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Enhancing the resilience of vulnerable social-ecological systems: pathways toward sustainable oases in southeastern Tunisia

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Oases have long been a source of life for farming communities in regions characterized by water scarcity. Adopting "resilience thinking" to analyze the capacity of oases to continue providing goods and services despite their vulnerability means considering the various components in one Social-Ecological System (SES). The oases of Gabès, located in southeastern Tunisia, as a SES, have witnessed several changes and shocks over the years, which contributed to increasing their vulnerability. Understanding the system dynamics of the oases of Gabès enables analyzing stakeholder connectivity and variables of influence to develop policy orientations toward preserving the SES. To achieve these objectives, a detailed survey was conducted with 240 farmers, 10 institutional stakeholders and 9 associations. The questionnaires included questions on social and ecological characteristics of the SES, connectivity and interactivity between key stakeholders, and identification of variables of influence and ways of improvement for the SES sustainability. The results identify several major challenges facing the SES, including water scarcity, land tenure, and the lack of adequate regulation and financial support for farmers. Furthermore, the power and influence analysis reveal that farmers have considerable influence over the SES's trajectory, especially their role in sustaining agricultural activity and maintaining ecosystem services. However, stakeholder perceptions are divided especially concerning the role of the industrial sector, which is often viewed as a threat to SES sustainability due to its impact on water resources and land use. The analysis enabled constructing a causal loop diagram discussing the impact of water resource availability on agricultural activities. It also highlighted key policy implications by presenting ways of improvement on issues related to improving water availability for irrigation, the development of an adapted financing framework, the implementation of adequate regulation measures, and the clarification of land tenure arrangements.

KEYWORDS

resilience, social-ecological system, interconnectivity, oases of Gabès, stakeholders, power and influence analysis

1 Introduction

Sustainable development has held a central place in global discussions and reflections for several decades. Confronted with mounting challenges such as environmental degradation, aquifers depletion, and growing socio-economic inequalities, the scientific community and decision-makers are promoting a pledge toward a viable balance between economic growth and ecological sustainability (Ruggerio, 2021; Carlsen and Bruggemann, 2022). This alignment relies on the imperative to foster equitable human development while preserving ecosystems and ensuring the responsible stewardship of natural resources for future generations. The relationship between humanity and nature is marked by a complex interconnectivity where human activities have an impact on ecosystems. As such, a deep understanding of these interactivity is crucial for shaping resilient, inclusive, and sustainable SESs (Cumming et al., 2006; Wang et al., 2024).

SESs refer to complex and dynamic interactions between social components (such as institutions, human behaviors, and economic practices) and ecological components (such as biodiversity and natural resources) (Preiser et al., 2018; Schlüter et al., 2019). These systems are characterized by a high level of complexity, notably marked by non-linear processes, feedback loops, and uncertainty regarding their evolution. As such, SESs can be influenced by different factors such as human activities and climate change (Schlüter et al., 2019; Biggs et al., 2021; Feng et al., 2021).

Furthermore, SESs function according to an adaptive cycle composed of four distinct phases: growth, conservation, collapse, and reorganization. This conceptual model, originally developed by Holling (1973) and further elaborated by Gunderson and Holling (2002), illustrates how complex systems evolve over time through iterative phases of stability and transformation. The initial two phases—growth and conservation—form what is known as the foreloop, a period during which resources accumulate, structures consolidate, and efficiency increases. However, this increased rigidity can reduce the system's capacity to adapt to unexpected shocks, making it more vulnerable to disruption. The latter two phases—collapse and reorganization—make up the backloop, a critical period characterized by system breakdown, release of accumulated capital, and the emergence of new configurations. These phases allow for renewal, innovation, and the potential redefinition of system trajectories (Gunderson and Holling, 2002; Walker and Meyers, 2004).

This model has profound implications for the governance and management of SES. It suggests that enhancing resilience involves recognizing which phase a system is currently in, and adapting strategies accordingly—for example, by building adaptive capacity during the conservation phase, or supporting innovation and experimentation during reorganization (Gunderson and Holling, 2002; Fath et al., 2015). Overall, the adaptive cycle framework offers a powerful lens through which to understand system dynamics, anticipate regime shifts, and design interventions that support long-term sustainability.

Closely linked to the adaptive cycle is the concept of resilience, which refers to the capacity of SESs to adapt or transform in response to changes. Resilience goes beyond simply absorbing shocks; it emphasizes the ability of systems to learn, reorganize, and innovate in the face of disturbances such as financial crises, climate change, or social upheaval. In this context, resilience reflects a system's potential to harness disruption as a source of renewal—generating novel ideas, institutional arrangements, and practices that contribute to its long-term viability (Abel et al., 2006; Allison and Hobbs, 2004; Anderies et al., 2006; Wang et al., 2024). Thus, the adaptive cycle provides a framework to understand system dynamics, resilience determines the system's capacity to move through these phases without losing essential structure and function.

Furthermore, a resilience thinking approach tries to investigate how systems, where people and nature are interacting, can be analyzed and managed to ensure sustainable provision of goods and services (Simonsen et al., 2015). There are, in most cases, significant differences between conventional management and development plans and approaches and those (plans and approaches) developed considering resilience as a central element. The conventional approach of managing SESs is based on a top-down decision, which has demonstrated its inefficiency. This approach often works well initially but then runs into problems. Indeed, responding to uncertainty, crises, and unexpected events involves increased controls, with transaction costs increasing as the system evolves and approaches the thresholds of key driving variables. Rather than focusing on the need to control variability and keep the system in an optimal status, management and governance based on the concept of resilience can focus on key control variables, alternative regimes, and thresholds (Blann et al., 2000; Adger et al., 2005; Anderies et al., 2006).

The oases of Gabès, located in southern Tunisia, constitute a SES that fulfills environmental, economic, and social functions. In addition to being a rich cultural heritage, they have shown an essential role in maintaining biodiversity, combating desertification, and adapting to climate change. The SES natural ecosystem is very rich and diverse; however, it has been largely impacted by human activity. In addition to a fragile environment, characterized by limited natural resources, inadequate agricultural practices resulted in decreased productivity (Mahdhi et al., 2022).

The SES has undergone a series of transformations, initially affecting the production system, which has had significant repercussions on its socio-economic and ecological dynamics. These changes, mainly of anthropogenic origin, involve the intervention of various actors in the management of this ecosystem, including public institutions, associations, and farmers (Carpentier, 2007; Carpentier and Gana, 2017).

Interconnectivity between its different components has contributed to shaping its capacity to adapt to changes and shocks. The social component has played an important role in changing the system landscape. The SES was characterized by abundant natural resources, large land size, and adapted social organization. During the past decades, it has been exposed to many events and shocks impacting its capacity to provide goods and services, such as degraded soil, decreased freshwater availability, and small size land due to fragmentation. This situation has been aggravated by the impact of external factors such as the establishment of several chemical industries in the region, which led to polluting the environment and decreasing farmers' interest in farming due to decreased productivity. Despite its vulnerability, the SES is still existing and, although some farmers have abandoned their farms as a reaction to decreased profitability, others are still cultivating their lands (Ben Saad, 2010; Ben Salah, 2011).

