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Challenges of soil health restoration in Tunisian cereal production systems: an analysis through the social-ecological systems framework (SES)

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ABSTRACT

Soil health is essential for sustainable and resilient agricultural systems, supporting food production and maintaining vital ecosystem services. In the Mediterranean region, including Tunisia, it is seriously threatened by both natural and anthropogenic factors, such as erosion, loss of organic matter, intensive agricultural practices, and inadequate land management. In this context, adopting farming practices that can preserve and restore soil health is crucial, but such a transition is far from straightforward. To explore what this transition entails, we applied the Socio-Ecological Systems (SES) framework as the guiding structure for our methodological approach. Data was collected through a literature review, eleven semi-structured interviews, a multi-actor workshop involving twenty participants, and a multi-criteria analysis. Results reveal a combination of technical, political, institutional, economic, and socio-cultural barriers that hinder the adoption of practices that can secure soil health. The most critical include (1) the absence of agricultural policies supporting transition, (2) limited communication and cooperation among actors, and (3) high implementation costs. The study concludes by emphasizing the need for a coordinated national strategy that fosters cross-sectoral collaboration and provides effective support for farmers transitioning toward sustainable soil management in Tunisia's cereal systems.

1. Introduction

Across Mediterranean landscapes, farmers are asked to produce more while preserving the soil on which their livelihoods depend. Soil fertility, quality, and health describe the soil's ability to support land functions, from productivity to ecosystem resilience (Janzen et al., 2021; Richelle and Brauman, 2023; Wang et al., 2024). In this paper, soil health' is defined as the soil's capacity to sustain ecological functions, productivity, and resilience—contributing to human well-being, climate regulation, and biodiversity conservation. Due to its focus on sustainability, resilience, and ecosystem health, soil health has attracted widespread interest from soil scientists, government bodies, and the private sector (Krzic et al., 2024). Although often used interchangeably with soil quality, the term 'soil health' increasingly emphasizes the broader societal and environmental relevance of soils (Fig. 1).

Soil health faces multiple threats—climate change, overuse, poor management—especially in Mediterranean regions with erosion-prone, low-organic soils (Hill et al., 2008; Aguilera et al., 2013; Mamehpour et al., 2021; Ferreira et al., 2022). In Tunisia, mean annual temperatures are projected to rise by 2–2.5 °C by 2050 and up to 4.5 °C by 2100, while average precipitation may decline by 10–20 % (World Bank Group, 2023; Nefzi, 2024). These changes are expected to intensify droughts,

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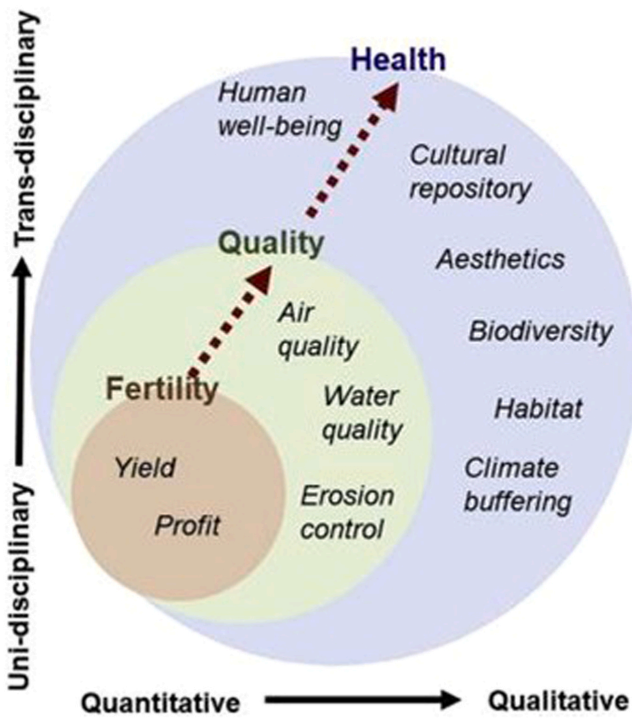

Fig. 1. Functions and services provided by soils. Source: Janzen et al., (2021).

reduce soil moisture, and enhance land degradation risks, undermining the sustainability of cereal-based systems. Such projections underscore the urgency of promoting adaptive and regenerative agricultural practices that enhance soil resilience and water retention.

In recent decades, a tendency for land privatization was detected, especially in the South Mediterranean, driven by state policies as well as spontaneous individual actions (Bourbouze et al., 2009; Bencherif, 2011; Bessaoud, 2013). Nonetheless, collective land is maintained in certain pastoral and territorial areas, governed by specific endogenous rules (Domínguez, 2012). Regardless of ownership status (Schlager and Ostrom, 1992), soil provides common goods, generating both positive and negative externalities—such as carbon storage or release, and erosion-induced dam siltation, which reduces irrigation and energy production. More broadly, soils support numerous ecosystem services vital to society (Ruppel, 2022).

Global initiatives such as IPBES et al., (2018), the Global Soil Partnership, the 4 per 1000 initiative (2015), and the EU Soil Health Law reflect the increasing global commitment to soil conservation. Soil conservation refers to the set of management actions aiming at preventing degradation, while sustainable soil management encompasses both conservation and restoration efforts that integrate social, economic, and environmental objectives. Despite this sustained and growing interest, a comprehensive and widely recognized scientific framework for addressing soil issues is still lacking. The concept of land neutrality, introduced at Rio+ 20 (2012) and developed under the UNCCD framework, remains largely based on biophysical indicators and does not integrate the local social dynamics nor the land tenure systems that are important to soil health decision-making (Rangé et al., 2024). Similarly, land degradation neutrality, as defined under SDG 15.3, focuses on balancing land degradation with restoration at broad scales, but does not explicitly integrate the social dynamics central to soil health decisions.

There is still much to be developed in a context-specific manner to effectively apply and monitor soil health practices (Norris et al., 2020). The effectiveness of many widely promoted practices still needs evaluation under local conditions. Sustainable soil management can rely on adopting agricultural practices that enhance soil quality, such as the use of organic fertilizers, intercropping, and crop rotation. Recent studies highlight that these practices are most effective when embedded in integrated management approaches combining agronomic and ecological dimensions (Jendoubi et al., 2019; Kaur et al., 2024). Recent studies in semi-arid Tunisian conditions demonstrate that conservation and rotation practices can significantly improve soil structure, nutrient dynamics, and microbial activity, while maintaining or even increasing yields (Chaieb et al., 2020; Jaziri et al., 2022). Likewise, introducing cover crops or mixed systems enhances soil organic matter, enzyme activity, and microbial diversity, which are key indicators of soil health (Elhaddad et al., 2024). These findings underscore the potential of regenerative approaches to restore fertility and resilience under Mediterranean climates increasingly stressed by climate change (Nefzi, 2024). Maghreb experience confirms that soil health thrives where farmers keep soils covered, limit tillage, harvest runoff, and co-manage land restoration (Khatteli et al., 2016).

We use the case of north-western Tunisia to explore how different agriculture practices—combined with governance and socio-economic factors—can contribute to soil health. Given that durum wheat cultivation represents roughly half of Tunisia's cereal area, we evaluated four alternative scenarios that could contribute indirectly to improving soil health and sustainability.

