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European stakeholders' perspectives on achieving more sustainable wheat cultivation across different pedoclimatic zones

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Introduction: Significant socio-agronomic challenges in wheat production have been revealed in recent years. Soil and nutrient depletion, combined with pest and disease outbreaks, have led to extensive external fertilizer and pesticide use. That situation exacerbates environmental pollution, biodiversity loss, and increases production costs.

Methods: This research identified particularly relevant current agro-environmental problems, barriers and priorities regarding the requirements of end users in wheat cropping systems. A survey was conducted, listing agronomic problems and farming practices. Stakeholders from five European pedoclimatic zones participated in the survey. Their responses were analyzed using univariate statistical techniques and multicriteria methodology. Subsequently, discussion groups with stakeholders were programmed to show, validate, and supplement the survey data.

Results and discussion: The study's findings underscore the need for enhanced learning and training, increased government support, and more enabling legislation to foster implementation of sustainable farming practices. Soil and nutrient loss, coupled with pest and disease incidence are contributing to widespread application of external fertilizers and pesticides that directly leads to environmental pollution, biodiversity loss and increased production costs. To address those issues, agricultural systems must adopt sustainable alternatives such as sustainable agriculture, resilient farming systems, and successful rural communities, avoiding resource depletion, as well as providing ecosystem services.

KEYWORDS

wheat production, agricultural practices, sustainable farming, stakeholders' perception, multicriteria decision method, soil conservation

1 Introduction

The world's population is projected to rise by 2 billion in 30 years, and reach 9.7 billion by 2050, and potentially 10.4 billion by the mid2080s. Under this context, cultivation of cereal crops, including wheat (*Triticum aestivum* and *T. turgidum*), is crucial for global food security, serving as a primary source of nutrition for billions of people and farmers' primary income worldwide. As expectations estimate that the population will grow for the next years, its world demand is projected to increase 50% by 2050 (Hunter et al., 2017).

Over the past five decades, agricultural practices have progressively intensified their reliance on finite resources. This dependency is manifested through several key avenues: the use of fossil fuels for operational activities, the synthesis and application of agrochemicals (fertilizers and pesticides), the extraction of mineral ores for potassium and phosphorus-based fertilizers, and the utilization of constrained freshwater reserves. These intensive resource inputs pose substantial challenges to environmental sustainability, impacting both agricultural productivity and global food security (Khan et al., 2024). European wheat production is reliant on intensive conventional agriculture and induces soil degradation and biodiversity loss through excessive mineral fertilization, intensive tillage, and inadequate conservation (Adams et al., 2025). These practices, including monoculture and lack of cover crops, deplete soil carbon, increase erosion, and compromise soil functionality, particularly worsened in Mediterranean regions (Calatrava et al., 2021). Intensive wheat production based on monocropping systems also results in a high vulnerability to pests, thus increasing the need for the application of excessive amounts of pesticides. Global pesticide applications reach approximately 3 million tons each year (FAO, 2020), while in the European Union, pesticide use amounts to almost 374,000 tons (European Commission, 2022).

In this sense, there is a critical need for alternative practices that minimize environmental impacts while increasing productivity. Therefore, a new alternative in wheat production is essential, to ensure food, income and nutrition for the population, whilst decreasing agriculture's use of environmental resources; such a shift toward sustainable agricultural practices is considered essential. This shift toward more sustainable agricultural practices (SAP) and precision agriculture (PA) has gained traction as a way to reduce dependency on chemical inputs, improve water use efficiency, and preserve soil health (Petrović et al., 2024). Practices such as water saving irrigation technologies, techniques for soil preservation like conservation tillage or mulching, and crop rotation or diversification, are essential for improving sustainability and crop productivity (Ding et al., 2021a; Kukal et al., 2014; Morugán-Coronado et al., 2022; Mancinelli et al., 2023).

To facilitate the transition toward sustainable agriculture, policymakers ought to establish incentive driven frameworks that encourage farmers to implement agroecological practices and contribute to biodiversity conservation, ultimately optimizing ecosystem service delivery (Rapiya et al., 2024). Policymakers have responded with several initiatives, including the EU "Green Deal" and the "Farm to Fork Strategy," aiming to drive adoption of sustainable farming practices that align with climate goals and boost resilience against environmental stressors (European Commission, 2020; Hendriks et al., 2022). Scaling up sustainable strategies with adoption to the "From farm to fork" policy could be a good occasion for wheat farms to save costs and time, boost crop yields and quality, whilst minimizing the climate change impact and preserving ecosystems (Berghuijs et al., 2024; Morales-Pablo et al., 2024; Michalis et al., 2025).

Nevertheless, the successful implementation of these practices is not straightforward. Farmers' reluctance to adopt sustainable agricultural practices, like organic farming and crop rotation, is primarily driven by perceived yield risks, high machinery costs, limited financial and human resources, and the economic uncertainties of crop diversification (Calatrava et al., 2025; Kassa Tarekegn Erekalo et al., 2025). Tenant farming and inadequate technical support further compound these challenges, resulting in a systemic impediment to implementing long-term, sustainable agricultural practices (Calatrava et al., 2021). Different soil climatic conditions across Europe, combined with diverse economic, social, and political contexts, mean that no single solution can address all these challenges. The assessment of farming practices needs to be region specific, incorporating both experimental research and local stakeholders' knowledge to find the most effective and context appropriate solutions (Andrieu et al., 2019; Mulema et al., 2022; Rittirong et al., 2024). Multi criteria decision analysis (MCDA) is employed in scenarios characterized by ambiguous solutions, experimental research and local stakeholders' perspectives, and the need to structure and prioritize information for effective action planning. MCDA offers a robust framework for integrating heterogeneous stakeholder viewpoints, helping consensus building, and informing best decision making. The synthesis of diverse opinions and the systematic prioritization of actions inherent in MCDA provide significant value in complex decision contexts. It can be observed that multi-criteria decision-making (MCDM) approaches have been extensively utilized to assess sustainability across diverse domains, owing to the complexity of the subject matter (Lindfors, 2021), and have been validated against big data studies to evaluate the sustainability of agricultural systems, yielding robust and satisfactory results (Kamali et al., 2017). The MCDM methodology has been successfully employed to evaluate farmers' agro-environmental issues and barriers to their adoption, as exemplified in potato cultivation (Morugán-Coronado et al., 2024).

