost as numerous as the economic ones. For Algeria, environmental factors were as numerous as the economic ones. For Spain, the number of social, and technological factors was close to the economic one.

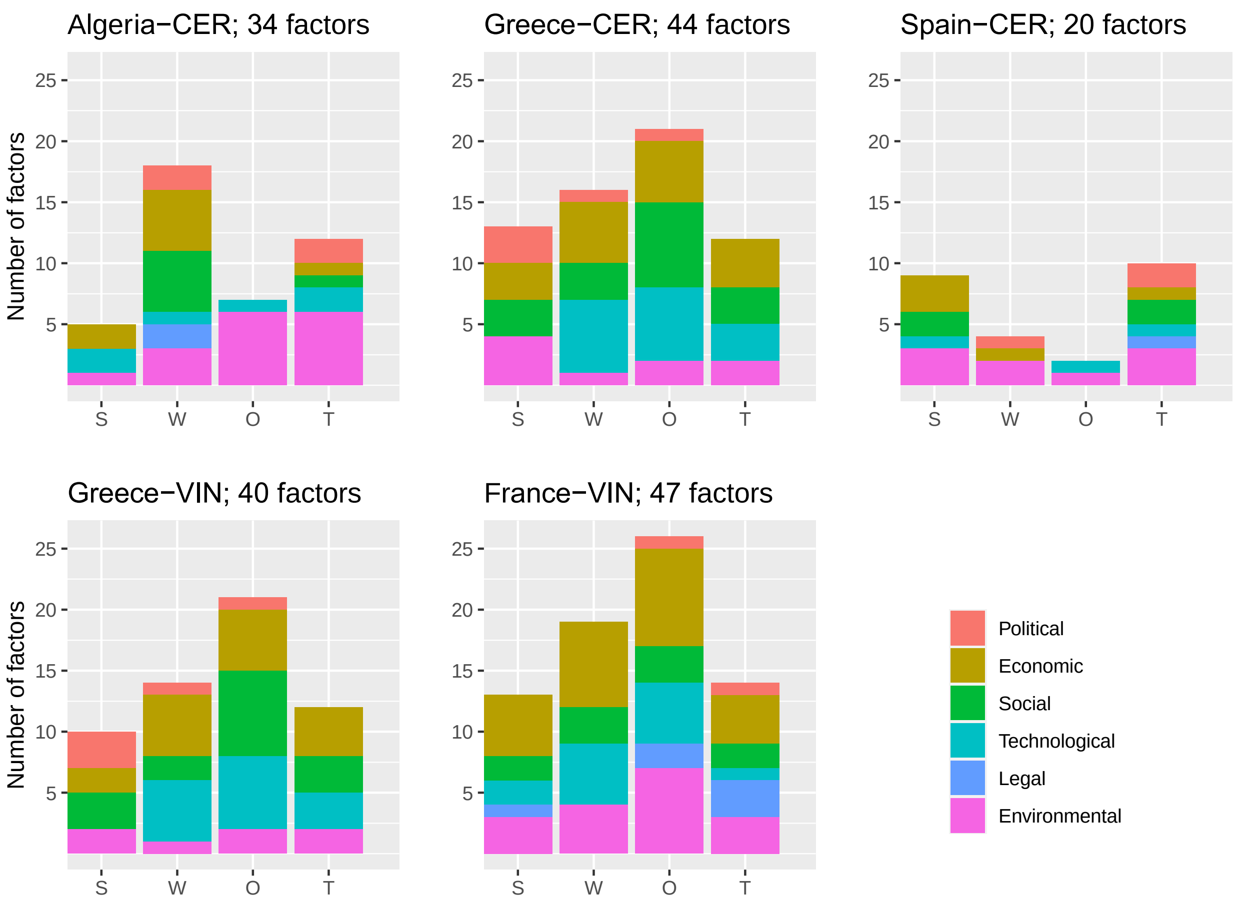

Figure 3. Number of factors for the SWOT/PESTLE analysis for the five case studies. The total number of SWOT factors is indicated in the title of each case study; note that a unique SWOT factor could belong to more than one class of PESTLE. The scores were obtained by counting the number of elements in each PESTLE class, according to the different SWOT classes. SWOT: Strengths, Weaknesses, Opportunities and Threats; CER: Cereal-based system; VIN: Vineyard-based system.