The objective of this research is to apply the concept of resilience to better understand how oases, as vulnerable SES, can continue to

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function and provide essential goods and services despite the changes and shocks that have contributed to the degradation of their various components. It also aims at identifying potential pathways to improve the sustainability of these systems. Investigating the system's composition and the interconnectivity between its components, through analyzing stakeholder perceptions, dynamics of power and influence among different groups, and causalities between the SES influent variables, enable understanding the system behavior and proposing policy recommendations for strengthening resilience and promoting long-term sustainability.

2 Materials and methods

2.1 Study area

The oases of Gabès, located in southeastern Tunisia (Figure 1), are conventional oases with archaic irrigation systems, high density of palm dates and trees, and a high rate of small land size due to land fragmentation (Carpentier and Gana, 2017).

They are characterized by arid climatic conditions and severe desertification with only 30% of arable land (ODS, 2020). Rainfall is very low with only 100 to 300 mm/year (Institut National de la Météorologie, 2022). Groundwater is the main source of irrigation, but it is also a cause of conflicts and competition between farmers. Planting and maintenance of trees are the main agricultural activities in the region with more than 76% of the local agricultural production (ODS, 2020). Many varieties are cultivated such as fig, pomegranate, vine, citrus, peach, apricot, apple, in addition to vegetables. Fodder crops, mainly alfalfa, are heavily planted and appreciated by livestock farmers. There are also aromatic crops (such as roses, basils, and mints) and industrial crops (such as henna and tobacco) in the oases.

This SES is characterized by a particular cropping system with three different crop layers: the upper level formed by date palms which are generally planted on the borders of the farm, the mid-level includes trees (such as fig and pomegranate), and vegetables (such as fodder and industrial crops) at the lower level. This cropping system has contributed to enriching the system biodiversity (Ben Saad, 2010; Ben Salah, 2011; Bayrem et al., 2013).

This type of production system also creates a special natural ecosystem through increased humidity and reduced evapotranspiration in a context of water scarcity. Socioeconomically, although consumed locally, crop diversification allows better market access through availability of different crops all year long. The SES produces certain rare varieties that are found almost exclusively in Gabès. This diversification has been adopted for decades and owes its development to the indigenous knowledge of the local communities and the oases characteristics, which provide appropriate climatic conditions for the growth of several crops. To cope with the decreasing productivity, livestock is commonly practiced by farmers in the SES and resulted in fodder production. Indeed, farmers, who have become breeders, find their benefit either by selling their production on the local market where demand remains high or by self-consuming it to mitigate the increase in fodder prices.

The oases of Gabès face important social, economic, and ecological challenges. Environmental problems such as the

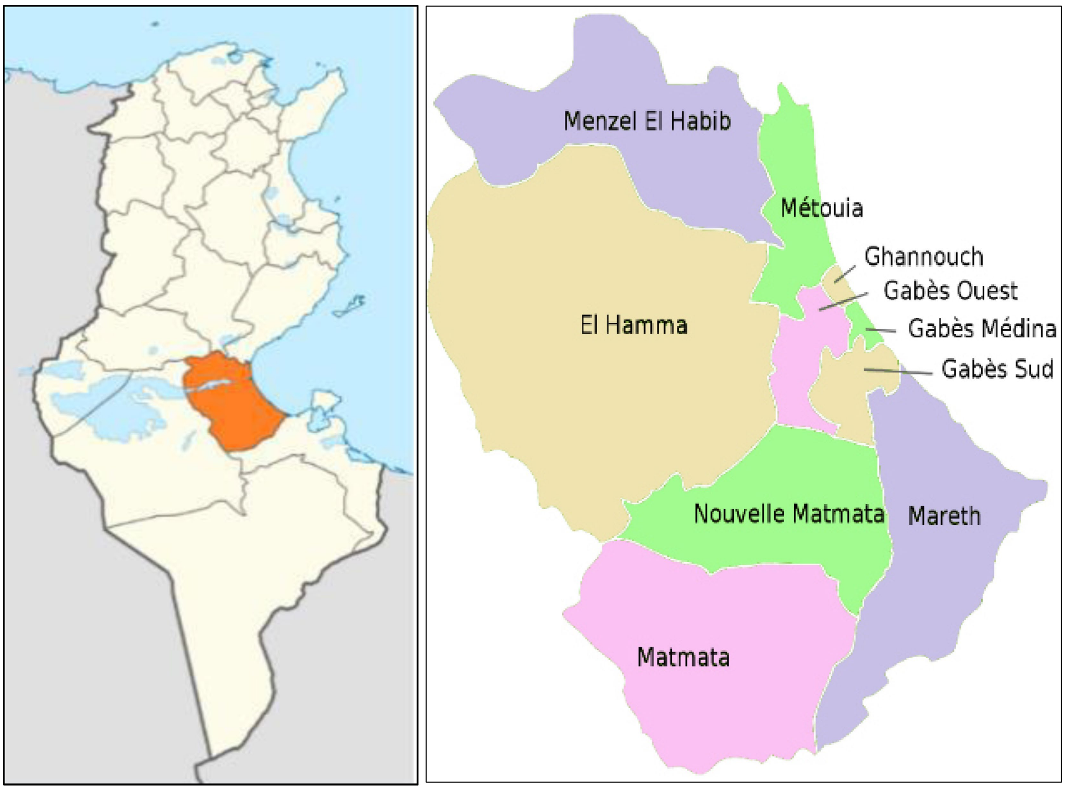

FIGURE 1
Location of the Gabès governorate (ODS, 2020).

degradation of natural resources combined with climatic and socio-economic challenges have reduced the possibility of sustainable investment strategies by local farmers, such as technology-based water saving techniques.

Many stakeholders are playing a role in the management of this SES. These are essentially governmental institutions, farmers, and civil society organizations (such as water user associations and environmental associations). The oases governance model has evolved over the years. Indeed, they were managed for a long time according to ancestral rules. In 1960, the national authorities decided to be fully responsible for the oases' management. In the 1990s, a more participatory governance approach was adopted where different actors participate in the decision-making process and the oases governance in general (Ben Saad et al., 2009; Carpentier and Gana, 2017).

2.2 Data collection

To analyze the resilience of the SES, three types of information were collected. First, historical data on the evolution of the SES were gathered, including major events, structural changes, and external shocks (such as environmental disruptions, socio-political changes, and economic crises) that have influenced its dynamics. Second, stakeholder-related information included the identification of key actors—such as farmers, local authorities, water user associations, NGOs, and technical services—their roles, levels of influence, and perceptions of system changes, as well as the nature of their interactions, whether collaborative or conflictual. Third, a set of qualitative (such as local knowledge and perceptions of environmental change) and quantitative data (such as crop yields and water table levels) was used to construct a Causal Loop Diagram (CLD), enabling the visualization of feedback mechanisms and the identification of variables driving the system's behavior and resilience.

Data collection started with literature review on historical data on the evolution of the SES, including major events and structural changes that have influenced its dynamics over time. Then, a series of open-ended interviews were carried out with 10 institutional stakeholders in Gabès. These included representatives from the Coastal Protection and Planning Agency (APAL), the Agricultural Investment Promotion Agency (APIA), local development institutions, the South Development Office (ODS), the Institute of Arid Regions (IRA Médenine), the Regional Commissary for Agricultural Development (CRDA) of Gabès and the extension services Unit (CTVs). In addition, interviews were held with 9 civil society organizations (three (3) water user associations and six (6) environmental associations). This first round of interviews aimed at defining boundaries of the SES, identifying stakeholders and variables of influence, and propose a causal loop diagram. The second round of interviews included detailed surveys conducted with the 19 institutional stakeholders' and associations in addition to 240 farmers representing 10% of the total number of land owners in the oases of Gabès. Farmers were selected randomly with priority given to women.