- **Scenario 1 (Sc1)** – Alternative rotations/cultivation practices for durum wheat where conventional cultivation of durum wheat adopts traditional cereal cropping system (crop rotation: durum wheat/cereal - durum wheat, soft wheat, barley, triticale, etc.)
- **Scenario 2 (Sc2)** –Cultivation of durum wheat with the adoption of a crop rotation by introducing a leguminous crop: durum wheat/legume (bean, field bean, fava bean, chickpea, etc.). Legume crops are able to improve soil fertility and crop productivity (Yfantopoulos et al., 2024) through the fixation of nitrogen in the area in the roots (Voisin et al., 2015). Moreover, the legume-cereal rotation allows the management of diseases and pests and helps control weeds (Yan et al., 2025). Thus, the cultivation of durum wheat on land previously cultivated with beans involves a reduction in nitrogen fertilizers as well as pesticides as we expect an improvement in yield (De Notaris et al., 2023).
- **Scenario 3 (Sc3)** – Cultivation of durum wheat with the adoption of a crop rotation by introducing the cultivation of rapeseed: durum wheat/rapeseed. Rapeseed improves the soil structure and fertility thanks to its taproots (which can reach up to 2 m) as well as the residues it leaves (enriching the soil with organic matter and nutrients) (Medimagh et al., 2020). Thus, the cultivation of durum wheat on soil previously cultivated with rapeseed involves a reduction in nitrogen fertilizers as well as pesticides as we expect an improvement in yield (Rathke et al., 2005).
- **Scenario 4 (Sc4)** – Integrated rotation combining rapeseed and legumes (rapeseed/durum wheat/legume). This combination is expected to improve soil physicochemical properties, reduce fertilizer and pesticide use, and enhance yield stability over time.

These scenarios are not agronomic trials but analytical tools to explore how farmers and institutions perceive and prioritize alternative pathways for soil health. Addressing this question requires an interdisciplinary approach that captures the interactions between social and ecological systems (Binder et al., 2013; Guimarães et al., 2018) and reflects the dynamics of social–ecological transitions in Mediterranean agriculture (Salvati, 2025). The Social–Ecological Systems (SES) framework (Ostrom, 2009) provides this integrative lens, linking human and ecological dimensions while emphasizing human dependence on nature and related ethical responsibilities (Bouma and Montanarella, 2016; Okpara et al., 2018). The study thus focuses on the governance and social conditions shaping farmers' capacity to adopt sustainable soil practices, rather than on agronomic performance alone. By systematizing diverse data and literature, including grey sources rarely integrated in the Maghreb, it contributes to new empirical evidence on soil health governance and demonstrates the value of the SES framework in supporting such interdisciplinary analysis.

The paper begins by presenting the case study, followed by an overview of the SES framework and the data collection methods. Next, the application of the SES framework is examined and discussed, and the final section summarizes the main conclusions, providing insights into pathways for enhancing sustainable soil management in the region.

2. Materials and methods

The study uses the SES framework as the main analytical structure guiding data organization, analysis, and interpretation. The framework served as a lens to integrate ecological, social, and governance dimensions relevant to soil health at the case study level. Three complementary methods—literature review, semi-structured interviews, and a multi-actor workshop—were combined to characterize the system's components and identify interactions among resource systems, governance structures, and actors. Additionally, a multi-criteria analysis (MCA) quantified stakeholders' preferences for alternative scenarios.

2.1. The case study

Tunisia, located on the southern Mediterranean shore, has a climate ranging from humid in the north to hyper-arid in the south (FAO, 2015). Agriculture is dominated by cereals, olive trees, and date palms, alongside small ruminant livestock. Cereal production remains the main source of agricultural output and employment (Chebbi et al., 2019). However, farming intensification and reliance on monoculture have led to extensive use of fertilizers and pesticides, causing soil degradation and reduced fertility, particularly in organic matter and water retention (Bouajila et al., 2013). Tunisia now exhibits one of the highest rates of soil organic carbon loss in the Mediterranean, with a consistent decline from north to south (Bahri et al., 2022).

2.2. The SES Framework

The SES framework (Ostrom, 2009; McGinnis and Ostrom, 2014) consists of four main subsystems (Fig. 2): Resource Units (RU), representing the tangible elements used by actors within broader Resource Systems (RS) which serve as the internal stock providing services; Governance Systems (GS) that define rules for Actors (A) regulating their interactions with the RS. These are embedded in a broader socio-economic and political context (S) and connected to other ecosystems (ECO) (Basurto et al., 2013). All components are linked through multiple direct and feedback links.

The framework breaks down the first- tier variables into second- tier variables, which includes a set of components considered relevant to understanding the sustainability problem. It is also possible to mobilize third-tier variables, when necessary, to provide a more detailed analysis of the system (Fig. 3; Hinkel et al., 2015).

2.3. The methods used to apply the SES framework in the case study

Using the SES framework, we focused on the governance processes influencing farmers' adoption of sustainable soil practices (Fig. 4), viewing soil as a central resource within a complex socio-ecological system (Berriet-Solliec et al., 2020). In this analysis, the RS corresponds to Tunisia's cereal sector, the RU to its main crops—durum wheat, barley, and soft wheat—and the GS to the policies and rules shaping A actors' decisions. The framework was applied by triangulating data from three sources: literature review, semi-structured interviews, and a multi-actor workshop.

The framework was adapted by selecting the most relevant second-tier variables for the Tunisian cereal context without altering the SES structure itself. This contextualization allowed us to focus on governance and actor-related factors influencing soil management decisions. Hence, from the 52 variables proposed at the second-tier level of the SES framework, 19 were selected and characterized based on their relevance to the research questions. To analyze the resource system (RS) and resource units (RU), we first characterized the sector by examining the distribution of this farming system—specifically, the clarity of system boundaries (RS2) and its proportion relative to other farming activities in Tunisia (RS3). Recognizing the context-dependence of management practices, we examined the regions most engaged in cereal production, considering both location (RS9) and spatial-temporal distribution (RU7). System productivity (RS5) and economic value (RU4) were also assessed, as production yields and economic returns directly influence farmers' decisions. Soil and water are critical resource units in cereal production and key to the overall questions we posed; hence we provide a snapshot about the status of these primary factors, particularly their growth and replacement rate (RU2). The governance system (GS) and its

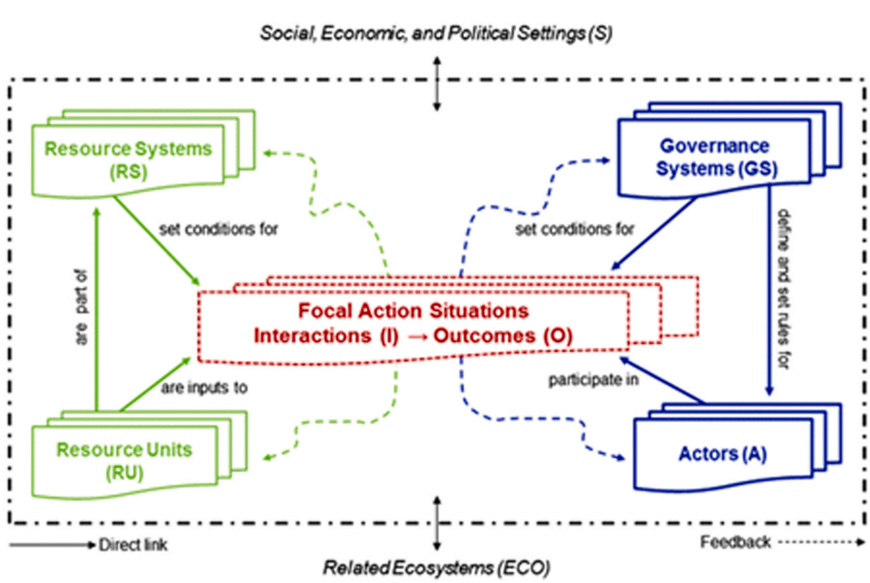

Fig. 2. First-tier components of the SES framework. Source: McGinnis and Ostrom, (2014).