Cereal-based systems

For cereal-based systems, local stakeholders in Greece expressed greater optimism regarding the considered agriculture compared to stakeholders in Spain or Algeria. In Greece, strengths and opportunities accounted for 56% of the total, whereas in Spain and Algeria, they represented only 40% and 33% respectively.

In Algeria, main strengths were related to economic and technological factors. But in Greece, the strengths were environmental, political, economic, and social, and in Spain they were mainly economic and environmental (Figure 3). While most categories of strengths were specific to one case study (Supp Mat 1B), some were common to the three case studies (Table 3). They addressed strengths (1) on infrastructures, resulting from political choices and allowing technological development, e.g., agri-food companies or capacities for seed storage or commercialization, and (2) on resources, either economic (e.g., high quality product for domestic market), social (well-educated agricultural population), technological (e.g., organic fertilizers), or environmental (e.g., livestock integration, natural resources richness).

Opportunities in Algeria predominantly revolved around environmental aspects, particularly the potential to grow new crops, improve yield and quality, and ultimately improve food (grain) and feed (forage) quality through diversification. For Greek cereal-based systems, opportunities were economic, social, and technological. Economic opportunities were linked to the region’s dynamic nature, characterized by new investments, emerging companies, and a growing tourism sector. Social opportunities were related to increasing skills associated with training, the arrival of a younger generation, and the emergence of cooperation networks in rural areas.

Technological opportunities were related to the development of agri-food technology and training opportunities for agricultural technologies. Little opportunity was identified in Spain, except for the opportunity of diversifying cropping systems, which seems to be linked with its strong water deficit. Opportunities common to the three case studies focused on economic, social, and environmental resources (Table 3). Interestingly, we can observe some correlation between opportunity levels claimed by local stakeholders, and water deficit, where foreseen opportunities decline as the local climate becomes drier.

In terms of weaknesses, most of the factors were related to economic and social issues in Algeria, economic and technological concerns in Greece, and economic and environmental factors in Spain. Although most categories of weaknesses were case-study specific (Supp Mat 1B), common ones related to labor and market (case studies in Algeria and Spain), and to resources (all three case studies). The labor category concerned both economic and social weaknesses, and were based on the difficulty for young people to pursue a farming career (Spain), or the difficulty to find workers for diversification species (i.e., market gardening in Algeria). For market (all economic factors), weaknesses addressed production costs (Spain) or the state-guaranteed price of wheat (Algeria). Resources included economic (e.g., small and fragmented farms in Algeria and Greece), social (e.g., lack of knowledge on production techniques in Algeria, low entrepreneurial skills in Greece), technological (e.g., missing information on soil and crop in Algeria, weak technology transfer in Greece), and environmental (e.g., exposure to pests and diseases in Spain, water issues in Algeria) weaknesses (Table 3).

In terms of principal threats, Algerian stakeholders identified the environment, economics, and technology. In Greece they identified economic, social, and technological threats, and in Spain they were environmental and legal. Most threats concerned categories of factors common to two or the three case studies. Common threats to the Algerian and Spanish case studies related to climate change (environmental issue), political choices in political, economic and legal categories (e.g., orientation of subsidies in Algeria, controls and standards in Spain), and regulations (i.e., legal factors concerning nitrogen fertilization regulation in Spain, the instability of regulations in Algeria). Two categories were common to the three case studies: market (all economic factors), and resources (social, technological and environmental factors). Market threats concerned the volatility of prices (Spain), high input prices in Algeria, and the current global crisis in Greece.

Table 3. Common themes for the cereal case studies resulting from the SWOT analysis. P: Political, Ec: Economic, S: Social, T: Technological, L: Legal, En: Environmental, nb: number of occurrences in each case study; DZ: Algeria; ES: Spain; GR: Greece.