Data collected are related to socioeconomic status of the farmers, including income levels, household size, and sources of livelihood. It also examined cropping practices, such as crop types and input use. Special attention was given to water management techniques, considering the scarcity of water resources in the region; this included irrigation methods, water source access, and conservation practices. Furthermore, the study investigated farmers' access to agricultural support services, including extension programs, financial assistance, cooperatives, and technical training. Finally, the survey addressed perceptions and local knowledge regarding environmental changes, such as climate variability, land degradation, and biodiversity loss, which are increasingly affecting the sustainability of oasis farming systems.

The results of the survey were used to analyze the stakeholder connectivity, identify variables of influence and construct the causal loop diagram, and propose ways of improvement toward achieving the SES sustainability.

2.3 The SES framework

The resilience of the SES is closely related to the power and influence exerted by different groups. SES dynamics have significant effects on the behavior of both individuals and groups within the system. Understanding these effects means exploring operational, formal, and informal rules that shape configurations of actors holding power to initiate and manipulate these processes driving the system's functionality and adaptability (Epstein et al., 2014; Van Zanten and Tulder, 2021).

The SES framework includes important consideration of the social component, where a link is established between power/influence approaches and institution-centered approaches to the study of SES. Power/influence centered approach focuses on the perception of the SES groups, including farmers, of the power and influence of stakeholders on the SES evolution and their control over and access to natural resources (Epstein et al., 2014).

It is important to understand who profits from changes and explore who takes what from whom. There are usually indicators of power/influence in the SES, such as the operational rules governing the system, which can be used to identify how different levels of access and control over resources are influenced by the system structure and interconnectivity between groups and how these relationships may influence social-ecological outcomes. The concept of power/influence refers to common idea that institutions, represented by rules, norms, and shared strategies, include within their structure the ability to influence societal outcomes. Institutional power/influence may be used and manipulated by individuals or groups to achieve their own interests, which can be the source of and the solution to social problems at the same time (Epstein et al., 2014; Bouchet et al., 2022).

An individual can have a small degree of power, even though the individual has absolute control if the amount of opportunity in a situation is small, which results in a high degree of influence. Power/influence is related to conflicts between two or more groups part of a SES and participating in some political environment (Ostrom, 2005).

Stakeholders were asked to rank (from −10 to +10) their perception of power and influence of different stakeholders using boxes as shown in the document. Points condensation indicates the perception of the interviewed stakeholders of power and influence of the other stakeholders. It indicates the power and influence of stakeholders on the SES evolution and their control over and access to natural resources. It complements the identification of social variables of influence and enables to identify how different levels of access and control over resources are influenced by the system structure and

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interconnectivity between groups and how these relationships may influence social-ecological outcomes (Figure 2).

The collected Venn diagrams were then systematically analyzed by comparing the spatial arrangements and proximities drawn by different respondents. This qualitative comparison allowed us to identify common patterns, divergences, and underlying perceptions regarding the distribution of power. By coding and categorizing the stakeholders' placements and intersections, we could quantify the perceived influence of each group and assess the degree of recognition and interaction among them.

Moreover, Causal Loop Diagram serves as a valuable tool to map the structure and feedbacks loops within a system, providing insights on the system's behavior and underlying dynamics. This approach supports the development of adaptative strategies in response to change. CLD reflects the reality through describing dynamic circular influence between variables connected through causal relationships (Haraldsson, 2004; Inam et al., 2015; Bouchet et al., 2022).

By analyzing interconnectivity and feedbacks among the system's components, the CLD is constructed around the most influential variables, as identified through stakeholder perceptions. This participatory approach ensures that the diagram reflects both the structural and functional aspects of the SES, highlighting key drivers, constraints, and leverage points for sustainable management.

The following box explains how to read the causal loop diagram (Figure 3):

The key variables were identified using different steps: literature review, iterative open interviews with stakeholders, and detailed questionnaires. All these steps also helped in analyzing causality between variables, directions changes, and if the loop reinforces the system behavior toward a balance or not. In our analysis, the steps followed include CLD construction based on literature review, first CLD revision based on open investigation, second CLD review based on detailed questionnaire, interpretation of system behavior, and formulation of policy scenarios (Dhirasasna and Sahin, 2019).

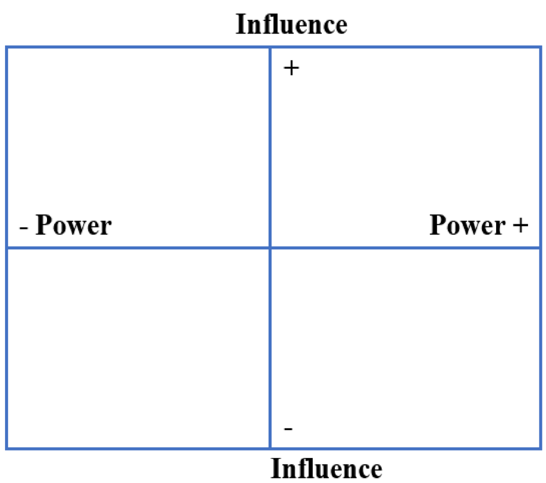

FIGURE 2
Corresponding boxes of power/influence.

3 Results

3.1 Socioeconomic profiles and characteristics of the local population

The survey included 240 farmers, with a notably low representation of women, who account for only 8% of the respondents. The questionnaire targeted farm owners and this result is meant to only showing the limited access of women to the property in the study area. The list of investigated farmers was provided by WUAs, and priority was given to women when interviewing farmers. The SES is primarily populated by an aging farming population, with 88% of the respondents being over 45 years old, and 40% of them being over 62 years old.

The oases of Gabès are composed of 4 main areas: Chenini, Chott Elferik, Chott Essalem, and El Manzel. While areas are largely similar in size, Chott Elferik is considered as a small oasis. In terms of land size, the SES is characterized by a high degree of small plots due to land fragmentation caused mainly by heritage. The survey revealed that only 14% of farmers have land size above 1 ha, with the largest landholding among the surveyed population is 5 ha. Notably, 67% of lands are below 0.5 ha, which affects land productivity and increases loss of agricultural land impacting SES resilience. The SES is facing serious land tenure issues. Land fragmentation and parcellation have increased over the years with 33% of farmers surveyed having 2 or more plots.

The oases of Gabès present a very special production system characterized by a multilayered cropping pattern, where different plant species are cultivated in vertical strata—from tall trees to understory cash crops. Despite the limited land size, 97% of farmers cultivate 2 crops and 90% opt for 3 crops. The economic performance of farmers is notably weak. Survey results indicate that 70% of farmers earn a gross annual income of less than 9,000 Tunisian Dinar (1 TND = 0,335 USD in 2025), placing them in the low to very low-income bracket. This declining profitability of agricultural activities has both positive and negative implications for the resilience of the SES. On the one hand, agriculture remains the primary source of income for only 34% of the farmers surveyed. The majority—approximately 64%—supplement their livelihoods through employment in either the public or private sectors. Reduced economic reliance on agriculture led to gradual disengagement from traditional farming practices and reduced investment in the land, potentially threatening the sustainability of the system.