Fig. 3. The first- and second-tier variables of the Ostrom (2009) social-ecological systems (SES) framework including minor refinements made by McGinnis and Ostrom (2014). Source: Hinkel et al#, (2015).

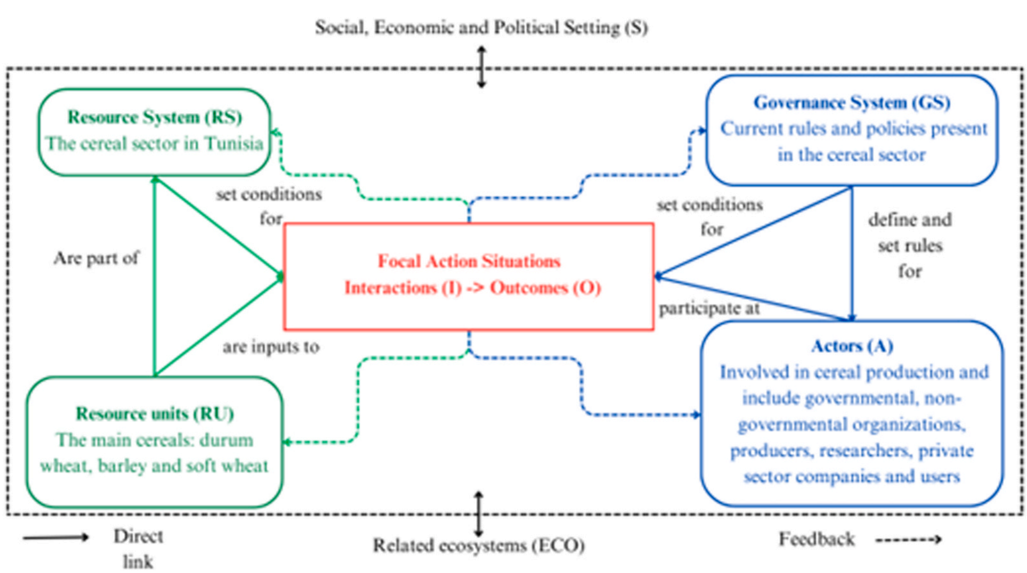

Fig. 4. Integration of SES framework components to the case study context and focus (Source: Personal work, 2024).

actors (A) were central to our analysis. We mapped and engaged with key stakeholders, including government organizations (GS1) and non-governmental organizations (GS2), while also examining their interactions (i.e., network structures, GS3) and identifying those in leadership or entrepreneurial roles (A5). Property rights (GS4) and formal and informal rules governing resource use (GS7, GS8) are crucial for decision-making in this context. Additionally, we considered the role of available technologies (A9), information-sharing mechanisms (I2), and investment activities (I5) in shaping management strategies.

2.3.1. Literature review

The literature review initially characterized the resource (RS) and governance (GS) components of the SES framework. For the literature review, we utilized two types of sources: white literature, consisting of academic publications accessed through platforms such as Science Direct, Research Gate, Open Edition, and Google Scholar. Fifty scientific articles were initially retrieved and narrowed to 13, focusing on agricultural practices in cereal production, their impacts on soil health in Tunisia, and the SES framework's second-tier variables. Keywords for the search included "the cereal sector in Tunisia," "cereal distribution in Tunisia," "typology of cereal farms in Tunisia," "agricultural policy in Tunisia" and "cereal farming challenges in Tunisia". To ensure comprehensive national coverage, we also included relevant studies addressing conservation agriculture, agroecological transition, land-use dynamics, and sustainable land management in Tunisia (Braiki, 2018; Cheikh M'hamed et al., 2022; Gharbi et al., 2025; Guesmi et al., 2023; Taamallah, 2010). Grey literature from governmental, administrative, and research institutions complemented academic sources, offering information often unavailable in scientific publications (Appendix table A1). For our study, we used reports from the Ministry of Agriculture in Tunisia, the National Agriculture Observatory (ONAGRI), the National Institute of Field Crops (INGC), among others. The literature included in the study comprised studies addressing cereal-based farming systems, soil and water management, or governance aspects of agricultural practices in Tunisia and comparable Maghreb contexts. Exclusion criteria filtered studies focusing exclusively on technical trials or those unrelated to the socio-ecological framing of soil management. These complementary sources, representing both scientific and applied knowledge, informed the characterization of 19 selected SES variables whenever possible while knowledge gaps were filled during the interview and workshop development.

2.3.2. Interviews

Interview data were then used to refine the actor (A) and governance (GS) components and to identify interactions and perceived constraints within the system. Semi-structured interviews allowed for a flexible exploration of pre-defined themes, adjusting emphasis according to interview flow and study needs. This was facilitated by the interview guide prepared in advance. The interview guide was prepared according to themes that consider the different components of the SES framework, namely RS, RU, A, GS, and interaction-outcomes (Appendix 1). It included two main sections. The first section focused on retrieving the interviewees' general perception of the cereal sector in Tunisia. The second part concentrated on understanding the interviewees' preference about their management of practices dedicated to soil health restoration, particularly legume-cereal and rapeseed-cereal rotations.

Stakeholders for the interviews and workshop were identified through mapping processes that classified actors across governance, farming, and research domains relevant to soil management. A snowball sampling approach was then used, allowing interviewees to suggest additional participants with relevant expertise or perspectives. This process ensured diversity across institutional levels (national, regional, and local) and professional backgrounds (farmers, researchers, extension officers, and policymakers). In total, 11 interviews were conducted in person (one serving as a test) in Arabic, at different dates and locations over a two-week period in May 2024. Authorization to record audio and take photos was obtained from the interviewees, facilitating the transcription process afterward. Participants included representatives of governmental (2) and non-governmental institutions (2), seeds and oil companies (3), research (3) and farmers (2, one of whom also works with the non-governmental institutions). At the end of the interview period, all recordings were transcribed, translated, and analyzed through content analysis and thematic coding. Content analysis was conducted manually following a four-step process: pre-analysis (highlighting key phrases), coding (labeling the relevant data), horizontal analysis (grouping codes into broader themes), and interpreting the results. Content analysis was developed by two researchers working separately in this task. After each researcher finalized its own analysis, they met and compared the themes identified by each one. From this comparison and discussion, we arrive at the content analysis result. The interviews contributed to refining the SES framework's actor and governance components by identifying the key decision-makers, institutions, and power relations. Findings were later crossed with the literature review and validated through the multi-actor workshop.

2.3.3. Multi-actor workshop

The workshop was designed based on insights from the interviews, ensuring that its themes reflected stakeholder perceptions and previously identified institutional dynamics. It served to validate information and deepen the understanding of cross-scale interactions among governance mechanisms, farmer behavior, and ecological processes. Following Pavelin et al. (2014), it was structured as a participatory space for collaborative problem exploration within a defined time and place. Twenty key stakeholders from diverse sectors—private companies, entrepreneurs, farmers, NGOs, representatives of supply and demand, public administration, and researchers—participated in the three-hour session held at INRAT (National Institute of Agronomic Research of Tunisia), Tunis, on June 6, 2024. Discussions were conducted in French, Arabic, and English. Using a combination of plenary discussions and small-group exercises, participants assessed alternative crop rotation scenarios, examined governance barriers, and validated the findings from the interview phase.