Theme	P	Ec	S	T	L	En	Case studies (nb)	Exemples of factor
Strengths								
Infrastructures	3			2			DZ (1); ES (1); GR (3)	Infrastructures for commercialization, seed storage, well developed facilities
Resources		3	4	1		7	DZ (2); ES (3); GR (7)	Livestock integration, resilient systems, rich natural resources, well-educated agricultural population
Weaknesses								
Labor		2	2				DZ (1); ES (1)	Difficult for young farmers to take over farms, labor availability issues especially in case of diversification with market gardening
Market		3					DZ (2); ES (1)	Very large price (set by the State) of some species, production costs
Resources		3	2	4		4	DZ (5); ES (2); GR (5)	High exposure to pest and diseases due to low diversity of species, difficulties due to small farm size and low level of knowledge on production techniques, water availability issues, weak technology transfer, young generation not interested by agriculture
Opportunities								
Resources			4	5		6	DZ (5); ES (1); GR (4)	Enhance the nutritional value for the livestock, preserve natural resources, young generation highly skilled in information technology, water saving thanks to new crops
Threats								
Climate change						2	DZ (1); ES (1)	Impact of climate change on crops
Market		3					DZ (1); ES (1); GR (1)	Economic pressure from debt and volatile market prices, recession, high prices of inputs
Political choice	2	1			1		DZ (1); ES (1)	Controls and standards decided by states and European Union, orientation of subsidies to specific crop
Regulations					2		DZ (1); ES (1)	Nitrogen regulation, instability of regulations
Resources			4	5		9	DZ (6); ES (3); GR (4)	High age of farmers, herbicide resistance, pressure on biodiversity, loss of farm autonomy

Vineyard systems

Both the French and the Greek case studies considered more strengths and opportunities than weaknesses and threats (51% and 55% positive factors in France and Greece, respectively; Figure 3). According to the stakeholders, the vineyard system presented mainly economic strengths in France, and political, economic, social and environmental strengths in Greece. Most categories of strengths were specific to one case study (Supp Mat 1C). Common categories related to market (economic factors), and resources (economic, social technological, and environmental factors) (Table 4). Market strengths related to marketing through labels and the type of container (France), and to the dynamism of agro-food companies (Greece). Resources involved soil quality, diversity of varieties, and willingness to act in France, and appropriate climate and educated agricultural population in Greece.

Stakeholders identified mainly economic, social and environmental opportunities in the French case study, whereas Greek stakeholders noted technological and environmental opportunities as well as the economic ones. Common opportunities related to Collective organization (economic, social and technological factors), Market (economic factors), and Resources (economic, social, technological and environmental) categories (Table 4). Opportunities for collective organization related to the possibility for farmers to move to more dynamic cooperatives (France), and to improved cooperation networks (Greece). All market opportunities were related to the different labels (organic, Protected) in the two case studies. Opportunities in the Resources' category included changing practices towards lower pesticide uses (e.g., resistant varieties, biocontrol, decision making tools) in France, and to the increasing skills, especially for young people, in communication, technology and innovation in Greece.

Most of the weaknesses identified in both vineyard case studies were economic and technological. They related to the categories Labor (economic, social and technological factors), Market (economic factors), and Resources (economic, social, technological and environmental factors). Labor weakness concerned the too large area per worker in France (constituting also a social weakness), and the low research capacity of agro-food companies in Greece (impacting technological innovation). Market weaknesses concerned the strength on label, but with another angle, i.e., the dominance of a specific label could expose farmers (France); in Greece it concerned the type of targeted markets, i.e., the domestic market, which was fragilized with the recession. Weaknesses belonging to the Resources category concerned the high pesticide use, with low alternatives in France, and the low entrepreneurial skills and knowledge of farmers in Greece.

The first threat identified in the two vineyard case studies was economic, followed by legal, social and environmental in France, and social technological, and environmental in Greece. Common threats were related to the Market (economic factors) and Resources (social, technological and environmental factors) categories (Table 4). Market threats concerned the increasing label requirements and the difficulty to build a market for resistant wine varieties (i.e., with a different taste) in France, and the general economic context linked to the recession in Greece. Threats on resources included water management in France, and the risk of pollution and impacts on biodiversity in Greece.

Table 4. Common themes for the vineyard case studies resulting from the SWOT analysis. P: Political, Ec: Economic, S: Social, T: Technological, L: Legal, En: Environmental, nb: number of occurrences in each case study; FR: France; GR: Greece.