3.2 Influence of management and governance practices on SES dynamics

In the oases of Gabès, farmers report a marked decline in satisfaction with water resource management compared to three decades ago. This perception highlights growing concerns regarding the efficiency and sustainability of current governance approaches. According to the survey, 67% of farmers expressed dissatisfaction with both the availability of water and the continuity of irrigation flows. Historically, farmers received water allocations from water user associations every 7 to 15 days. However, in 2024, this interval has significantly increased, with water being distributed only once every

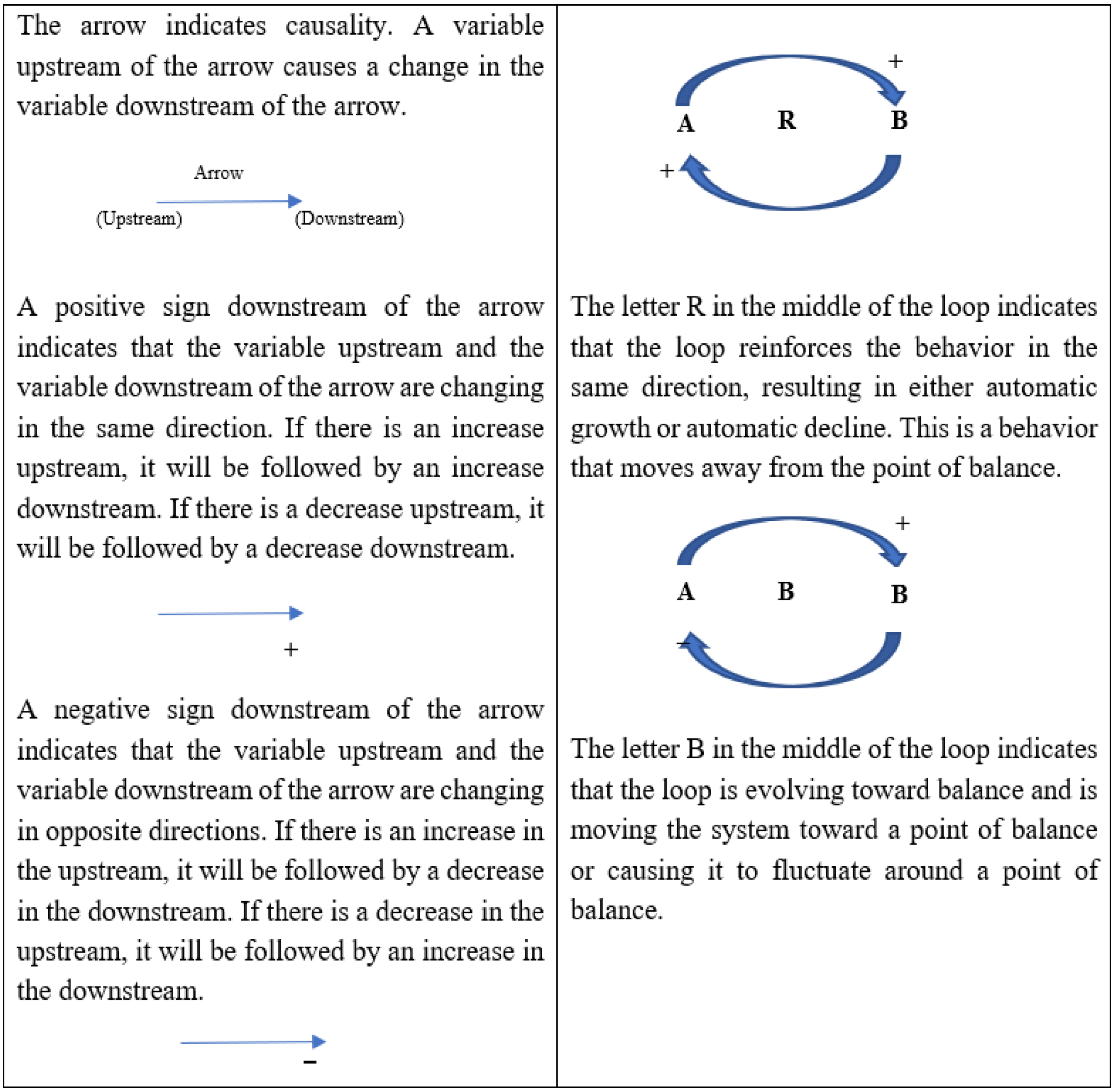

FIGURE 3
Causal loop diagram explanation (Haraldsson, 2004).

two to three months. This new water allocation regime undermines agricultural productivity and threatens SES resilience.

Nonetheless, 33% of the farmers indicated that water scarcity started before the 1990s, although less severe at that time. This suggests a long-term decline in water availability, exacerbated by insufficient adaptation and management measures over the years.

Soil quality ranges from good to moderate. Farmers reported soils rich in nutrients, with adequate moisture levels, relatively high productivity, and low salinity—favorable conditions that have traditionally supported the multi-layered cropping system of the oases.

On land tenure, 66% of farmers considered land sizes in the past to be acceptable, with less fragmentation. In contrast, 34% perceived that land tenure challenges began to intensify in the late 1980s, a trend that has since worsened due to inadequate strategies. Also 34% of farmers indicated that agricultural profitability was higher three decades ago, highlighting a broader trend of economic decline in the sector that contributes to growing disinterest in traditional farming and reduced investment in land maintenance.

Products marketing follows the same logic where markets, in particular local ones, are accessible with a facility to find agreements with intermediaries. However, when it comes to institutional support, farmers express strong dissatisfaction with both local and central authorities. Over 70% of farmers surveyed believe that local institutions have failed to fulfill their responsibilities in providing the necessary technical and financial assistance. This finding confirms a widespread perception among respondents that agricultural producers—viewed as the backbone of the social-ecological system—are not receiving the support they are entitled to.

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3.3 Stakeholders' connectivity in SES

3.3.1 Identification of stakeholders' roles

In the oases of Gabès, qualitative analysis revealed that farmers are at the core of the SES. As such, the analysis of connectivity begins with examining the interactions between farmers and other key stakeholders. In the oases of Gabès, analysis of farmers' perceptions highlights the critical role this group plays in the preservation of the oases system. Indeed, 82% of farmers prioritize their role in terms of ensuring continuity of ecosystem services, preserving indigenous practices, and transferring knowledge across generations.

The continuation of agricultural activity is widely perceived as the primary factor influencing the evolutionary trajectory of the SES over time. This perception underscores that maintaining farming practices is not only essential for livelihoods, but also for sustaining ecological and social balance within the oases.

Farmers' perception of local authorities' role in the SES is mainly around the provision of technical and financial support, as well as facilitating development initiatives. 60% of farmers highlight the importance of technical and financial support provided to farmers as the main cause of resilience. Technical support is related to extension services, rehabilitation projects, capacity-development, and assistance with livestock management. Financial support focuses on providing adapted and affordable financial services to improve agricultural production. The remaining 40% of farmers view agricultural development as the central role of national authorities. They perceive a strong link between developing adequate strategies, policies and governance framework and resilience of the SES, particularly in terms of natural resources management. This is especially crucial in the context of overexploitation of surface and groundwater, pollution, and land fragmentation, all of which pose significant threats to the oases' sustainability.