The current study focuses on understanding the perceptions of key stakeholders (farmers, researchers, and policymakers) about the barriers and opportunities for the implementation of sustainable agricultural practices in wheat production. By integrating stakeholder insights with scientific evidence, this research enables a more comprehensive understanding of the challenges and pathways for advancing sustainable wheat farming across Europe.

2 Materials and methods

2.1 Areas of study and pedoclimatic zones

As part of the European Soildiveragro project, this research investigated various European pedoclimatic zones: Mediterranean South (MDS), Lusitanean (LUS), Atlantic Central (ATC), Continental

Abbreviations: SAP, Sustainable agricultural practices; PA, Precision agriculture; CAP, Common agricultural policy; MDS, Mediterranean South; LUS, Lusitanean; ATC, Atlantic Central; CON, Continental; BOR, Boreal; MCDM, Multicriteria decision methods; MCDA, Multicriteria decision analysis; TOPSIS, Technique for Order Preference by Similarity to Ideal Solution; IPC, Integrated Pest Control.

TABLE 1 Wheat cultivation area and production in 2020, and associated climatic data by region and period.

Case studies	Code	Area (ha) 2020	Production 2020 (tonnes)	Minimum temperature (°C)	Maximum temperature (°C)	Average temperature (°C)	Average rainfall (mm/year)
Mediterranean South (Murcia) Spain	MDS[a]	9,377	16,410	5 (1996–2020)	29 (1996–2020)	17 (1996–2020)	312 (1996–2020)
Lusitanean (Galicia) Spain	LUS[b]	13,462	36,075	2 (1981–2010)	26 (1981–2010)	14 (1981–2010)	1,299 (1981–2010)
Atlantic Central, Belgium	ATC[c]	32,710	300,651	0 (1991–2020)	22 (1991–2020)	11 (1991–2020)	837 (1991–2020)
Continental, Germany	CON[d]	2,001,600	15,272,000	0 (1991–2020)	18 (1991–2020)	9 (1991–2020)	791 (1991–2020)
Boreal, Finland	BOR[e]	198,800	677,400	−2 (1991–2020)	16 (1991–2020)	7 (1991–2020)	653 (1991–2020)

[a] Sistema de información agrario de Murcia. https://www.carm.es/web/pagina?IDCONTENIDO=1174&RASTRO=c1415$m&IDTIPO=100 and http://siam.imida.es/apex/f?p=101:1:945708657526308.
[b] Anuario de estadística (2020) Ministerio de Agricultura, pesca y alimentación https://www.mapa.gob.es/es/estadistica/temas/publicaciones/anuariodeestadistica/2021/; Informe meteorológico anual 2022. Meteogalicia https://www.meteogalicia.gal/datosred/infoweb/clima/informes/estacions/anuais/2022_es.pdf.
[c] Statbel, https://statbel.fgov.be/en/themes/agriculture-fishery/farm-and-horticultural-holdings#figures, Final estimate and Royal Meteorological Institute, https://www.meteo.be/fr/climat/climatdelabelgique/normalesclimatiquesauccle/generalites.
[d] Statistisches Bundesamt (https://www.destatis.de) and Deutscher Wetterdienst (https://www.dwd.de).
[e] Natural Resources Institute Finland [referred: 11.4.2022]. Access method: https://www.luke.fi/en/statistics/cropproductionstatistics and Finnish Meteorological Institute https://www.ilmatieteenlaitos.fi/vuositilastot.
Pedoclimatic zones. MDS, Mediterranean South; LUS, Lusitanean; ATC, Atlantic Central; CON, Continental; BOR, Boreal.

(CON), and Boreal (BOR), in Spain, Belgium, Germany, and Finland. The location of the different zones can be seen in Supplementary Figure S1, together with data on average wheat yields and climate parameters in Table 1.

2.2 Stakeholders survey

The stakeholder survey was based on a standardized basic structure. The survey content was developed taking into account the knowledge of the partners in each region and the bibliographic information gathered from the literature and collected in Francaviglia et al. (2020) and Morugán-Coronado et al. (2020).

First of all, the generic version of the questionnaire was tested on a small sample of Spanish stakeholders; it was then adapted to the specific agronomic issues and farming practices of each group of regions with the participation of each corresponding partner. All survey questionnaires were provided in both English and the native language of the country, except in the case of Spain, where only Spanish was used. To maximize participation from stakeholders across their areas of expertise, the questionnaire was offered in the native language of each participating country. The questionnaire contained five key sections:

- Section 1 Project introduction and informed consent.
- Section 2 Personal data.
- Section 3 Main wheat agronomic problems and their severity, one question.
- Section 4 Understanding of end-users' priorities for sustainable crop production, one question.
- Section 5 Effectiveness of existing agriculture strategies clustered in: tillage, fertilization, soil conservation and pest and disease control (20 questions, five per group).

The stakeholder survey incorporated targeted questions designed to prompt respondents' critical thinking regarding localized challenges and the practical viability of agricultural interventions within their specific study areas. This approach aimed to elicit detailed insights into existing problems and potential farming practices. While this information was not directly integrated into the primary analysis for identifying diversification strategies, crops, or farming practices, its purpose was to engage respondents in more in-depth consideration of their unique contexts and the practical implications of future agricultural approaches.

Stakeholder recruitment was achieved by leveraging networks within farmers' associations and agricultural cooperatives, companies and public research centers, which sent the information by email. Surveys were implemented in 2020 with commercial online surveying platform (Survey Monkey) that allowed respondents to complete the survey utilizing different digital platforms, including computers, tablets, and smartphones. Data cleaning removed surveys with inconsistencies or missing information.