Theme	P	Ec	S	T	L	En	Case studies (nb)	Exemples of factor
Strengths								
Market		4					FR (3); GR (1)	Labels, bulk sales, small agro-food companies but flexible and dynamic
Resources		1	5	1		5	FR (4); GR (5)	Soil quality, diversity of varieties, willingness to act, appropriate climate, well-educated agricultural population
Weaknesses								
Labor		2	1	1			FR (1); GR (1)	Too large farm area per worker, low proportion of research personnel in agro-food companies
Market		3					FR (2); GR (1)	Labels, bulk sales, traditional products for domestic market
Resources		2	2	8		4	FR (6); GR (5)	Soil types, high pesticide use with few alternatives, low entrepreneurial skills and low knowledge about innovation, young generation not interested by agriculture
Opportunities								
Collective organization		1	4	2			FR (2); GR (2)	Move to dynamic winery, improved cooperation networks in rural areas
Market		6					FR (5); GR (1)	Labels and their associated market dynamics
Resources		2	5	9		6	FR (7); GR (5)	Changing practices for lower pesticide use (biocontrol, resistant varieties, tool), young generation highly skilled in information technology, increasingly rapid development of agro-food technology
Threats								
Market		5					FR (4); GR (1)	Increasing label requirements, economy seriously affected by the economic and debt crisis
Resources			3	3		4	FR (3); GR (4)	Water management (competition with other uses), risk of increasing environmental pollution due to the increase in tourism and agriculture activities, pressure on biodiversity

3.3. Cropping system diversification options

All options for diversification designed by the local stakeholders focused on plot scale, and some of them could have implications at the farm scale (e.g., if it involved changing work organization because of a different crop calendar, or required new machines, extra-labor, or integrated organic sources from livestock production). Most diversification options were related to substitution strategy and redesign (Table 5).

For the vineyard case studies, most options related to the management of the inter-rows and to a lesser extent the management of the vines themselves. Of the eight options designed, three were common to both case studies: animal grazing (substitution option if livestock is not owned by the winegrower); cover-cropping with sown varieties (substitution) of *Poaceae* such as barley (*Hordeum vulgare* L.) or triticale (*Triticosecale* Wittm.) or legumes such as pea (*Pisum sativum* L.) or faba bean (*Vicia faba* L.) for the inter-row management; and changing vine varieties (more local varieties in Greece, more resistant or juice varieties in France) (redesign). Note that changing varieties would have implications at the farm scale, possibly affecting the work calendar and wine composition. Two options were designed only by the Greek stakeholders: cover cropping with spontaneous vegetation in the inter-row (substitution) and cropping in the inter-row with aromatic or medicinal plants (redesign). The three options designed uniquely by French stakeholders involved technological development with the installation of photovoltaic panels above the vines (efficiency), tree planting as in agroforestry systems (redesign), and developing other crops such as those for market gardening, aromatic and medicinal plants, or cereals (redesign), although feasibility depended on water availability.

Table 5. Initial systems and co-designed type of diversification for the five case studies

Case study	Initial system	Type of diversification	Other changes	ESR
Algeria-CER	2-year rotation	Replacing 1 crop in the rotation	NA	S/R*
		3-year rotation by adding 1 and/or replacing barley by another crop		R
		Intercropping (1 species)		S
Greece-CER	2-year rotation	2-year rotation by adding 1 new crop in the rotation	Tillage, fertilization	R
		Intercropping (several species)		S
Spain-CER	2-year rotation	4-year rotation by adding 1 and/or replacing barley by another crop	Tillage, fertilization, crop protection	R
Greece-VIN	Vines only	Cover cropping (spontaneous)	NA	S
		Cover cropping (sowing, several species)		S
		Cropping in the inter-rows		R
		Animal grazing in the inter-rows		S
		Changing grape varieties (local)		R
France-VIN	Vines only	Tree planting	NA	R
		Animal grazing in the inter-rows		S
		Changing grape varieties (resistant or juice)		R
		Cover cropping (sowing, several species)		S
		Changing to other crops (several species)		R
		Photovoltaic production		E