Civil society organizations are considered an important pillar of the SES, represented by different associations, including water user associations and environmental associations. However, only 70% of farmers were able to define the role of these associations, with focus on water user associations, whose role is confined to water distribution. Nevertheless, many farmers acknowledge the significant contribution of environmental associations to the SES sustainability, recognizing their role in addressing broader ecological challenges. Indeed, 44% of farmers think that associations' role is connected to all components of the SES, meaning the human and the ecosystem together. 31% of farmers focus on WUAs and their water allocation role against 25% who are more highlighting associations' technical and financial support. This relation between farmers and environmental associations has contributed to stabilizing farming practices and strengthening farmers' long-term commitment to their land. As a result, cases of land abandonment have decreased, agricultural activity has been sustained over time, and farmers have shown increased engagement in the preservation and sustainability of the SES. Rather than being passive recipients of environmental initiatives, farmers are assuming active roles in shaping and implementing sustainability actions.

Farmers perceive the industrial sector as a threat to the SES through its impact on natural ecosystem, whether in terms of natural resources use, such as water resources, or in terms of impact of pollution on agricultural activities. In addition, this sector has an important power and influence in attracting labor force and financing. The tourism sector is perceived as contributing to a better marketing of the oases goods and services, which has an impact on the farmer income and activity and leads to the SES sustainability. However, the role of the private sector remains debatable. Farmers' opinions are divided into two groups: on the one hand, the private sector is viewed as capable of producing goods more efficiently, thereby ensuring the continuous supply of products to local markets and contributing to additional employment opportunities. On the other hand, there are concerns about the negative impacts of private sector involvement, related to unfair competition with smallholder farmers, overexploitation of water resources, and the conversion of agricultural land into commercial spaces for advertising, which undermines the agricultural vocation of the oases.

3.3.2 Types and nature of relationships between groups

In the oases of Gabès, there is a significant perception of direct relationships, respectively, with farmers (86%), associations (71%), and local authorities (51%) (Table 1). These findings highlight the farmers' prioritization of maintaining agricultural production according to their own interests. Mutual support among farmers plays a key role, as they share experiences and knowledge within the community to collectively overcome challenges.

The role of water user associations in water allocation, along with the close ties some environmental associations maintain with farmers, grants them legitimacy in serving farmers' interests. In contrast, industry, tourism, and the private sector are perceived as direct competitors to farmers, particularly regarding land use, water overexploitation, and the attraction of labor force. Moreover, their activities negatively impact the SES through pollution, which degrades soil and water quality, and contributes to the loss of agricultural biodiversity.

TABLE 1 Type and nature of relationships among farmers and between farmers and other stakeholders.

Stakeholders	Type of relationships between farmers and other stakeholders		Nature of relationships between farmers and other stakeholders		
	Direct	Indirect	Collaboration	Conflict	Neutral
Farmers	86%	14%	69%	30%	1%
National authorities	51%	49%	45%	54%	1%
CSO	71%	29%	65%	35%	0%
Industry	50%	50%	1%	98%	1%
Tourism	32%	68%	31%	58%	11%

The findings related to the nature of relationships between farmers and other stakeholders are closely linked to the types of relationships, except in the case of local authorities. Farmers primarily collaborate with one another, with 69% reporting such relationships, followed by collaboration with CSOs at 65%. This highlights a strong, interest-driven relationship between farmers and CSOs, with both parties focused on addressing shared concerns such as agricultural practices, environmental sustainability, and resource management. The relationship with national authorities is more formal and less direct. Farmers highlighted their important role in resources governance but are dissatisfied with their technical and financial support.

However, 98% of farmers perceive industry as their direct competitor for land use, in addition to overexploitation of water resources and the attraction of young labor away from agriculture. This competition negatively impacts the SES through pollution generated by chemical production units, which degrade soil and water quality and contribute to the loss of genetic heritage. These tensions have contributed to farmers perceiving the industrial sector as both powerful and harmful, reinforcing the perception of an unbalanced development model that prioritizes industrial growth at the expense of ecological integrity and social sustainability.

3.3.3 Power and influence analysis

Farmers perceive their role in the evolution of the SES as both crucial and central. They are seen as holding power and influence in preserving the oases and ensuring the system's resilience to changes.

The continuation of agricultural activity is widely regarded as the main factor determining the evolution trajectory of the SES. This perception highlights that maintaining agricultural practices is essential not only for livelihoods but also for preserving the ecological and social balance within the oases. Farmers can play an important role in this process if they are actively involved in the participatory development of sustainability strategies. Their engagement is key to enhancing the governance model of the SES, ensuring its long-term resilience and durability.

Farmers also acknowledged the important role played by CSO in influencing the evolution of the SES. They emphasized the critical role of WUAs in managing water allocation as an essential factor in sustaining agricultural activities. Environmental associations were similarly recognized for their advocacy efforts in promoting the preservation and sustainability of the SES. As a result, farmers attributed to these organizations a level of power and influence that is nearly equivalent to their own, reflecting a shared responsibility in shaping the SES's trajectory and resilience. They perceive these associations as key agent of development, through their contributions to the preservation of oases by safeguarding traditional knowledge and local products, the protection of the natural ecosystem, and the strengthening of capacities not only of farmers but also for vulnerable groups such as women and young people. Effective coordination between associations and national authorities could pave the way for a comprehensive approach to oases sustainability, potentially opening the door to increased international and technical support for national efforts aimed at preserving these unique environments.

Farmers expressed divided opinions regarding the power and influence of national authorities within the SES (Figure 4). Their level of influence is perceived as lower than that of farmers and CSO. Some farmers believe that national authorities have had little to no impact on the evolution of the SES or have influenced it in a negative way. In terms of power, opinions range from positive to negative and this ambivalence reflects an overall negative perception of national authorities by farmers.

The tourism sector is perceived as having both positive power and influence within the SES (Figure 4). Farmers differentiate between two types of tourism-related activities. On the one hand, the construction of hotels is viewed as overexploiting the already scarce water resources, which threatens the ecological balance of the oases. On the other hand, farmers recognize that integrating tourism with local SES dynamics has enabled them to diversify their income by selling non-agricultural products and local goods from the oasis. This connection has also contributed to increased agricultural investment, supporting the continuity and stability of agricultural production.

Similar perceptions were observed for both the industrial and private sectors (Figure 4). Farmers' opinions are divided into two main groups: some perceive these sectors as having high power but low influence, while others see them as having low power but high influence. However, there is a consensus that both sectors have a negative impact on the SES, particularly the industrial sector, which is seen as a threat, mainly due to its environmental consequences such as pollution and resource overexploitation. Regardless of how their influence or power is ranked, the overall perception among farmers points to their detrimental role on the SES. These impacts not only threaten the ecological integrity of the oases but also undermine the viability of traditional farming practices, further weakening the resilience of the SES.

To understand the current perception of power and influence attributed to the industrial sector, it is important to examine the historical context of development in the region (such as policy choices, infrastructure investments, and land use priorities). The establishment of industrial production units near the oases began several decades ago as part of national development strategies led by central authorities. Since then, private industrial companies have been actively encouraged and incentivized to expand their operations in the area. This occurred despite persistent complaints from local communities and repeated reports from national authorities highlighting the negative consequences of industrial activities on the SES. These longstanding tensions have contributed to farmers' view of the industrial sector as both powerful and harmful, reinforcing a perception of unbalanced development that prioritizes industrial growth over ecological and social sustainability.