2.3 Stakeholders participating in the survey

The survey was distributed to three distinct stakeholder groups for completion for each study area: (1) farmers producing wheat; (2) specialized agricultural technical advisors in wheat cultivation were consulted from cooperative, public, private, and industry sectors; and (3) others, such as research scientists, agricultural policy administrators, and environmental conservation organizations, etc., with experience in the wheat cropping system. A cohort of 224 participants offered data, satisfying the smallest threshold for decisional group formation as per the methodology of Delphi method (Okoli and Pawlowski, 2004). Participant selection adhered to the expert criteria delineated by Skulmoski and Hartman (2007), specifically encompassing proven subject matter expertise, active participation propensity, and effective communication capabilities. Recruitment of qualified individuals, who have authentic knowledge of wheat cultivation within the defined study areas, was facilitated through collaborative efforts with agricultural cooperatives, farmers' associations, and agribusiness entities, seeking experts from their membership database. It must be noted that the study did not intend to survey a representative sample of a population, but to gather the perceptions of stakeholders that were carefully selected based on their expertise through a systematic sampling of respondents rather than a random sampling among individuals pertaining to a population.

Table 2 details survey participation by stakeholder type within each study area. Reaching all stakeholders proved challenging in some study areas. We encountered respondents who left questions unanswered, citing a lack of knowledge or confidence regarding the issues involved. Certain private technical advisors included in the survey also maintain active farming operations. For this study, they were categorized as technical advisors, although they may also manage farms themselves.

2.4 Analysis by multicriteria decision making methodology

The answers to the survey questionnaire were analyzed and summarized using univariate statistical techniques and multicriteria analysis methods (Calatrava et al., 2021). In some questions, the percentage of stakeholders selecting each answer was considered. In the case of the identification of the most relevant agronomic problems and related end-users' needs (survey parts 3 and 4), respondents qualitatively evaluated the severity or priority using ordinal linguistic labels, more specifically, a six-point ordinal scale was used, that ranged from 'Very low' (0) to 'Very high' (5). Stakeholder qualitative evaluations, expressed through ordinal linguistic descriptors, underwent a numerical conversion to facilitate quantitative analysis. Once numerically converted to a 0–5 scale, the weighted average value of said scale was used (Calatrava et al., 2021).

A six-point scale was selected to deter respondents from using the middle value as a 'face-saving' measure and to acknowledge the inherent lack of neutral positions in evaluating problem severity or farming practice effectiveness, thereby encouraging the selection of 'do not know/no response' options (Sturgis et al., 2012). The identification of the most effective farming practices for each area (section 5 of the questionnaire) was done using Multicriteria Decision Making Methods (MCDM). Stakeholders assessed the effectiveness of farming practices, within each group of practices, to address each need (objective), i.e., stakeholders assessed farming practices depending on the objective in question. Their answers were analyzed using MCDM to establish the relative importance of various farming methods, as perceived by stakeholders. The selection of MCDM was justified by its capacity to integrate expert judgments, thereby providing a more comprehensive understanding of the decision-making problem. The determination of each alternative's suitability, based on survey responses, was achieved through the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981; Lai et al., 1994; Zeleny, 2014); the detailed methodology is described in Morugán-Coronado et al. (2024).

2.5 Discussion groups

Once the survey results were analyzed, for the purpose of validating and supplementing the outcomes, stakeholder discussion groups were facilitated to present and analyze the results. Discussion groups were organized for each studied pedoclimatic zone, trying to ensure a holistic perspective, involving a multitude of stakeholder types, such as agricultural producers, technical experts, public administrators, researchers, input providers, value-chain participants, and NGO representatives. The survey respondents were also invited to participate. Results were presented and discussed separately for each farming practice category and moderated by the responsible person in charge of the study area; the information of the debate was recorded by handwritten minutes, and by photographs.

Building on the stakeholder survey results, we facilitated discussions to explore their perspectives. This included:

a) Gauging their level of agreement with the survey findings.
b) Identifying any additional issues they felt were important.
c) Encouraging them to elaborate on any points of disagreement.

The discussions assessed the following key areas: identifying the most pressing agronomic challenges facing wheat crops in Europe, the potential effectiveness of different farming practices in tackling these problems, the feasibility of implementing these practices on a practical level and any potential barriers that might hinder the adoption of these practices.

TABLE 2 Count of participants, gender, classification by type and age, by study area, (with "not defined," ND, used for sex not specified).

Study area	Female	Male	ND	Farmers	Advisory services	Researcher/ academic	NGO	Total respondents	Average respondent age (years)
MDS	4	18	0	14	5	3	0	22	45.1
LUS	12	46	0	56	10	4	1	71	45.8
ATC	3	63	0	56	4	5	1	66	51.7
CON	1	16	0	14	1	1	1	17	45.0
BOR	6	42	0	31	8	7	2	48	49.9

Pedoclimatic zones. MDS, Mediterranean South; LUS, Lusitanean; ATC, Atlantic Central; CON, Continental; BOR, Boreal.

TABLE 3 Stakeholder-derived mean scores, based on qualitative assessments, quantified agronomic and environmental problem severity (0 = very low to 5 = very high).