To collectively reflect on barriers and opportunities for improving soil health in Tunisia's cereal systems, the workshop centered on a guiding question: *"Under which conditions can transitions toward sustainable soil management be achieved in Tunisian cereal systems?"* This question was formulated to align with the SES perspective. The session began with short presentations outlining the workshop's objectives and context, followed by the introduction of four management scenarios (Sc1–Sc4). Participants discussed the benefits and trade-offs of each scenario and jointly selected the one they considered as most promising (Fig. 5). Scenario 4 was chosen for detailed discussion, as it was viewed as offering the greatest benefits for soil health, productivity, and gross margins, despite higher management and transition costs (Fig. 6).

The workshop concluded with a brainstorming session designed to encourage active participation and collective reflection. Participants identified key barriers to adopting crop rotation—such as limited knowledge transfer, technological constraints, political and regulatory hurdles, and local values or traditions—and proposed practical solutions to overcome them. Insights from the workshop were then triangulated with literature and interview data to highlight convergences and divergences in stakeholder perspectives. This integrative step reinforced the SES-based analysis by linking individual perceptions with collective deliberation.

2.4. Multi-criteria analysis

The Multi-criteria analysis (MCA) added the quantification of trade-offs among economic, environmental, and managerial dimensions identified in the previous methodological steps. Hence, to further scrutinize the management options proposed to improve soil health in cereal production in Tunisia, we applied a group multicriteria decision-making (MCDM) process for the evaluation of alternatives using economic, environmental, and social criteria. Given the presence of multiple stakeholders, the study evaluated different group decision-making aggregation techniques, to synthesize individual preferences into a collective ranking.

The MCDM requires a clear definition of the decision problem, objectives, alternatives, and criteria. In our case, the decision problem was formulated as: *Which crop rotation scenarios for durum wheat in Tunisia best balance economic profitability, environmental protection, and managerial feasibility?* The objectives comprise (i) maximizing gross margins, (ii)

Fig. 5. Different moments of the workshops.

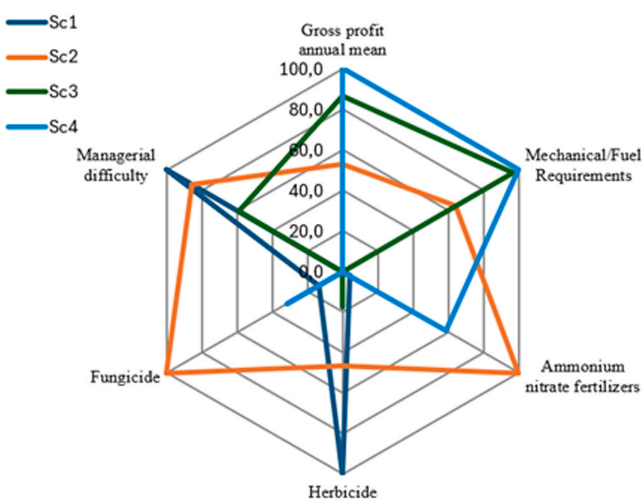

Fig. 6. Performance of alternative scenarios (worst values in the central point, origin of the axes, best values in the outer line).

reducing environmental pressures (fertilizer, pesticide, fuel), and (iii) ensuring manageable knowledge and risk requirements for farmers. Four alternatives (Sc1 to Sc4 detailed at the introduction) were defined accordingly. Criteria were elicited through workshops and interviews and represent both measurable biophysical/economic factors and qualitative managerial feasibility assessments.

Detailed farm-level data on durum wheat and rotation crops were collected from eight stakeholders, including development agents, agronomists, engineers, and farmers. Using these data, we estimated gross margins and input requirements—labour, machinery, and material inputs—as proxies for environmental impacts. Stakeholders identified key evaluation criteria: gross margin (monetary value), machinery use (hours/ha), ammonium nitrate (quintals/ha), herbicides and fungicides (litres/ha), and the perceived managerial difficulty of implementing each practice.

Because not all criteria were considered equally important, their relative importance was established through the Analytic Hierarchy Process (AHP; Saaty, 1995), assigning percentage-based priority weights derived from pairwise comparisons of scenarios. The managerial difficulty criterion, a composite measure of knowledge, expertise, and risk exposure, was also assessed using AHP to translate qualitative judgments into quantitative scores. All criteria were normalized to ensure comparability across evaluation dimensions.

This approach builds on the AHP tradition while adapting it to assess managerial feasibility in the Tunisian cereal context. Cardinal performance scores (in percentages summing up to 1) were then derived for land suitability subclasses—such as soil texture—by ranking qualitative categories from most to least suitable (Senapati and Das, 2024). Data from literature, interviews, the multi-actor workshop, and the MCA were triangulated to inform the SES characterization presented in the results section.

3. Results

The following section presents an integrated characterization of soil health challenges in Tunisia's cereal systems through a SES lens. Rather than providing a purely biophysical description, it examines how ecological conditions, governance structures, and actor interactions jointly shape soil management (Table 4). The results combine the multicriteria analysis (Section 3.1) with the SES framework application (Sections 3.2–3.4), drawing on evidence from the literature review, interviews, and the multi-actor workshop (Table 1)

3.1. Multicriteria analysis

The multicriteria analysis (MCA) evaluated trade-offs among alternative crop rotation scenarios, quantifying the social and environmental implications of transitions toward improved soil health. The conventional scenario (Sc1) ranked lowest, being outperformed by all alternatives in every criterion except herbicide use (Table 1). Although full crop rotation across Tunisia's arable land would be ideal, wheat monoculture still predominates due to the managerial challenges

Table 1
Performance (payoff) matrix for multicriteria analysis.

Criteria	Gross profit annual mean	Mechanical/ Fuel Requirements	Ammonium nitrate fertilizers	Herbicide	Fungicide
Units	DT	H	Quintal	Liter	Liter
Sc1-B/C (q)	1426.8	11.65	3	1	1
Sc2-B/L	1617.4	9.22	1.0325	1.7875	0.33
Sc3-B/CLZ	1737.5	7.99	3.08	2.22	1.11
Sc4-CLZ/B/L	1786	7.87	1.88	2.47	0.862
Weights	50 %	20 %	10 %	10 %	10 %

farmers face when adopting rotational systems. To maintain consistency, managerial difficulty was included as an additional evaluation criterion. Individual priorities were aggregated using the geometric mean of reciprocal preference values, as in the original pairwise comparison matrices (Table 2). Results show that Sc4 involves the highest managerial difficulty, while Sc1 (wheat after cereal) remains the farmers' preferred option, with aggregate results displaying high consistency (CI threshold = 0.10).

We populated the payoff matrix by appending the last column of Table 2 into Table 1 measuring the performance of alternatives against the six criteria selected, rendering all alternatives non-dominated or Pareto efficient as shown in Fig. 5. Thus, each scenario excels in at least one criterion, meaning final selection depends on decision-makers' preferences.