3.4 Perspectives for improved SES sustainability

Among the key drivers of SES resilience are well-designed and contextually adapted national policies and strategies. Farmers are the primary beneficiaries of the oases' sustainability and can provide valuable orientations for preserving the SES. Following a consultation process with national authorities, associations and farmers to identify the main variables influencing the proper functioning of the system, six ways of improvement were developed and discussed with farmers. This consultation process was conducted in two phases. In the first phase, open-ended interviews were conducted with these stakeholders to identify the variables and in the second phase, more in-depth interviews and working sessions were held, allowing participants to

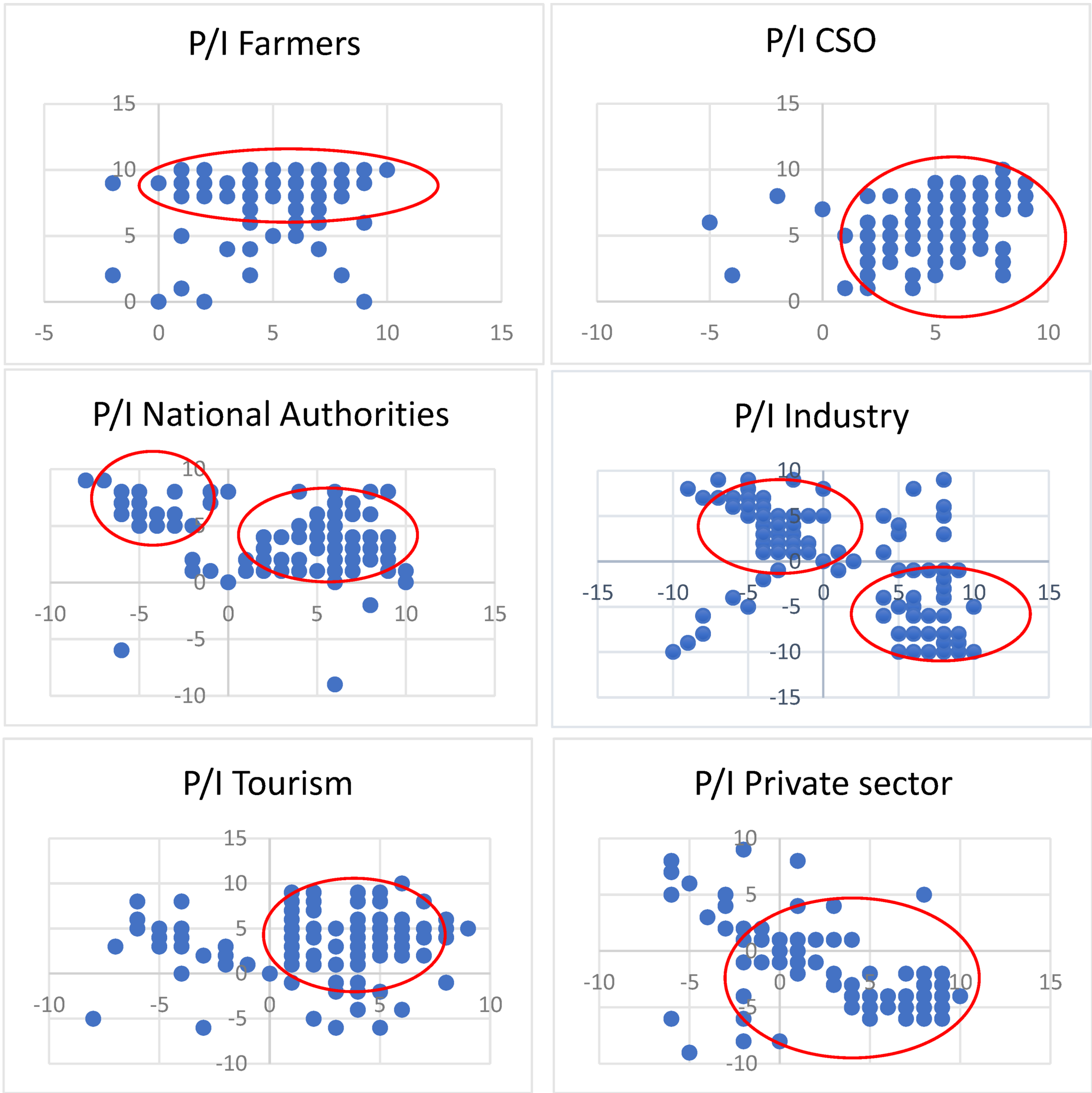

FIGURE 4
Power and Influence levels of SES stakeholders.

co-develop a set of improvement measures based on the previously identified variables.

Farmers were invited to identify the priority variables that should guide the design of sustainability strategies for the SES. Based on the previous analysis, the key variables identified relate to water, land, soil, financing, good agricultural practices, and regulation. This participatory exercise enabled the development of propositions. Farmers were then asked to rank these issues in order of priority by selecting one or more propositions they considered most urgent and impactful. This approach not only captured their local knowledge and perceptions but also helped shape context-specific ways for improving the resilience of the SES.

The ways of improvement developed in collaboration with farmers and stakeholders represent strategic options to address the key challenges facing the SES. Each one targets specific priority areas identified during the consultation process. They are as follows:

i. *Increasing water availability:* Expanding access to water resources for agricultural use by exploring non-conventional resources such as treated wastewater, seawater desalination, and rainwater harvesting.
ii. *Improving soil quality:* Implementing practices and interventions aimed at restoring and maintaining healthy soil, thereby increasing agricultural productivity and ecosystem stability.
iii. *Addressing land fragmentation:* Encouraging the formation of cooperatives or other collective land management models to overcome the negative effects of land fragmentation and promote more efficient and equitable land use.
iv. *Developing an adapted financing framework:* Establishing a supportive financial system that includes targeted incentives, accessible agricultural credit schemes, and capacity-building initiatives tailored to the specific needs of farmers.
v. *Adopting green agricultural technologies:* Promoting the use of environmentally friendly technologies such as efficient irrigation systems, conservation agriculture practices, and climate-smart agriculture practices.

vi. *Strengthening regulations:* Enforcing regulations that safeguard agricultural activities and protect land use from competing pressures, ensuring long-term viability of farming in the oases.

The most frequently cited ways of improvement by farmers revolve around enhancing water availability, financing, and land tenure. Among these, the issue of water availability for irrigation was recognized as the top priority, with 98% of farmers promoting that policies and strategies to address water scarcity must be clearly defined. The first proposed solution for addressing water scarcity is the use of treated wastewater, alongside the need to revise and update the regulations governing its reuse. These regulations should be adapted to advancements in treatment technology to ensure the delivery of quality suitable for irrigation. However, a key challenge with treated wastewater in Gabès is the level of contamination from surrounding industrial activities, which may compromise its quality.

Financing is another key issue frequently cited by farmers (70%). Over the past few decades, the decreasing availability of adapted financial solutions has significantly hindered farmers' ability to improve agricultural productivity, thereby contributing to the increasing vulnerability of the SES. To address this, the introduction of affordable and innovative financial solutions that are specifically adapted to the needs of farmers could play a crucial role. Such financial mechanisms would not only encourage farmers to invest in sustainable agricultural practices but also help enhance the overall resilience of the SES, ensuring its long-term sustainability.

Land tenure is the third scenario cited by 50% of farmers. Challenges related to land tenure have significantly contributed to the vulnerability of the SES, primarily by reducing agricultural productivity. Given that the size of land holdings cannot be expanded, one potential solution proposed by farmers is to group them into cooperatives or other collective land management models. These groups could be formed based on geographical proximity, common crops, or shared interests, which would allow for more efficient land use and increased productivity. Additionally, issues related to soil quality, regulations, and technology were also identified, respectively, as important factors.