PROBLEMS	MDS	LUS	ATC	CON	BOR
Low and/or variable yields	2.95 (1.31)	**3.23** (0.91)	2.32 (1.24)	2.87 (1.34)	2.92 (1.03)
Rainfall scarcity in growing period	3.1 (1.14)	2.59 (1.19)	2.29 (1.11)	**3.00** (1.31)	2.71 (0.99)
Rainfall excess	n.r.	2.88 (1.08)	n.r.	1.47	2.17 (1.02)
Irrigation water scarcity	2.6 (1.38)	2.40 (1.21)	1.31 (1.01)	n.r.	n.r.
Water pollution by leaching or runoff of nutrients	2.11 (1.03)	2.50 (1.15)	1.95 (1.16)	n.r.	1.58 (1.01)
Waterlogged soils/inadequate drainage	n.r.	3.12 (1.27)	2.05 (1.15)	n.r.	2.73 (1.36)
High incidence of pests	2.10 (1.21)	2.91 (0.80)	**2.35** (0.98)	1.80 (0.77)	1.43 (0.67)
High incidence of fungal diseases	2.20 (1.17)	2.93 (0.84)	2.81 (1.01)	2.40 (0.91)	1.81 (0.98)
High incidence of bacterial diseases	1.90 (1.05)	2.30 (1.10)	1.72 (0.99)	n.r.	n.r.
High use of phytosanitary products	1.63 (1.01)	2.76 (1.03)	2.59 (1.04)	2.20 (1.06)	1.68 (1.05)
Development of resistance to phytosanitary products	2.11 (1.13)	2.63 (1.04)	2.60 (1.18)	2.50 (1.43)	2.14 (0.99)
High weed pressure	2.55 (1.36)	2.84 (1.08)	2.12 (1.21)	3.00 (1.25)	n.r.
Low soil fertility	2.67 (1.12)	2.95 (0.87)	2.18 (1.29)	1.60 (1.10)	2.48 (1.07)
Low soil microbial biodiversity	2.22 (1.04)	2.41 (1.00)	2.17 (0.94)	1.79 (1.23)	2.64 (1.06)
Low number of earthworms in soil	2.11 (1.01)	2.68 (1.14)	2.03 (1.16)	1.57 (1.15)	2.29 (1.04)
Low presence of beneficial invertebrates/insects in the soil	2.37 (1.04)	2.50 (1.11)	2.22 (1.08)	2.00 (0.98)	2.41 (1.14)
Loss of organic matter	**3.14** (1.42)	2.47 (1.10)	2.06 (1.07)	1.47 (0.98)	2.50 (1.19)
Excessive use of machinery	2.85 (1.03)	2.74 (1.04)	2.12 (1.10)	1.80 (0.97)	2.40 (1.17)
Soil compaction	3.10 (1.45)	2.75 (0.99)	2.20 (1.22)	1.60 (1.15)	**3.17** (1.17)
Soil erosion	2.95 (1.50)	2.35 (1.05)	1.49 (1.21)	1.33 (0.12)	1.79 (1.01)
Soil acidification	n.r.	2.44 (1.03)	1.88 (0.96)	1.00 (0.96)	n.r.

'Not relevant' (n.r.) responses, outside the study's scope, were excluded from the questionnaire. Standard deviations are in brackets. The agricultural problems with the highest values in each area are highlighted in bold.
Pedoclimatic zones. MDS, Mediterranean South; LUS, Lusitanean; ATC, Atlantic Central; CON, Continental; BOR, Boreal.

3 Results and discussion

3.1 Understanding stakeholder perspectives on key agro-environmental problems by pedoclimatic zone

By means of a six-level qualitative scale, from very low to very high (subsequently translated to a 0–5 numerical scale), respondents valued how intense agro-environmental concerns were for their crops and research areas. Surveyed stakeholders in the 5 pedoclimatic zones largely did not rate agronomic difficulties as highly or very highly severe (Table 3).

The analysis revealed distinct water-related challenges. Rainfall scarcity was identified as a primary constraint in MDS, CON, and BOR, while excess precipitation, leading to soil waterlogging and/or inadequate drainage, was a major issue in LUS and BOR. The high incidence of pests, fungal diseases in the LUS and ATC and weeds in LUS and CON zones, and the resulting high level of use of phytosanitary products, was identified as one of the major problems, while these were among the less severe problems for stakeholders in the MDS and BOR study areas. Regarding soil management, the reduction in soil organic matter content and soil compaction were perceived as severe problems in the MDS and BOR followed by the LUS but were less severe for stakeholders in the other pedoclimatic zones. The agro-environmental problems that were less severely perceived by stakeholders related to water pollution from nutrients leaching and/or run-off, soil biodiversity and fertility, soil acidification and soil erosion. The exceptions were again the MDS study area, where soil erosion was among the most relevant problems, and the CON study area, where low soil biodiversity was perceived as a more severe problem than in the other pedoclimatic zones.

3.2 Aligning development objectives with the most critical needs of end-users

In order to find solutions for the main agronomic problems of wheat production, the stakeholders were required to give a qualitative value to the priority of several objectives, after they had already assessed the severity of the agro-environmental problems (Table 4), measured on a six-interval scale ranging from very low to very high (qualitative answers were converted to a 0–5 scale). Their answers are consistent with the previous identification of relevant problems (Table 3).

Table 4 illustrates the stakeholders' prioritization of objectives to address wheat production's agronomic challenges in each area. Across

TABLE 4 Stakeholder qualitative prioritization of objectives by pedoclimatic zone (mean scores; 0 = low to 5 = high; n.r.: not included).

Objectives	MDS	LUS	ATC	CON	BOR
Increase soil fertility	4.00 (1.02)	**3.29** (0.77)	3.27 (1.00)	3.43 (1.28)	4.04 (1.01)
Mobilize soil nutrients during plant growth	3.59 (1.01)	**3.29** (0.75)	3.20 (0.88)	3.29 (1.20)	3.88 (0.79)
Reduce the incidence of pests and diseases	3.14 (1.28)	3.19 (0.83)	3.38 (0.99)	3.21 (0.80)	3.25 (1.14)
Increase soil organic matter content	**4.14** (0.83)	2.95 (0.74)	**3.49** (0.95)	3.50 (1.02)	4.00 (1.22)
Improve soil structure to improve aeration. Water retention and rooting	4.09 (0.92)	3.12 (0.95)	3.34 (0.93)	3.50 (1.22)	**4.38** (0.91)
Increase soil biodiversity	3.86 (0.91)	3.02 (0.90)	3.03 (1.01)	3.54 (1.27)	4.07 (1.06)
Reduce soil erosion	3.76 (1.09)	2.58 (0.98)	2.17 (1.19)	2.43 (1.20)	3.04 (1.27)
Reduce soil pollution	3.36 (1.18)	2.70 (1.02)	2.00 (1.18)	2.43 (1.00)	2.62 (1.14)
Reduce soil salinization	3.29 (1.38)	2.24 (1.18)	n.r.	n.r.	n.r.
Reduce soil acidification	n.r.	2.73 (0.94)	2.49 (1.20)	2.29 (1.07)	n.r.
Improve water infiltration/drainage systems	3.76 (0.89)	2.69 (1.11)	n.r.	2.64 (1.39)	3.87 (1.24)
Improve water quality	n.r.	2.67 (1.18)	2.58 (1.18)	n.r.	3.13 (1.39)
Reduce the incidence of weeds	n.r.	2.76 (1.01)	n.r.	**3.57** (0.76)	3.11 (1.27)

Standard deviations are in brackets. The agricultural objectives with the highest values in each area are highlighted in bold.
Pedoclimatic zones. MDS, Mediterranean South; LUS, Lusitanean; ATC, Atlantic Central; CON, Continental; BOR, Boreal.