CER: cereal-based system, VIN: vineyard system, NA: no information, ESR: Efficiency-Substitution-Redesign framework; E: Efficiency; S: Substitution; R: Redesign; * S in case of replacing one cereal by another or R in case of replacing one cereal by a legume

For cereal-based systems, two main options were designed by stakeholders: changing the rotation in the three case studies and intercropping (growing two crops together) in two case studies. Several species were suggested for intercropping, mostly *Poaceae*, legumes (e.g., pea, faba bean) or a mixture of both, in Greece and in Algeria. In Spain, this option was mentioned, but considered unfeasible in terms of water availability. Changes in rotation involved replacing one crop with another crop or crop mixture or extending the rotation by adding one or more crops (Table 6). Two to five alternative rotations were designed by stakeholders, depending on the case study (Table 6), with one (Spain) to four (Algeria) rotations including legumes (pea in all case studies, chickpea in Algeria only, vetch as an intercropping species in Greece only). The introduction of leguminous species in the rotations varied among the case studies: replacing barley in Algeria and Spain, mixed with winter barley in Algeria and Greece. Rapeseed was also an option to change the rotation in Greece and Spain: in Greece, it was introduced between the two main crops (wheat and barley); in Spain, rapeseed replaced barley. Market gardening was designed as replacing winter barley in the Algerian case study, this option was only feasible for the farm type with access to irrigation.

Table 6. Co-designed changes in rotation in the three cereal-based case studies

Case study	Initial rotation*	New rotations*
Algeria-CER	Wheat- barley	Wheat- chickpea
		Wheat- pea- chickpea
		Wheat- barley- pea
		Wheat- barley/ pea intercropping
		Wheat- market gardening
Greece-CER	Wheat- barley	Wheat- rapeseed- barley
		Wheat- pea- barley
		Wheat- barley/common vetch intercropping- barley
Spain-CER	Wheat- barley	Wheat- pea- wheat- barley
		Wheat- rapeseed- wheat- barley

*All rotations include winter-type cultivars only (except for market gardening) for grain production; Durum wheat for Algeria and Greece, Aestivum wheat for Spain.

3.4. Linking SWOT/PESTLE analysis with diversification options

In the Algerian case study, the addition of legumes and reduced N fertilization could enhance the national value of fodder, make better use of water (opportunity), and respond to the threat of increased mineral N and herbicide prices (Supp Mat A1, last column). However, the way to overcome identified weakness regarding the difficulty of finding workers for legumes was not addressed by the stakeholders, neither the high prices of inputs for legumes (identified as a threat). Surprisingly, stakeholders proposed diversifying crop rotations, despite the current political context pushing for wheat. In addition, market gardening, envisioned in Algeria, may be problematic because of the species' water requirements and the lack of workers. Diversifying the rotation could help to increase yield, thanks to the break crop effect.

For Greece (both systems), growing legumes, as well as other diversification options, could take advantage of the rising demand for diversified products and reduce the threat of increasing pollution due to agricultural activities. Rapeseed did not seem to be an appropriate response to any weakness or threat identified by stakeholders. Most other weaknesses were not addressed by the diversification options designed by stakeholders (Supp Mat 1A), which could even worsen some issues.

In the Spanish case study, the option to introduce legumes and oilseeds would diversify the cropping system, address weaknesses of the cereal rotation, and support pest control and herbicide resistance, especially for rapeseed (i.e., there are more active ingredients available). It could also help with nitrogen legislation. Legume introduction coupled with reduced N fertilization at the cropping system scale, along with a shift in N fertilization to mainly pig slurry (instead of synthetic) and reduced tillage, could decrease production costs and help facing the volatile market prices. The feasibility of this system, with regards to possible evolutions of the Nitrogen regulation, was not discussed by stakeholders. In addition, it is unclear how these systems would address other threats (e.g., aging of farmers, difficulty for young to take over farms, land competition).