3.5 Feedback loop analysis: impact of water resources availability on agriculture

In the oases of Gabès, water scarcity has significantly impacted agricultural activities, leading to changes in farmers' behavior. In response to these challenges, farmers have been adapting by making new decisions and adopting different strategies. The following causal loop diagram illustrates the interaction between key variables, highlighting how the availability of water resources influences the dynamics of agricultural activities (Figure 5).

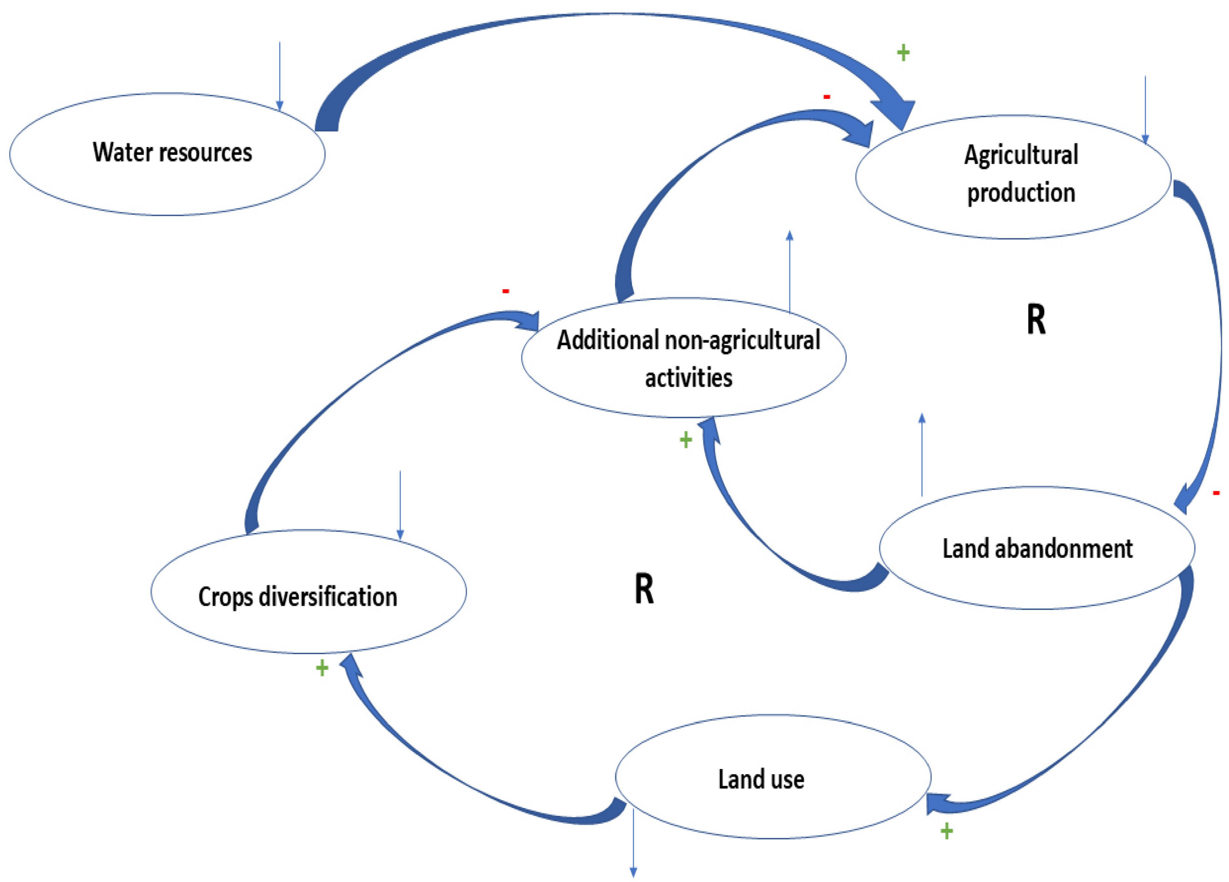

FIGURE 5
Causal loop diagram representing the impact of water resource availability on agricultural activities.

There is a direct correlation between water resources availability and agricultural production. A reduction in water availability for irrigation directly impacts crop yields. This, in turn, leads to decreased revenues, resulting in increased land abandonment and a reduction in land size, which affects crop diversification. Land use and crop diversification are correlated. A decline in agricultural production, inter alia due to water scarcity, has led to a higher rate of land abandonment on the one hand, and increased adoption of non-agricultural activities by farmers unable to rely only on the weak agricultural production. Indeed, farmers with small land size are increasingly seeking employment in the public or private sector to cover their expenses formerly covered by agricultural activity as the main and only source of income. Those who did not abandon their lands, because of their social importance in the local culture, use their non-agricultural activity revenue to maintain their farms. According to national authorities, this additional revenue has enabled farmers to dig more wells to compensate the lack of water quantities distributed by the WUAs and which is originally the reason of declining agricultural production and land abandonment. Farmers who can afford more water for irrigation are diversifying crops. In contrast, abandoned lands are used for construction and are no more suitable for agriculture which leads to loss of agricultural land due to urbanization.

In the causal loop diagram, "R" indicates that the SES tends to evolve far from a balanced status. This means that agricultural activity in the oases is being abandoned in favor of other activities, which informs us of the system trend toward degradation. Water availability has a significant impact on the SES evolution. Therefore, if water for irrigation is available, agricultural activity can influence the evolution of the SES toward preserving its actual trajectory and preventing regime shifts. Continuity in water supply can significantly influence farmers' decisions to continue investing in agricultural activity, which will have a direct impact on the sustainability of the ecosystem and other factors such as employment, quality of life and marketing. As freshwater is becoming more and more limited, national strategies should consider incorporating the use of non-conventional water resources for agriculture and keeping the use of freshwater exclusively for domestic use.

4 Discussion

Analyzing the resilience of SES primarily involves understanding the behavior and interactivity of its components to assess its capacity to cope with changes and continue delivering services and goods (Wu et al., 2020). As explained in the previous sections, the oases of Gabès have reached a critical level of vulnerability, threatening their sustainability and even their very existence. The SES has undergone several challenges that have significantly influenced its evolutionary trajectory, with each stakeholder playing an important role in its sustainability (Carpentier and Gana, 2017).

Analyzing connectivity between actors is essential to understanding how their interactions contribute to the resilience of the SES and its ability to respond to changes. 'Resilience thinking' follows a non-linear system behavior over time, emphasizing interconnections throughout the system. This perspective allows for the exploration of system connectivity and the illustration of system dynamics under different scenarios. Causal loop diagrams can be used to visually represent these connections (Dhirasasna and Sahin, 2019). Perceptions, cognitions and preferences within SESs are influenced by acceptance of people of their roles in the existing order of things. This influence often stems from their inability to envision or imagine alternatives, or from viewing their roles perceived as traditional or inherently accepted roles as naturally beneficial. Analyzing the interconnectedness between SES stakeholders begins with understanding not only the perception of each group of its own role but also how roles and actions of all groups collectively impact the system (Partelow, 2018). In the oases of Gabès, connectivity analysis has revealed the important role of farmers in the SES resilience through maintaining the continuity of the agricultural activities. Farmers contribution to the SES resilience is linked to the interest-based relationship with associations and national authorities, respectively. Knowledge and cognitions accumulated over years of collaboration have shaped their capacity to recognize their potential and their limits in contributing to the SES resilience.