As criteria are measured in different units, the weighted sum is calculated after the normalization of performance values using as denominator the distance between the best and the worst value in each criterion. For production-oriented farmers—prioritizing gross margin and machinery use—Scenario 4 is preferred. When environmental and managerial criteria gain weight, Sc2 outperforms the others, followed by Sc4, aligning with expert opinions on the contribution of leguminous crops to chemical nitrate substitution and the beneficial effects of rapeseed in rotation with wheat (normalized performance matrix and preference profiles are detailed in Appendix 2 and 3). Sensitivity analysis shows that varying weight combinations produce different rankings of alternatives (Table 3). This demonstrates the dependence of decisions on subjective farm and site-specific preferences, so that the weight elicitation process is of paramount importance.

3.2. Resource systems (RS) and resource units (RU)

Cereals are staple foods in Tunisia, covering one-third of arable land—around 1.2 million hectares annually—70 % of which are under monoculture. Northern Tunisia, benefiting from favorable rainfall and soils, produces 66 % of national cereals, compared to 44 % from central and southern regions (RS9, Fig. 7). In general, durum wheat is cultivated to provide farmers needs in semolina and pasta. Barley is mainly used for animal feed but also for traditional dishes, while soft wheat is used for flour, bread, biscuits, and pastries.

In Tunisia, the cereal sector is the largest consumer of nitrogen fertilizers, with 80 % of these fertilizers allocated to cereal production. Cereal cultivation is primarily rain-fed, with almost 6 % of cereal-growing areas irrigated (RU7). Consequently, it is predominantly practiced in the northwest of the country, where rainfall is higher and the soil is favorable for wheat, particularly durum wheat. The system boundaries (RS2) are well-defined and encompass a large area (RS3).

Despite agricultural policies supporting and encouraging cereal farmers, and efforts to increase yields through high quantities of nitrogen and potassium fertilization (RU2), yields remain highly variable and below production potential (RS5). Low productivity stems from natural factors (soil fertility, climate), technical aspects (seed quality, practices), and structural issues (small farm size, weak sector organization). For instance, 2023 was an exceptional year marked by irregular rainfall, causing losses for most farms. To compensate for these losses, the prices of various cereals (durum wheat, soft wheat, barley) increased by 10 dinars compared to 2022 (RU4).

Interview and workshop participants reported reductions in arable land, water shortages due to climate change, and continued use of outdated seeds. Political and institutional support is deemed insufficient, particularly due to the lack of support from the state and institutions, pushing some farmers to adopt less sustainable methods. Despite its benefits for soil fertility and yields, crop rotation with faba beans or rapeseed remains limited in Tunisia. Other practices —conservation agriculture, forage crop rotation, and cover cropping—also enhance fertility and water retention but remain scarcely adopted.

Table 2
Group preference values and priorities for managerial difficulty criterion.

Alternative scenarios	*Sc1*	*Sc2*	*Sc3*	*Sc4*	Priorities
(Sc1) Wheat production after cereal (convent.)	1	0.56	0.41	0.33	*11.55 %*
(Sc2) Cereal-legume rotation	1.79	1	0.55	0.33	*16.48 %*
(Sc3) Rotation with rapeseed into wheat	2.43	1.80	1	0.45	*25.72 %*
(Sc4) Rapeseed-cereal-legume rotation	3.05	3.06	2.21	1	*46.25 %*
		Consistency index (CI)			1.70 %
		CI divided by random index			1.89 %

3.3. Actors (A) and Governance Systems (GS)

The analysis of stakeholders involved in the cereal sector in Tunisia reveals a diversity of roles and responsibilities across different types of organizations. Each stakeholder plays a distinct role in shaping the cereal sector's functioning and evolution in Tunisia. Given its importance, the cereal sector is administered (GS1) by the state through the Office of Cereals (OC) and the General Compensation Fund (CGC). These two bodies set prices at different stages of the cereal supply chain (price policy), ensuring that the price to producers is sufficient to allow acceptable profits and the price to consumers is lower in line with purchasing power. Thus, subsidy policies support both producers and consumers, helping secure national food supply (GS7). Chemical fertilizers are subsidized for cereal producers, and producers must buy seeds from and sell their cereal crops to specific organizations. The Office of Cereals, the General Compensation Fund and other government organizations (Table 5) play a crucial role in improving cereal production through research into new varieties or by providing training and support to producers. However, coordination within this network remains weak (GS3). Around 250,000 producers are involved in cereal farming, representing 43 % of all farmers, with most of them operating small farms of 10 ha or less.[2] Of these, nearly 80,000 focused primarily on monoculture cereal production as their main activity, further intensifying the challenges facing the sector (A1). Most of these farmers are also tenants, which diminishes their motivation to consider soil sustainability. Land fragmentation from inheritance and family division further exacerbates the issue (GS4). Tunisia generally lacks locally adapted mechanisms to monitor and regulate cereal land use. Agricultural lands are not fenced, allowing livestock to enter fields without the owner's permission, often leading to overgrazing issues (GS8). Small farmers struggle with mechanization for planting, harvesting, and weeding, often relying on rented machinery (A9). There are efforts to encourage and support the sector. According to interviews, the National Institute of Field Crops has adopted a leader farmer approach in the cereal sector (A5). Leader farmers are selected, coached, and trained to disseminate best practices through their experiences and demonstration plots to smaller farmers. Each leader farmer mentors about ten satellite farmers, who in turn become leaders. This initiative is implemented by the National Institute of Field Crops in partnership with the "Protection and Rehabilitation of Degraded Soils in Tunisia" (ProSol) project. Nonetheless, this support remains limited, and participants identified financial barriers as major obstacles to transition, with difficulties in accessing financing, credit, and the necessary equipment for modernizing production.

[2] Numbers retrieved from the final project report available at the National Observatory for Agriculture in Tunisia: Khaldi, R., Saaidia, B., 2018. Analyse de la filière céréalière en tunisie et identification des principaux points de dysfonctionnement à l'origine des pertes (Rapport Final).

Table 3
Ranking of alternatives for different weight sets.

Criteria	Scen 1	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6	Scen 7
Gross profit	0.375	0.4	0.25	0	0.5	0.125	0.375
Mech/fuel requirements	0.0625	0.2	0.125	0.25	0	0.1875	0.0625
Ammonitre	0.0625	0.1	0.125	0.25	0	0.1875	0.0625
Herbicicde	0.0625	0.1	0.125	0.25	0	0.1875	0.0625
Fongicide	0.0625	0.1	0.125	0.25	0	0.1875	0.0625
Management difficulty	0.375	0.1	0.25	0	0.5	0.125	0.375
	Rank	Rank	Rank	Rank	Rank	Rank	Rank
B/C (q)	4	4	4	3	3	2	4
B/L	1	2	1	1	2	3	1
B/CLZ	2	3	2	4	1	4	2
CLZ/B/L	3	1	3	2	4	1	3