TABLE 5 Stakeholder qualitative prioritization of tillage objectives by pedoclimatic zone (mean scores; 0 = low to 1 = high; n.r.: not included).

Case of study	MDS	LUS	ATC	CON	BOR
Conventional tillage	0.241	**0.651**	**0.665**	0.371	0.365
Minimum tillage	**0.738**	0.420	0.561	**0.591**	0.423
Shallow tillage	0.200	0.473	0.439	0.342	**0.675**
Tillage according level curves	0.470	0.108	0.227	0.152	0.099
No tillage without herbicides (mechanical weed control)	0.306	0.236	0.000	0.216	0.428
No tillage with herbicides	0.271	0.192	0.221	0.365	0.324
None of these are effective	0.100	0.589	0.157	0.109	0.350

The agricultural strategies with the highest values in each area are highlighted in bold.
Pedoclimatic zones. MDS, Mediterranean South; LUS, Lusitanean; ATC, Atlantic Central; CON, Continental; BOR, Boreal.

all pedoclimatic zones, enhancing soil organic matter, improving soil structure for aeration, water retention, and root development, mobilizing soil nutrients during growth, and boosting soil fertility were identified as the most pressing needs. Increasing soil biodiversity was also highly prioritized, with pest and disease reduction receiving notable attention in the LUS and ATC pedoclimatic zones.

3.3 Identifying successful farming practices

Stakeholders were requested to identify the farming techniques they deemed most effective, from a provided array of agricultural practices, for the purpose of addressing the problems previously defined. Respondents selected from a supplied inventory of farming techniques, with the option to introduce additional practices not featured on the standard list, and the priority given to each group of farming practices, as determined by the multicriteria assessment (utilizing a normalized 0–1 ranking scale), is presented in Tables 5–8. Detailed information concerning the barriers to implementing sustainable agricultural techniques across the study zones is available in Supplementary Table S1. The following subsections (3.3.1 through to 3.34) detail the key findings for each particular cluster of agricultural practices and provide guidance concerning agricultural policy and operational implementation (European Commission, 2023a, 2023b).

3.3.1 Identifying the most appropriate tillage practice to pedoclimatic zone conditions

Stakeholders in the pedoclimatic zones chose different tillage practices as being the most adequate ones for each end-user's need to be fulfilled (objectives). Evidence from the multi-criteria assessment, Table 5 indicates discrepancies across the zones and underscores the existing debate concerning conventional intensive soil disturbance and alternative conservation tillage approaches. Despite those discrepancies, the predominant stakeholder preference across the study areas was for conventional or minimum tillage, with the latter encompassing shallow or non-inversion soil disturbance and/or decreased tillage frequency. Sustainable soil management practices, specifically shallow tillage and no-till systems demonstrated secondary preference in a subset of study areas but were assigned lower ratings in other instances.

TABLE 6 Stakeholder qualitative prioritization of fertilization objectives by pedoclimatic zone (mean scores; 0 = low to 1 = high; n.r.: not included).

Case of study	MDS	LUS	ATC	CON	BOR
Addition of solid organic matter/manures	**0.636**	**0.598**	**0.705**	**0.540**	0.449
Use of green manure	0.294	0.532	0.591	0.508	**0.850**
Incorporating crop residues to soil	0.465	0.217	0.272	0.355	0.193
Combination of manure and mineral fertilizers	0.307	0.394	0.270	0.189	0.162
Precision agriculture to optimize fertilization	0.445	0.333	0.251	0.310	0.185
Use of biostimulants. Etc.	0.245	0.259	0.219	0.000	0.105
Addition of slurries	0.000	0.068	0.146	n.r.	0.027
None of these are effective	0.088	0.595	0.177	0.117	0.184

The agricultural strategies with the highest values in each area are highlighted in bold.
Pedoclimatic zones. MDS, Mediterranean South; LUS, Lusitanean; ATC, Atlantic Central; CON, Continental; BOR, Boreal.

TABLE 7 Stakeholder qualitative prioritization of soil conservation objectives by pedoclimatic zone (mean scores; 0 = low to 1 = high; n.r.: not included).

CASE OF STUDY	MDS	LUS	ATC	CON	BOR
Crop diversification	0.446	**0.756**	n.r.	**1.000**	**0.835**
Addition of organic matter	0.576	0.346	n.r.	n.r.	0.343
Maintain vegetation cover (natural or cover crops)	**0.682**	0.303	0.403	0.376	n.r.
Mulching (with crushed offcuts from pruning. Etc.)	0.564	0.149	0.452	0.000	n.r.
Maintain strips of vegetation between lines	0.205	0.000	0.122	0.264	n.r.
Hedges or natural vegetation on the edges of the plots	0.216	0.034	0.256	0.088	n.r.
Erosion barriers or margins with vegetation	0.343	0.000	0.035	n.r.	n.r.
Use of catch crops to reduce N/P leaching		0.225	**0.779**	0.133	0.310
Avoiding plant protection products	0.081	0.160	0.076	0.000	0.173
None of these are effective	0.000	0.524	0.158	0.103	0.097

The agricultural strategies with the highest values in each area are highlighted in bold.
Pedoclimatic zones. MDS, Mediterranean South; LUS, Lusitanean; ATC, Atlantic Central; CON, Continental; BOR, Boreal.

Conventional tillage was assigned the highest rank in the LUS and ATC pedoclimatic zones, followed by shallow and minimum tillage, although the ranking differences were not very large and the overall number of stakeholders choosing less intensive tillage options was greater than the number opting for conventional tillage. This would suggest that the stakeholders' preference for less intensive tillage is clear. Stakeholders in the other three pedoclimatic zones expressed greater preference for more sustainable tillage. Stakeholders in the MDS zone gave the highest value to minimum tillage, followed by contour tillage (consistently with the greater concern about the soil erosion problem), while in the CON study area, respondents also gave the maximum rating to minimum tillage but followed by conventional tillage and no tillage with application of herbicides, both with very similar ranking scores. In the BOR study area shallow tillage was the preferred option, followed by no tillage with mechanical weed control and minimum tillage, both with very similar ranking scores (Table 5).