In the oases of Gabès, some farmers are practicing non-agricultural activities which provided additional financial support to cover their agricultural activities and reduce land abandonment. Preserving the land in the local culture is not only related to its social value, but also to its capacity to provide additional income, although weak. Abandoned lands are prey to urbanization which is a factor of vulnerability. Clément (2017) highlighted the importance of farmers as indigenous leaders in preserving the oases through maintaining agricultural activities. The diversification of income sources within the SES provides financial support that helps sustain agricultural activities, despite their limited profitability. In this way, off-farm income plays a stabilizing role, allowing farmers to maintain their land and continue farming, which contributes to the overall resilience of the SES (Borychowski et al., 2020; Manevska-Tasevska et al., 2021).

The capacity to deal with the interactive dynamics of social and ecological systems requires an entire network of interacting individuals and organizations at different levels that create timely links around relevant issues. Key groups in these networks establish functional links within and between organizational levels in times of change and facilitate the flow of information and knowledge applied in the context of local ecosystem management (Gunderson et al., 2006). In the oasis of Gabès, connectivity dynamics between framers, associations, and national authorities played an important role in the SES resilience through exchanging information around issues of importance to preserving the SES such as availability of water resources, addressing land fragmentation, financing, adequate regulation frameworks, and improving soil quality. Farmers are empowered and farming practices are enhanced through social links with the other key groups to preserve the SES.

The interactions between farmers and CSOs are likely built around mutual support and the pursuit of common goals, with farmers benefiting from the advocacy, resources, and technical assistance provided by CSOs (Unver et al., 2021). In contrast, the relationship with national authorities appears to be less collaborative and more formal. While national authorities are key players in the governance of resources such as water and land, their role in supporting farmers seems to be less direct or interactive. This may stem from the top-down nature of governmental structures, where farmers may perceive local authorities as distant or disconnected from the immediate challenges they face daily (Dawson et al., 2023; Morizet-Davis et al., 2023). From the perspective of farmers' interests, particularly in terms of the authorities' role in enhancing the resilience of the SES, absence of strategic and operational actions carries a cost, affecting both ecological and social components of the system (Fischer et al., 2015; Hariram et al., 2023).

Ways of improvement related to water availability, financing, and land tenure were most frequently cited by farmers, reflecting the key drivers of vulnerability. These are areas where actions are urgently needed to improve the sustainability and resilience of the SES (Wang et al., 2024). Farmers strongly support the exploration of non-conventional water sources, such as treated wastewater, seawater desalination, and water harvesting, as potential solutions to meet irrigation needs. This would help ensure a more reliable and sustainable water supply for agricultural activities, which is critical for the long-term viability of farming in the oases (Hariram et al., 2023; Dhawi and Aleidan, 2024). In addition to wastewater reuse, seawater and brackish water desalination are also suggested as costlier yet effective alternatives to meet the growing demand for water. Lastly, water harvesting is proposed as a secondary option, particularly given the increasing unpredictability of rainfall patterns, which further exacerbates water scarcity (Salgot et al., 2017; Mannina et al., 2022). Financial solutions should extend beyond agricultural credits and microcredits but also to incentives related to adopting new technologies, improving water use efficiency, and implementing climate-smart and greener agricultural practices. Additionally, rethinking conventional reimbursement models is essential to better accommodate the seasonality of agricultural activities. This approach to financing can empower farmers to invest in sustainable practices, driving both agricultural productivity and the SES resilience (Coomes et al., 2019; Wang et al., 2024).

5 Conclusion

The resilience concept applied to the oases of Gabès, as a social-ecological system, helps to understand the system's capacity to cope with various challenges while continuing to provide goods and services. This analysis has revealed a complex interconnectivity between its different components. Stakeholders, constituting the social component of the system, perceive farmers as the hardcore of the system, playing a pivotal role in shaping the SES response to changes and shocks.

The power and influence analysis revealed that farmers hold significant power and influence in shaping the system's evolution toward preserving its capacities. However, opinions were divided regarding other groups, except for the industrial sector for which two groups with different perceptions were identified. Despite these differing views, the industrial sector is largely perceived by farmers as a threat to the SES.

Developed ways of improvement aiming at preserving the SES and ensuring its sustainability are issues related to water availability, financing, and land tenure individually or as combined scenarios. All these elements enabled the design of a causal loop diagram explaining the causality between water resource availability and agricultural activity. Freshwater availability for irrigated agriculture activity has a direct correlation with agriculture production, land abandonment, additional non-agricultural activities, land use, and crops diversification.

Looking at the oases from a resilience perspective could contribute to their preservation. Developing public policies depends on the stakeholders and variables dynamics identified in the analysis of the system and their degree of power and influence. In the oases of Gabes, water, financing, and land tenure should be the focus for public policies aiming at preserving the SES.

Innovative solutions can address the water shortage such as the use of treated wastewater and the update of its regulation. This regulation should be adapted to treatment technology to ensure a quality suitable for irrigation. However, one of the main challenges of treated wastewater in Gabès is the level of contamination from surrounding industrial activities, which can compromise their quality. Seawater desalination and water and soil conservation are also potential solutions to satisfy irrigation needs. This would help ensure a more reliable and sustainable water supply for agricultural activities, which is essential for the long-term viability of agriculture in the oases (Hariram et al., 2023; Dhawi and Aleidan, 2024). Rainwater harvesting is proposed as a secondary option, particularly given the increasing unpredictability of precipitation patterns, which further exacerbates water scarcity.

Adapted financial mechanisms would not only encourage farmers to invest in sustainable agricultural practices but would also help strengthen the overall resilience of the SES, thus ensuring its long-term sustainability. Financial solutions should go beyond agricultural credits and microcredits, including incentives related to the adoption of new technologies, improving water use efficiency, and implementing climate-smart and more environmental-friendly agricultural practices. Furthermore, it is essential to rethink conventional reimbursement models to better account for the seasonality of agricultural activities. This comprehensive approach to financing can enable farmers to invest in sustainable practices, thereby boosting both agricultural productivity and the resilience of the SES (Coomes et al., 2019; Wang et al., 2024). Given that the land size cannot be increased, properties can be grouped into cooperatives or other collective land management models. These groups could be formed based on geographical proximity, common crops, or shared interests, allowing for more efficient land use and an increase in productivity.

These strategies can be more efficient if developed and implemented in an integrated and collaborative manner. The variables emerged from the previous analysis are connected to stakeholder perception of where urgent interventions are needed to preserve the SES. However, designing strategies based on the three variables (water, financing, and land tenure) only can lead to creating uncontrolled system behavior where feedback loops are not well understood and considered. Results of this analysis suggest that the oases of Gabes are no longer in the foreloop as no sign of growth is seen, and the SES seems to be currently in the backloop. The current situation of the SES tends to suggest that the collapse phase has started quite some time ago, but it remains difficult to determine when the migration to the reorganization phase of the system will occur.

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

HC: Conceptualization, Writing – original draft, Methodology, Visualization, Investigation, Formal analysis. MD: Writing – review & editing, Validation, Supervision, Methodology. IG: Writing – review & editing. AB: Supervision, Writing – review & editing.

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Conflict of interest

The 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.2025.1623641/full#supplementary-material

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