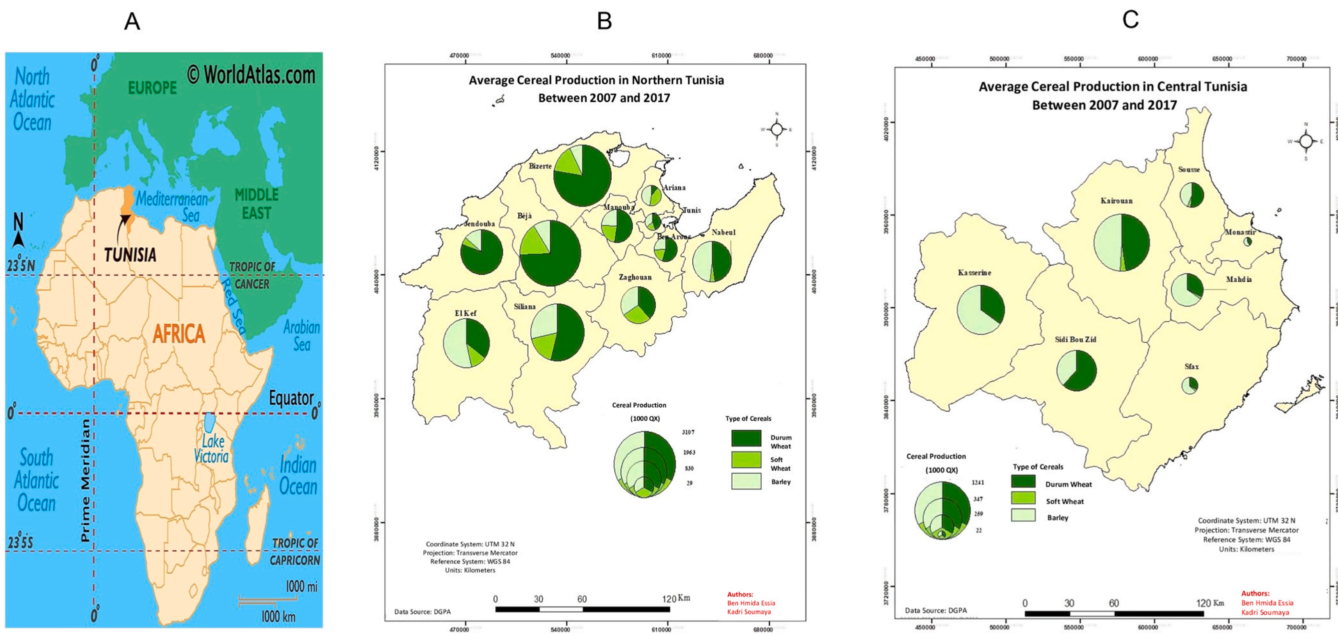

Fig. 7. Tunisia Location and the spatial distribution of cereal production in northern and central Tunisia between 2007 and 2017 (Source: ONAGRI site http://www.onagri.tn/pfe/cereale.html).

3.4. Interactions (I)

According to the interviewees and participants of the participatory workshop, cereal farmers (I2) exchange information on current agricultural challenges, the importance of sustainability, and the need to transition to best practices to address issues such as soil degradation, water shortages, and declining yields. This exchange takes place through training sessions, field visits, forums, online platforms, and television programs, facilitating dialogue between farmers and researchers. Despite such efforts, knowledge-sharing remains limited, especially among smallholders, who face major barriers to engaging in the transition. Key challenges include reluctance and resistance from some farmers due to the perceived risks of change, as well as financial constraints that hinder their ability to invest (I5) in sustainable practices. Participants also stressed the need for stronger policy integration in collaborative networks and substantial reinforcement of extension services, given the low farmer-to-agent ratio.

These challenges were also reflected in the MCA of the scenarios developed to enhance soil health. When evaluating different management practices, participants did not consider all criteria equally important. Based on production-oriented preference set and the performance of alternative scenarios, Scenario 4—cultivation with crop rotation incorporating legumes and rapeseed—emerged as the highest-ranked option. It was followed by Scenario 2, which involved crop rotation with a leguminous crop. Despite individual differences, Scenario 4 consistently ranked highest—followed by Scenario 2, aligning with expert views on the benefits of rapeseed-wheat rotations.

These results provide a comprehensive overview of Tunisia's soil health governance context. In the following section, we discuss their implications for the transition toward sustainable cereal systems.

4. Discussion and conclusions

This discussion links the MCA and socio-ecological characterization results to broader debates on sustainable soil management and agricultural transitions. It is organized in three parts: (i) implications of the results for soil health management in Tunisia's cereal systems; (ii) the role of governance, knowledge, and farmer decision-making; and (iii) context-specific limitations related to the agro-pedoclimatic diversity of Mediterranean regions.

Cereal systems in north-western Tunisia remain largely rainfed and constrained by shallow, low-fertility soils and irregular rainfall (Jendoubi et al., 2019; Chaieb et al., 2020). Combined with limited mechanization and technical support (Bencherif, 2011; Bessaoud, 2013), these conditions reinforce farmers' reliance on durum wheat monocropping. Although the analysis demonstrated that crop rotations can enhance profitability while reducing input use, their adoption remains limited by managerial complexity and the need for specialized

Table 4
Synthesis of key socio-ecological variables characterizing the Tunisian cereal system, based on triangulation of literature, interviews, and workshop data.

First-Tier Variables	Second-Tier Variables	Case Study Characterization	Source
Resource System (RS)	RS2 Clarity of system boundaries RS3 Size of resource system	The boundaries of the system are clear and include a large area of Tunisia. Cereals occupy one-third of the country's cultivable land, amounting to one and a half million hectares annually characterized by the predominance of monoculture which currently covers more than 70 % of the total areas of cereals	Jean-Louis and El Hassan, (2014); Mouelhi et al., (2016); Fig. 7
	RS5 System productivity	Despite strong efforts to improve cereal yields, productivity remains highly variable, not exceeding 2.5 t/ha for durum wheat, 2.1 t/ha for soft wheat, and 1.6 t/ha for barley between 2002 and 2016. In 2023, the cereal yields in Tunisia remain significantly lower than those of the cereal-producing countries of the north of the Mediterranean (3.2 against 7 tons per hectare in France).	Khaldi and Saaidia, (2018); African Development Bank Group, (2023)
	RS9 Location	66 % of cereal-growing areas are in the north of the country, while 44 % are in the center and south	Mani, (2019);Zaghi, (2024); Fig. 7
Resource Units (RU)	RU2 Growth and replacement rate	To increase cereal productivity, farmers use two types of fertilization: nitrogen fertilization in relatively high quantities and potassium fertilization. Durum wheat is the most demanding in terms of nitrogen fertilization, typically requiring a dose of 4 q/ha in irrigated areas and 3–3.5 q/ha in rainy areas for good yields. Soft wheat comes next, with a required amount of 4 q/ha in irrigated areas and 3 q/ha in rainy areas, followed by barley, which requires a dose of 2.5 q/ha in all conditions. As for potassium fertilization, both wheat crops need about 1 q/ha in irrigated areas. In rainy conditions, however, durum wheat requires around 0.5 q/ha, whereas soft wheat and barley do not require additional potassium and rely entirely on soil absorption, making extra potassium inputs unnecessary.	INGC, (2024);Annabi et al., (2013);Ben hamouda et al., (2015); Khaldi and Saaidia, (2018);Chebbi et al., (2019);Zouhair et al., (2021);Mnasri, (2021);Zaghi, (2024); Interviews
	RU4 Economic value	In Tunisia, cereals play a significant economic and social role. They account for approximately 30 % of the Utilized Agricultural Area (UAA) and 9 % of agricultural use, as well as 50 % of agricultural employment, and constitute the basic food for the Tunisian population. In 2021/2022, the prices were 130 dinars per quintal of durum wheat (1300 dinars per ton), 100 dinars per quintal of soft wheat (1000 dinars per ton), and 80 dinars per quintal of barley (800 dinars per ton). However, 2022/2023 was an exceptional year due to severe droughts, and the Grain Office decided to increase the purchase price of cereals by 10 dinars per quintal (100 dinars per ton) to support producers and offset their financial losses caused by the drought.	
	RU7 Spatial and temporal distribution	In Tunisia, cereal farming depends mostly on rainfall, with only around 80,000 ha being irrigated (6.6 %). This practice is mainly in the northwest, where rainfall is higher. Durum wheat is grown in monoculture in both the humid and semi-arid regions and favors fertile, deep clay-limestone and clay-alluvial soils. Barley, the second most planted cereal, thrives in various soil types, with well-drained loamy soils being ideal. Soft wheat is also cultivated in the north, preferring less fertile, shallow soils and is best grown on well-drained, low-slope land to prevent water stagnation and fungal diseases.	
Governance Systems (GS)	GS1 Government Organizations GS2 Non-Governmental Organizations	Complete description in the Table 5	
	GS3 Network structure	We have not identified any network structure, although the cereal sector range from production to final consumption, including the Office of Cereals, the Ministry of Agriculture, the Ministry of Commerce and Industry, cereal producers, cooperatives, private collectors, and agro-food companies. We did not identify any formal or informal network structure that implies coordination between stakeholders.	Khaldi and Saaidia, (2018); Interviews
	GS4 Property rights systems	Most agricultural land used for cereal production belongs to the state, and private owners, who mostly rent out their land. The fragmentation of agricultural land, including areas dedicated to cereal crops, is a significant phenomenon in Tunisia, mainly linked to inheritance traditions and laws. These practices lead to the continuous division of land among heirs, resulting in the predominance of farms smaller than 5 ha. This situation affects cereal production by making it difficult to achieve economies of scale, limiting mechanization and the adoption of modern techniques, and potentially reducing productivity on small plots.	Imache and Jamin, (2012); Ben Kahla et al., (2017); Interviews
	GS7 Constitutional rules	The cereal sector is regulated by public authorities through the Office of Cereals and the General Compensation Fund. Subsidy	Makhlouf, (2010); Rastoin and Benabderrazik, (2014)