Stakeholders were surveyed concerning the impediments to the adoption of enhanced sustainability tillage methodologies within the specific crop and research locales (Supplementary Table S1). Whilst the answers exhibited considerable divergence across study areas, the predominant consensus pointed to inadequate farmer understanding of effectiveness, established traditional routines, and the need for adequate technical consultation as the most significant constraints.

These findings highlight that farmers have some information about conservative farming practices related to tillage, but that the lack of knowledge is higher than the concern for the environmental impact. This study identifies the key barriers to knowledge transfer through technical advice and agricultural extension services.

No tillage can be an interesting technique in arid areas. Conversely, in areas with frequent rainfall, tillage facilitates water drainage and avoids waterlogging. This fact agrees with the point of view of the stakeholders interviewed in this survey. The pedoclimatic zones with the highest accumulated rainfall were in favor of conventional and minimum tillage (Tables 1, 5). On the contrary, the study areas with lower rainfall opted for no tillage. Conservation agriculture, with crop residues and weeds, improves soil water retention, especially in dry years, compared to conventional tillage. Recent studies show increased extreme precipitation globally, and regional droughts are expected to worsen, especially in Mediterranean areas (Ramesh et al., 2017; Gandía et al., 2021). Rainfall pattern changes in rainfed cereals alter weed biology and crop interactions (Ramesh et al., 2017), requiring farmers to adapt for sustainability. Results presented in Gandía et al. (2021) indicated that minimal tillage practices yielded the greatest grain production and the lowest straw biomass, suggesting better wheat grain formation and residue mineralization.

Additionally, a study has demonstrated the positive impacts of diminished and zero-tillage practices for the provision of ecosystem

TABLE 8 Stakeholder qualitative prioritization of pest and diseases control objectives by pedoclimatic zone (mean scores; 0 = low to 1 = high; n.r.: not included).

Case of study	MDS	LUS	ATC	CON	BOR
Crop diversification	**0.758**	**0.938**	n.r.	**0.670**	1
Increase soil invertebrates biodiversity	0.492	0.179	n.r.	0.344	n.r.
Pest alerts	0.193	0.155	0.346	0.217	0.019
Trap crops	0.189	0.082	0.376	0	n.r.
Use of biostimulants and mycorrhizae	0.360	0.215	n.r.	0.250	n.r.
Use of pesticides	0	0.229	0.332	0.262	0.071
Ploughing	n.r.	0.225	n.r.	n.r.	0.102
Allelopathic crops	0.122	n.r.	0.335	0.000	n.r.
None of these are effective	0.263	0.380	**0.732**	0.375	**0.164**

The agricultural strategies with the highest values in each area are highlighted in bold.
Pedoclimatic zones. MDS, Mediterranean South; LUS, Lusitanean; ATC, Atlantic Central; CON, Continental; BOR, Boreal.

services, through improvements in soil organic matter, improved water holding capacity, soil structure and increased soil microbial abundance and activity, and decreased greenhouse gas emissions (Morugán-Coronado et al., 2015). Tillage is often accompanied by soil structure degradation, leading to subsoil compaction, soil surface sealing, erosion and decreased soil organic matter as experts have shown (Six et al., 2000; Van Capelle et al., 2012). Seasonal ploughing can negatively affect soil quality, biodiversity, productivity, and their provision of ecosystem services (Ding et al., 2021b). The same point of view has been shown in several studies whose results show that avoiding or limiting soil disturbance in wheat growing areas helps to increase soil aggregation and its physic-chemical properties compared to conventional intensive tillage (Sharma et al., 2005; Liu et al., 2013). In addition, zero and minimum tillage have been shown to increase wheat yields while conserving soil and water (Erenstein and Laxmi, 2008; Gupta et al., 2022). Accordingly, even with the persistence of conventional tillage as the preferred methodology in some study areas, a substantial number of stakeholders recognize that a shift toward less intensive tillage alternatives, aimed at diminishing ploughing frequency and depth, is imperative to confront the agri-environmental concerns within their areas.

Considering the point of view of stakeholders, commitment to conservation agriculture can be one of the best options in the drive toward more sustainable wheat production. Conservation agriculture techniques can ensure soil conservation, reduce erosion, boost water infiltration, maintain soil moisture content, increase nutrient availability, improve yield and regulate optimum temperature for grain formation, in addition to increasing carbon storage and enhancing the proliferation of soil biodiversity that encourage soil health and ecosystem services (Reeves et al., 2015). Implementing soil conservation techniques to strengthen crop resilience provides a degree of protection against the impacts of climate change, such as those caused by higher temperatures and the increasingly frequent incidence of drought and flood events (Friedrich et al., 2012). The selected soil conservation methodologies tend to be directed mostly toward the amelioration of soil health rather than toward the mitigation of soil loss. Particularly, crop diversification and the introduction of organic matter are identified as the most effective alternatives in a major proportion of the study areas.

3.3.2 Evaluating optimal fertilization practice in each pedoclimatic zone

The fertilization practices were chosen by stakeholders according to what they consider as the most appropriate to fulfill each end-user's needs (the reassessed objectives). Whilst regional differences are evident in the multi-criteria evaluation results (Table 6), a stronger consensus is apparent when contrasted with the evaluation of tillage techniques.

Stakeholders in all pedoclimatic zones gave the maximum rating to adding soil organic matter, followed by implementing green manure, apart from the BOR study area where it was the other way around. In the case of the MDS study area, the 2nd and 3rd preferred choices were the incorporation of crop residues to the soil health and employing precision agricultural techniques to maximize fertilization efficiency. The 3rd preferred alternatives in the other pedoclimatic zones were incorporation of crop residues into the soil in the CON and ATC study areas and the combination of manure and mineral fertilizers in the LUS and ATC pedoclimatic zones (Table 6).