For the French vineyard case study, intercropping would not help increase yield (production lower than the objectives was seen as a weakness), but it would help to reduce herbicide use (weakness) and thus help adapting to changing pesticide regulations, including a glyphosate ban (threat). This would however require extra work, a topic already identified as a weakness in the current system. Introducing resistant varieties would (partly) solve the weaknesses and threats regarding pesticide uses (which are mainly fungicides), and increasing demands for labelling. One option designed for vineyard systems was livestock grazing, which could reduce the use of herbicide or mechanical weeding in the winter, and promote cooperation among farmers. In the French case study, it could help with the questions regarding herbicide use and legislation. For the Greek case study, it could contribute to a more dynamic image of farm work for young people (weakness of low attractiveness), improve synergy among farmers (opportunity), and at the same time help reduce environmental pollution (threat).

4. Discussion

4.1. Diversified systems to face current and future local challenges?

Although the results of the SWOT/PESTLE analyses indicate that the environmental, social and political contexts mainly differed between case studies, co-designed diversification options were relatively similar. Therefore, our initial hypothesis was not supported. For cereal-based cropping systems, alternatives relied on relatively well-known levers for diversification, namely intercropping (synchronic in Algeria and Greece) and modifying crop rotations. However, those levers may be (relatively) new for stakeholders, especially for farmers who have not tested them yet. Moreover, the fundamental knowledge on the biological objects behind these levers needs to be contextualized to their specific situations (Toffolini et al., 2017), i.e. translated into specific, local ways of doing and effects. In this study, this could have been useful to deepen the analysis of these levers, by providing for instance their agronomic advantages and limits, using indicators, on these specific situations. Indeed, Périnelle et al. (2022) showed that alternative systems may be diverse according to the diversity of farms, even being part of the same region. In our study, co-designing according to (farm-) specific sets of situations and priorities could have led to a larger diversity of options. These two studies (Périnelle et al., 2022; Toffolini et al., 2017) also highlighted that current systems mostly do not mobilize those levers, and that although their fundamental functioning is well known, those options appeared new to the stakeholders, making such co-design studies important to the collective reflections on future, locally adapted, systems.

Crop diversification was seen as an opportunity in all case studies. Environmental benefits of the co-designed options are well known. For instance, intercrops in non-row crops can reduce water erosion (Battany and Grismer, 2000), and if composed of legume species, they can reduce the need for nitrogen fertilization (Bedoussac et al., 2015; Jensen et al., 2020). However, while diversification reduces environmental impacts in long term experiments, it can however result in lower and/or more variable yields (Colnenne-David et al., 2017). Consequently, there is a potential trade-off between yield and environmental preservation, e.g., biodiversity (Kremen and Miles, 2012). For instance, in semi-arid environments, cover crops can compete for water and often reduce yields of subsequent crops (Nielsen and Vigil, 2005). For legumes, Cernay et al. (2015) showed that yields were more variable than non-legumes. These lower productivities could cause issues with regards to food security, unless the production at the cropping system scale would compensate for these losses. Overall, the ecological-economic trade-offs are highly dependent on context, and the short-term costs for farmers could be too high with regards to the longer-term ecological benefits potentially leading to higher and less variable yields (Rosa-Schleich et al., 2019). This outlines the need to assess, locally, the performances of the co-designed systems.