(continued on next page)

Table 4 (*continued*)

First-Tier Variables	Second-Tier Variables	Case Study Characterization	Source
		policies aim to support both producers and consumers to ensure national food security and social stability.	
	GS8 Monitoring and sanctioning rules	Generally, there are no locally adapted rules in Tunisia for monitoring and sanctioning the use of cereal lands. Agricultural lands are not fenced, allowing livestock to easily enter without the owner's permission, often causing overgrazing issues.	Interviews and data from the INGC, (2024)
Actors (A)	A1 Number of Actors	Cereals involve approximately 250,000 producers (43 % of agricultural operators), mostly small farms. About 80,000 operations primarily focus on monoculture cereal production.	Rastoin and Benabderrazik, (2014), Khaldi and Saaidia, (2018); Interviews
	A2 Socio-economic attributes	The age structure of cereal farmers reveals a trend toward aging, with an average age between 56 and 60 years. Additionally, the level of education is considered low, which limits farmers' ability to assimilate information	
	A5 Leadership and entrepreneurship	Leadership in the cereal sector exists through initiatives like the national institute of field crops (INGC), which employs an approach involving satellite farmers and lead farmers. These lead farmers are selected, coached, and trained to disseminate best practices through their experiences and demonstration plots to small farmers. However, participants of the workshop indicated that the impact of this approach is limited and not reaching the most needed farmers.	El Hani, (1997);Braiki, (2018);Annabietal, 2013; Benhamoudaetal, 2015;Khaldiand Saaidia, (2018);Chebbietal, 2019; Elmakari, (2016); Zouhairetal,2021;Mnasri, (2021);Zaghi, (2024); INGC; Interviews; Workshop
	A9 Technology Availability	Tunisian farms are generally categorized into three types: large (>50 ha), which are rare and feature diversified cropping systems with advanced mechanization; medium (<50 ha), where mechanization is moderate and often involves renting combine harvesters; and small (<10 ha), which are the majority and use traditional monoculture systems with rented mechanization equipment	
Interactions (I)	I2 Information Sharing	Information transfer between farmers and researchers occurs through training days, field visits, forums, and online platforms, but it is considered limited	El Hani, (1997);Taamallah, (2010); Annabi et al., (2013);Ben hamouda et al., (2015);Khaldi and Saaidia, (2018);Chebbi et al., (2019);Zouhair et al., (2021);Mnasri, (2021);Cheikh M'hamed et al., 2022;Guesmi et al., (2023);Zaghi, (2024); INGC, (2024); Interviews; Workshop
	I5 Investment Activities	Small cereal farmers lack the capacity to invest in new sustainable agricultural practices, such as direct seeding. The adoption of new technologies in the cereal sector has been slow at the farm level. This includes new cereal varieties and species for crop rotation, as well as recent agronomic practices for soil management, irrigation, fertilization, and crop protection. However, these technologies are not yet well suited to local conditions and are mostly limited in cereal-growing areas.	

equipment. These barriers illustrate how biophysical constraints intersect with governance and capacity gaps, hindering transitions toward more sustainable soil management.

Aggregate performance assessments (e.g., weighted-sum methods) often privilege alternatives with strong production outcomes, yet overlook operational constraints, leading to desirable but unrealistic choices. To address this, studies in different contexts have applied non-compensatory outranking methods to better evaluate alternative cultivation practices and identify suitable incentive mechanisms for promoting sustainable transitions (Król et al., 2018; Zobeidi et al., 2024). Those non-Maghreb agronomic studies are strictly used as methodological examples to further enhance the robustness of the current analysis. Additionally, since the data used in this study relied on average values and did not account for spatial variation, incorporating pedoclimatic conditions would enhance the relevance of the results by aligning them with local environmental and farm-specific characteristics. For this purpose, spatial MCDA that has increasingly been used in land use and conservation studies (e.g. Strager and Rosenberger, 2006, Comino et al., 2014) could be adapted in future research to evaluate crop rotation suitability at landscape level. Such integration would strengthen the capacity to identify priority areas for soil restoration and to account for heterogeneity in local conditions.

Our results align with earlier studies showing that the adoption of soil health–enhancing practices remains limited. Recent analysis from the Maghreb (e.g., Gharbi et al., 2025; Guesmi et al., 2023), emphasize the institutional and economic trade-offs shaping the adoption of sustainable soil management practices. Smallholders managing less than 10 ha face strong climatic and institutional uncertainty, while the transition toward conservation and rotation practices remain constrained (Cheikh M'hamed et al., 2022; Souissi et al., 2023; Gharbi et al., 2025). This is in line with national assessments showing that conservation agriculture in Tunisia remains at an early stage of scaling and that this pattern reflects governance barriers rather than agronomic infeasibility (Cheikh M'hamed et al., 2022). Among small farms in Tunisia, our study highlights resistance to change connected to a combination of local factors, also identified by others (Guesmi et al., 2023; Souissi et al., 2023: Gharbi et al., 2025). The technical, economic, and institutional constraints identified reflect systemic governance weaknesses rather than isolated operational challenges. Although gender was beyond this study's scope, its relevance is acknowledged, and further detailed research is needed.