In terms of fertilization practices, stakeholders across a major proportion of the investigated pedoclimatic zones consistently favored the application of solid organic matter and manures, as well as the implementation of green manuring, as the most efficacious fertilization options. The incorporation of crop residues in the soil and the use of precision agriculture techniques to optimize the application of fertilizers were also perceived as effective alternatives, especially in the MDS study area. This is consistent with the relevance given by stakeholders to the need for improving soil conditions. Other evaluated alternatives showing significant promise were the integration of biostimulants and biofertilizers are not perceived as highly effective alternatives, which may be due to a lack of knowledge and experience with them.

In any case, stakeholders point out the need to reduce inorganic fertilizers use and to increase organic matter intake to improve characteristics of the soil. It is well known that prolonged application of chemical fertilizer accelerates the mineralization of the organic carbon content present in soil, resulting in reduced soil organic carbon being accumulated in soil (Aumtong et al., 2023). Organic fertilization, as a viable alternative to chemical inputs, possesses the capacity to furnish crops with appropriate levels of various trace elements, as well as to regulate soil water status, nutrient dynamics, air exchange, thermal regimes, and microbial populations (Bolan et al., 2003).

Alternatives to conventional fertilization practices require optimizing fertilization use through precision agriculture techniques, using sustainable sources of nutrients through manure application, the integration of crop residues into the soil, the adoption of green manure techniques, and/or the use of biostimulants and other new generation fertilizers. More sustainable fertilization practices can be highly effective in avoiding nutrient deficiencies and improving crop production whilst limiting mineral fertilizer use (Nazir et al., 2021), protecting biodiversity, soil structure and fertility (Ranva et al., 2022) and enhancing soil organic carbon content (Lal, 2010; Sainju, 2014).

The perceived inadequacy of biostimulants and biofertilizer practices among certain stakeholders underscored the demand for specialized technical consultation. These formulations, designed to minimize chemical fertilizer dependency through microbial nutrient liberation, which in turn boosts crop production and quality, face limited acceptance. While biostimulants usage alleviates the environmental burdens of excessive conventional fertilization, including soil and water contamination, farmer adoption is hindered by a lack of comprehension of the operational principles and a deficiency of demonstrated economic and ecological benefits when compared to chemical fertilizers (Ramakrishna et al., 2019).

3.3.3 Ranking soil conservation strategies best suited for various zones

The results obtained through the multi-criteria assessment of conservation practices chosen by stakeholders are shown in Table 7, in which differences were found. The most preferred alternatives for soil conservation were crop diversification in the LUS, CON and BOR pedoclimatic zones. In the MDS and ATC, vegetation soil covers were the most chosen conservation practices. In the ATC study area, catch crops were also chosen (Table 7). The other preferred practices relating to soil cover alternatives were mulching and cover crops in the MDS, LUS and to the incorporation of organic matter which, were also the most preferred choices in these and in the BOR pedoclimatic zone.

According to FAO (2006) three fundamental factors promote farmers' interest in crop diversification: risk management, adaptation to differing agro-ecological conditions, and responsiveness to market demands and food security concerns. Increased risks of flooding and crop failures due to fluctuating precipitation and crop diseases are forcing farmers to diversify their crop choices as a strategy to cope with these risks (Khanal and Mishra, 2017; Asante et al., 2018). Furthermore, crop diversification has beneficial effects on soil health (Feliciano, 2019; FAO, ITPS, GSBI, SCBD, and EC, 2020). This is due to the synergistic effects of crop diversification, leading to diminished weed and insect pressures, reduced dependence on nitrogen fertilization (especially with legume integration), and mitigating erosion through cover crop utilization. Moreover, the implementation of crop diversification can induce lower pest and disease pressures and strengthen food security by enabling farmers to secure ample, nutritious, and varied food supplies in locales where market availability is restricted (Mukherjee et al., 2015; Van den Broeck and Maertens, 2016). Soil cover practices, such as mulch application, natural vegetative cover, or cover crops, are also pointed out as effective options.

3.3.4 Evaluating priorities in pest and disease control practices by each study area

Within pedoclimatic zones (MDS, CON, LUS, and BOR), stakeholders assigned the highest preference rating to crop diversification, with trap crops and pest alerts also being chosen. Statistical analyses revealed significant differences between the primary ranking scores and those of the second-ranked practices. Across some studies, pesticide application was ranked second, but with diminished scores compared to the preferred option. In the ATC study area, however, many stakeholders prioritized 'no effective practices,' assigning it a ranking score over twice that of trap crops and pest alerts (Table 8).

Across the six studied domains, substantial agreement exists regarding the suitability of integrated pest control (IPC) (Morugán-Coronado et al., 2024). The minority of stakeholders who did not endorse this approach cited diverse concerns, notably the perceived complexity of implementation and the requisite financial investment for expert consultation. There was thus a consensus to minimize reliance on pesticides, protecting human health and the environment. Regarding the control of pests and diseases, practices like crop diversification and promoting soil biodiversity were seen as viable alternatives to heavy pesticide use. The successful management of diverse wheat insect pests has been facilitated by biological control, implemented alone or in synergy with cultural practices (Lieve, 2016). The introduction of red clover (*Trifolium pratense* L.), alfalfa (*Medicago sativa* L.), ryegrass (Lolium spp.), and meadow fescue (*Festuca arundinacea* Schreb.) to induce apparent competition led to a demonstrable improvement in wheat aphid parasitoid population densities and parasitism efficiency (Langer and Hance, 2004).

3.4 Outcomes of facilitated discussion groups

To validate and expand upon the survey findings (summarized in Table 9), the results were disseminated to a broader spectrum of stakeholders during organized discussion sessions. The participants in these sessions largely corroborated the survey's conclusions, the different discussion groups generally agreed on the primary agronomic challenges and end-user requirements across the pedoclimatic zones (presented in Supplementary Table S1). The participants placed special emphasis in all discussion groups on the need to introduce long-term crop rotations to cope with weeds, pests and diseases problems and to maintain continuous vegetation cover to prevent erosion and increase soil biodiversity. Furthermore, discussion groups participants highlighted the significance of marketing and profitability factors, issues outside the scope of the survey, as it was principally focused on agronomic concerns.