The co-designed options were mostly related to substitution and redesign. Jeuffroy et al. (2022) proposed four axes to analyze workshops and their outputs, including the level of exploration, and the ways creativity is stimulated. In terms of exploration, the type of options co-designed was similar among case studies. However, the number of options, and their level of detail, differed among case studies. This could be linked with the output needed by local researchers for the following step. For example, modelling in the Spanish case study required specific inputs (e.g., details on fertilization, tillage), which is known to limit exploration (e.g., Delmotte et al., 2017). This could be also linked to the local Spanish context, where disruptive diversification strategies might be commercially unfeasible due to lack of market or machinery requirements. For instance, in intercropping for grain production, it might be difficult to have control products authorized for two species at a time that can even differ in their phenological stage. These difficulties could have pushed Spanish stakeholders to focus more on crop management practices. Deeper exploration was performed in vineyard systems, especially in the French case study. This could be related to the larger economic margin (as compared to cereals), which could allow experimenting with less “pragmatic” management options. This could also be related to the relatively large percentage of researchers, whose diverse points of views stimulated exploration (as highlighted by Vourc’h et al., 2018). However, this may have biased the outcomes of the participatory processes, as it prevented us from highlighting ideas, knowledge, and experiences of the primary users of co-designed systems, which is considered key by Groot Koerkamp and Bos (2008). This over-representation of researchers in the two vineyard systems’ case study was not intentional, but due to last minute withdrawal from participation by other types of actors. It could be linked with the existing work relationships between researchers and local stakeholders, which differed between case studies, and are recognized key for successful participatory projects (Ericson, 2006). In terms of stimulating creativity, as identified by Jeuffroy et al. (2022), our choice of study participants was also crucial, and aimed at bringing together open-minded people with different horizons and scales of action. We also stimulated creativity by identifying tacit knowledge behind each alternative and encouraging the group to reflect on this knowledge in order to explore new diversification options. Lastly, disruptive knowledge was shared during workshops hosted by researchers and specific participants. Further knowledge could have been brought by stakeholders, e.g., less water-demanding crops to adapt to climate change (Olesen et al., 2011). However, typical summer crops are unfeasible without irrigation water, and current crops, such as barley, are climate-resilient alternatives and are often cultivated in severe water-stress conditions (UnNisa et al., 2022). Other options could include wheat varietal mixtures aimed at increasing water-use efficiency (Adu-Gyamfi et al., 2015).

4.2. Originalities and limitations of the method and co-designed systems

We did not include olives in the list of main Mediterranean cropping systems. As a perennial crop, diversifying olives orchards could be inspired by options designed for vineyards, although trees provide different specificities (shading, rooting system, harvest periods). In Southern France, De Lange et al. (2023) identified three main types of diversified systems by local farmers: 1) combining olive trees with fruit trees (fig, peach, or apple trees) in the same rows, either by replacing olive trees with fruit trees (new plantation) or by planting fruit trees in-between existing olive trees (existing plantation); 2) cropping in the inter-row (market gardening, medicinal plants); and 3) adding livestock for grazing. Note that the two last options were also designed by local stakeholders as alternative options for vineyard systems.

The SWOT analyses we performed with stakeholders helped to clarify the context in which alternative systems were co-designed, i.e., the baseline situation. Combining SWOT and PESTLE frameworks allowed us to build an understanding on the current realities of all case studies (as highlighted by Nazari et al., 2018). A few studies combined SWOT and PESTLE frameworks on a diversity of topics, e.g., fossil fuel energy industry (Widya Yudha et al., 2018), irrigation water management (Nazari et al., 2018), policy planning (Parra-López et al., 2021) or autonomous vehicles for weed treatments (Tran et al., 2023). As far as we know, this is the first work combining these two frameworks with a participatory design approach. Our objectives, with these two frameworks, was twofold. First, we aimed to build, with stakeholders (mobilizing SWOT only), a comprehensive overview of the context of each case study. Second, we aimed, to compare the contexts between the case studies with the combination of the two frameworks. We reached these two objectives. Among the studies mobilizing SWOT and PESTLE, a few used participatory methods. For instance, Parra-López et al. (2021) identified PESTLE issues in the literature, which was reviewed by six experts (one of each domain); this was followed by the construction of SWOT by focus groups with larger participation, and the common factors were merged. Tran et al. (2023), as we did, divided the SWOT factors according to the PESTLE categories. They built it according to literature, and then discussed it with 10 experts. In addition, Tran et al. (2023) prioritized the factors in further steps. Prioritizing could have been helpful in our study. Indeed, when designing alternative systems, stakeholders rarely referred to elements of the SWOT matrices, even though facilitators tried to encourage it. We hypothesized that combining the analysis of environmental, social and political contexts (i.e., SWOT analysis) and the co-design approach on a unique workshop would be sufficient for stakeholders to design new systems according to their specific, multidimensional context, which appeared to be false. To reach this objective, which can help to codesign *ad hoc*, local systems, one option could be to identify, with the stakeholders, the most important factors (as Tran et al. (2023)), with the risk of losing key information of the whole context. Another option would have been to classify the SWOT factors in the PESTLE with the stakeholders, or with experts, and then have it validated by participants, in another workshop. Given that, in most case studies, participants were not familiar with participatory approach, building SWOT and/or PESTLE on literature, as Parra-López et al. (2021) and Tran et al. (2023), could have lowered their implication. Last, one difficulty that appeared in our study was the difficult distinction between internal (S-strengths and W-weaknesses) and external (O-opportunities and T-threats) of the SWOT analysis. In some cases, stakeholders analyzed factors as current (O and W) and future (O-T) factors (Supp Mat