Using the SES framework, we examined the interlinked challenges and found that isolated interventions are insufficient to drive the agricultural transition needed. A multi-level strategy is required. This approach is widely supported in the literature on agricultural transitions, which underscores the importance of coordinated efforts across multiple levels to achieve sustainable outcomes (Guimarães et al., 2019; Magrini et al., 2019). Stakeholder engagement proved crucial for identifying transition pathways tailored to the Tunisian context. Despite cultural particularities, these pathways closely align with those observed in European settings (Sutherland et al., 2014; Esgalhado et al., 2021), particularly in the following areas:

- Raising farmer awareness through training, resource access, and knowledge exchange is essential for overcoming barriers and enabling inclusive, sustainable change.

Table 5
Actors and their characteristics constructed with the data collected by the interviews.

Actors		Action
Government organizations	DGPA: General Directorate of Agricultural Production	The administrative body responsible for designing and implementing government policy on plant and animal production
	DG/ACTA: General Directorate for the Planning and Conservation of Agricultural Land (national policymaker)	The DG-ACTA plays an important role in developing and implementing several strategies and plans to preserve agricultural land, soil, water, and vegetation cover by assessing resources, conducting analyses, and promoting measures for the sustainable use of these natural resources.
	ACES CRDA: Water and Soil Conservation Districts from the *Regional Commissary for Agricultural Development* (regional implementer under CRDA)	Implements DG/ACTA strategies locally in geographically delimited areas and manages soil and water conservation practices
	OC: Cereals office	The OC holds a monopoly on local purchases (only wheat) and the import of all cereals intended for consumption
	INGC: National institute of field crops	The INGC is one of the main public organizations involved in implementing the national strategy to achieve food security. It focuses on enhancing the development, transfer, and dissemination of sustainable agricultural technologies to increase the production and quality of major crops
Non-governmental organizations	AVFA: Agency for Agricultural Dissemination and Training	The role of the AVFA is to implement training and agricultural dissemination programs outlined in the economic and social development plans.
	UTAP: Tunisian Union of Agriculture and Fisheries	The UTAP is a Tunisian agricultural union that represents farmers, defends their interests, and protects their rights
	ATAE: Tunisian Association for Environmental Agriculture	Support and guidance for farmers to transition towards sustainable agriculture
	APAD: Association for Sustainable Agriculture	
Private Sector Companies	Carthage Grains	Carthage Grains specializes in the local processing of oilseeds into vegetable oils and meals intended for animal feed
	COSEM: Central Mutual Seed Company	Ensures the multiplication of selected seeds derived from the varietal developments of INRAT and collects cereals
	SOSEM: Private Seed Company	Operates in the field of the multiplication and marketing of seeds
	AgroSystème	Sells seeds
	CMA:Agricultural Multi-Service Counter	A company established in 2001, its main activity is the collection and storage of cereals as an agent for the Cereals Office
Research Institutes	INRAT: National Institute of Agricultural Research of Tunisia	Conducts research and develops new seed varieties adapted to biotic and abiotic stress. Others conduct research on new adapted species and varieties, analyzes the microbial flora of the soil to improve plant nutrition and adaptation, and works on the rehabilitation of contaminated soils
	INAT: National Agronomic Institute of Tunisia	
	CBBC: Centre of Biotechnology of Borj Cedria	
Users	Producers	Cereal production
	Collection centers	Collect cereals
	Mills; bakeries	Transformation of cereals into semolina, couscous, pasta, flour, bread, among others
	Grocery stores, supermarkets, restaurants, etc	Distribution of products to consumers

- Promoting farmer organization: Supporting the formation of producer groups enhances solidarity, knowledge sharing, and collective action.
- Adopting supportive public investment policies—redirecting public funding to explicitly promote agroecological transition—is crucial. Currently, such support is largely confined to environmental strategies, with limited integration in agricultural policy—except for organic farming (Jalkh et al., 2024).
- Improving access to suitable equipment is vital to enable conservation agriculture. For example, tillage equipment remains largely inaccessible to smallholders due to high costs, with most existing equipment made available through international cooperation projects.
- Enhancing access to credit: More accessible financing would empower farmers to invest in sustainable practices.
- Targeted support should focus on small cereal farms (<10 ha), which are highly vulnerable yet essential for the transition. Currently, subsidies focus primarily on chemical fertilizers for cereal crops, a policy that undermines sustainable practices.

Together, these transition pathways reinforce that improving soil health is a shared responsibility among farmers and society at large, where researchers, industry actors, and policymakers play pivotal roles (Hughes et al., 2023). Soil should be managed as a common good, requiring policy frameworks that ensure shared responsibility and inclusive governance mechanisms. Farmers' land management decisions arise from complex interactions and cannot be explained by simple, linear models (Burnham et al., 2023). This study demonstrates the multifaceted transition toward sustainable cereal management in Tunisia and underscores the vital role of collective action.

Most cereal farmers in Tunisia (62 %), operate on small plots of less than 10 ha and face structural barriers that prevent farmers transitioning independently. The proposed threshold of 10 ha is based on national agricultural statistics indicating that most Tunisian cereal farms fall below this size, with a strong predominance of holdings under 5 ha (Table 4). Rather than adopting a legal or fixed definition of "small farms," this threshold is used to distinguish farmers who face higher constraints in terms of mechanization, credit access, and capacity to implement rotation or soil conservation practices (Bencherif, 2011; Bessaoud, 2013; Gharbi et al., 2025).

Given projected temperature increases and reduced rainfall, promoting soil health practices is not only an environmental goal but also a key adaptation strategy for Tunisia's agriculture. Integrating these aspects within a socio-ecological framework helps to reveal both the opportunities and constraints for sustainable intensification in cereal-based systems. Key levers for improving soil governance in Tunisia are: (i) better coordination between the General Directorate for the Planning and Conservation of Agricultural Land and the Regional Commissary for Agricultural Development to align national and local programs; (ii) integrating soil health objectives into subsidy schemes; and (iii) strengthening participatory monitoring to involve farmers and cooperatives in policy evaluation.

Tunisia's agricultural governance is fragmented, with overlapping mandates among agencies, creating uncertainty in implementing sustainable soil management measures (Taamallah, 2010; Cheikh M'hamed et al., 2022). Framing soils as key ecosystem-service providers can help reorient cereal-system policies toward long-term sustainability, if policymakers have clear evidence that productivity can be sustained under recurrent drought. Similar constraints exist across Mediterranean countries such as Spain, Italy, and Morocco, but Tunisia's highly centralised system still limits effective horizontal collaboration between institutions.

Achieving sustainable soil management in Tunisia's cereal systems calls for a coordinated, multi-level governance framework that bridges institutional, sectoral, and spatial boundaries, aligning national policies with local realities. Strengthening cooperation between governmental agencies, research institutions, and farming communities is essential to ensure that policies are not only technically sound but also socially legitimate and economically viable. A national strategy explicitly focused on soil health—integrated into agricultural, environmental, and climate policies—would provide the foundation for long-term resilience. By positioning soil as a strategic natural asset and public good, Tunisia can foster a transition that balances productivity, sustainability, and equity, contributing to the broader Mediterranean and global agendas for sustainable land use.

CRediT authorship contribution statement

Stelios Rozakis: Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Amélie Bourceret:** Writing – review & editing, Validation, Supervision. **Aya Khamassi:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Maria Helena Guimarães:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Fraj Chemak:** Validation, Supervision. **Mélanie Requier-Desjardins:** Writing - review & editing, Validation, Supervision.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2025.107909.

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