The discussion group participants validated the general efficacy of the survey respondents' preferred farming practices in addressing the primary agro-environmental challenges within each study site (Hashemi et al., 2022; Csambalik et al., 2023). Nevertheless, the participants identified limitations associated with the selected practices, notably an elevated weed proliferation under significantly reduced tillage frequency and increased soil compaction with reduced-intensity tillage as in previous work (Di Bene et al., 2022).

The survey data revealed a general convergence of opinion regarding the challenges associated with the uptake of more

TABLE 9 Agricultural practice preferences, as expressed by stakeholders and scaled from 0 (minimum) to 1 (maximum) using multicriteria analysis.

Study areas	Tillage practices	Fertilization practices	Soil conservation practices	Pest and disease control practices
MDS	Minimum tillage (0.74); Contour tillage (0.47)	Addition of solid OM/manure (0.64); Incorporating crop residues to soil (0.47); Precision agriculture (0.45)	Vegetation covers (0.68); Addition of OM (0.58); Mulching (0.56)	Crop diversification (0.76); Increase invertebrates' biodiversity in soil (0.49)
LUS	Conventional tillage (0.65); Shallow tillage (0.47)	Addition of solid OM/manures (0.60); Use of green manure (0.53)	Crop diversification (0.76); Addition of OM (0.35)	Crop diversification (0.94); Use of pesticides (0.23)
ATC	Conventional tillage (0.66); Minimum tillage (0.56)	Addition of solid OM/manures (0.70); Use of green manure (0.59)	Catch crops to reduce N/P leaching (0.78); Mulching (0.55)	Trap crops (0.38); Pest alerts (0.36)
CON	Minimum tillage (0.59); Conventional tillage (0.37)	Addition of solid OM/manures (0.54); Use of green manure (0.51)	Crop diversification (1.00); Vegetation covers (0.38)	Crop diversification (0.67); Increase invertebrates' biodiversity in soil (0.34)
BOR	Shallow tillage (0.68); No tillage w/o herbicides/Minimum tillage (0.42)	Use of green manure (0.85); Addition of solid OM/manures (0.45)	Crop diversification (0.84); Addition of OM (0.34)	Crop diversification (1.00)

Pedoclimatic zones. MDS, Mediterranean South; LUS, Lusitanean; ATC, Atlantic Central; CON, Continental; BOR, Boreal.

sustainable agricultural methodologies. The perceived knowledge gap among farmers concerning the actual effectiveness and practical implementation of sustainable soil management practices was particularly significant as it was consistently raised within discussion fora and represents an important barrier for cropping sustainability (Sargiotis, 2025). Deficiencies in established precedent practices and the necessity for specialized technical guidance were additionally emphasized. However, in the Lusitanean discussion group the greatest focus was put on the lack of support from the administration for the adoption of new farming practices. Regarding crop diversification, farm size was pointed out in the MDS discussion as a significant barrier for its implementation, while participants in the LUS discussion group highlighted the lack of industries for marketing the new diversification crops that might be planted, as was previously identified at European scale (Zabala et al., 2023). Lastly, the conflicting regulations concerning manure use were indeed in some points prohibiting/hampering measures that could be taken to enhance soil quality (due to large problems with nitrogen levels) and the legislation was also pointed out as a relevant barrier in the ATC and LUS discussion groups.

Climate change has also affected, and will continue to affect, wheat production in Europe, and will do so in different ways depending on the area. The forecasts are not encouraging. The OECD (2023) forecasts that wheat production will increase by 5% in northern Europe and by 10% in the southern regions. Likewise, the current political situation with the war in Ukraine and Russia, Europe's main wheat producers, will compromise the supply, as well as fertilizer prices. Thus, it is clear that any information or suggestions on measures that farmers and countries can take to increase their resilience is of interest to the public.

Our findings are consistent with European policy directives and the Common Agricultural Policy (CAP) (European Commission, 2023b), but they advance beyond generalized recommendations by specifying best practice strategies for individual regions, considering their unique environmental constraints as determined by regional specialists. This work highlights the need for further investigation into the efficacy of these practices in mitigating the identified challenges, and to quantify the degree of their impact.

4 Conclusion

Although our study is based on surveys conducted in 2020, it does unfortunately reflect persistent challenges that, despite being addressed by the EU in the form of guidelines, have yet to be widely implemented at the individual farmer level. While certain CAP policies with their associated incentives have shown progress, not all issues have received similar attention. The results after MCDM and the discussion groups highlight that some farmers have a lack of knowledge on the efficacy of certain practices, stemming from insufficient knowledge transfer by technical advisors and administrative bodies, who do themselves demonstrate proficiency. Moreover, discrepancies were observed between established agronomic recommendations and the observed trajectory of agro-environmental challenges. These identified knowledge gaps represent potential areas for subsequent investigative studies. In numerous cases, these issues are of concern and may impede the EU's short-to-medium-term wheat production objectives.

In conclusion, agricultural financial support measures must be reinforced to eliminate knowledge gaps and barriers to the adoption of more sustainable wheat production practices. Additionally, practical agricultural transfer and training initiatives for farmers must be implemented.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AM-C: Conceptualization, Writing – original draft, Software, Resources, Writing – review & editing, Visualization, Investigation, Formal analysis, Validation, Methodology, Data curation, Supervision. JC: Writing – review & editing, Formal analysis, Data curation, Resources. LM: Writing – review & editing, Writing – original draft. FA-V: Resources, Writing – review & editing. EP: Writing – review & editing, Resources. AT: Resources, Writing – review & editing. SS: Resources, Writing – review & editing. D-AB: Resources, Writing – review & editing. HW: Writing – review & editing, Resources. SF: Resources, Writing – review & editing. DF-C: Project administration, Data curation, Methodology, Formal analysis, Investigation, Funding acquisition, Resources, Writing – review & editing. MG-L: Validation, Methodology, Visualization, Data curation, Supervision, Conceptualization, Software, Investigation, Resources, Writing – original draft, Formal analysis, Writing – review & editing.

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Conflict of interest

D-AB was employed by FlächenAgentur Rheinland GmbH.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1615755/full#supplementary-material

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