1A). This difficulty could have been overcome by an extensive review of all factors, with stakeholders, after a verification by the researchers. Those limitations would advocate longer participatory process, involving more than a unique workshop. Another limitation of the results of our study concerns potential biases linked to participants, particularly their limited number in almost all case studies, as well as their limited diversity, although those characteristics are common in design workshops (e.g., Jeuffroy et al., 2022).

One original aspect of our approach was to include SWOT analyses in the co-design process as a baseline, placing the agricultural systems in their wider environment. On the first hand, Notz et al. (2023) applied the DEED method (Describe, Explain, Explore, Design developed by Giller et al., 2011) to co-design and assess diversification of arable crops with legumes. The diagnosis phase (construction of the baseline)) of their approach focused on determining the current challenges faced by agricultural systems, which could be described as weaknesses (e.g., high dependence on mineral fertilizers, high fertilizer use) in the SWOT analysis. The DEED approach allows loops (Falconnier et al., 2017), which were not applied in Notz et al. (2023) who indicate that they continue to work on their case study to foster learning. The work should also continue for our study. Indeed, as noted by Notz et al. (2023), participatory redesign can support the transition and should be part of “a process of close stakeholders interactions” (Notz et al., 2023), with learning, peer-networking, and outlets as key elements for a successful transition (Mawois et al., 2019). On the other hand, Périnelle et al. (2021) used on-farm innovation tracking (Salembier et al., 2016) as a baseline for co-design with stakeholders. Identifying such local systems, already realized by some farmers, can help to design options both innovative and feasible (i.e., already practiced). Indeed, recent studies highlighted the role of on-farm field experiments in supporting the emergence of new systems (Salembier et al., 2023) and steering the transition by building common knowledge (Navarrete et al., 2018) through a joint exploration conducted with researchers, farmers, and other stakeholders (Lacoste et al., 2022). As noted by Salembier et al. (2023), this emphasizes the need for combining methods to support the design and transition process. In our study, the process was limited to co-designing new systems with stakeholders, which can be seen as a first step of such methods. In that sense, our approach allowed to build *in abstracto* prototypes (i.e., virtual solutions in real-growing solutions in Jeuffroy et al., 2022), that need to be tested and refined in the field, iteratively, using a step-by-step design process (Meynard et al., 2023). According to these authors, implementing the co-designed systems, together with their *in situ* evaluation, is essential to make it “real” by anchoring it in action, which may be a condition to transition.

5. Conclusion

In this study, we collaborated with local stakeholders to design diversified alternatives for vineyard and cereal-based systems. The local context was analyzed through the incorporation of a SWOT matrix, examined with the PESTLE framework, five case studies in four Mediterranean countries. Our hypothesis was that co-designed systems would differ between case studies, according to their environmental, social and political contexts, leading to fine-tuned locally *ad hoc* systems, responding to different types of threats and weaknesses. However, while case studies differed in terms of pedoclimatic, economic and social conditions, diversification strategies were relatively similar in all of them. Diversifying with legumes, either as intercropping or in the rotation, was an option common to almost all case studies. Most options were related to substitution and redesign strategy. Those options would primarily respond to environmental and economic threats and to a lesser extent, social issues; they would tackle only a small part of all identified issues. Some options could be seen as adaptations to climate change but might not be sufficient to face future climate conditions, which may require redesign to tackle all local issues in a systemic way. To reach this objective, our method could be improved by carrying out, with stakeholders, the PESTLE analysis to increase the depth of the systemic context analysis. Considering explicitly the context could help to co-design *ad hoc* system, and thus to foster the transition. Next steps should consider the in-field experiment of these systems with farmers to stimulate learning, while considering market possibilities.

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