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The water–energy–food–ecosystem nexus in North Africa dryland farming: a multi-criteria analysis of climate-resilient innovations in Morocco

Emirjona Kertolli[1,2*], Paolo Prosperi[1,2], Rachid Harbouze[3], Rachid Moussadek[4,5], Ghizlane Echchgadda[6] and Hatem Belhouchette[7,8]

*Correspondence: emirjonakertolli1@gmail.com

[1] CIHEAM-IAMM, UMR MoISA, 34093 Montpellier, France
[2] MoISA, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, IRD, Montpellier, France
[3] Agronomic and Veterinary Institute Hassan II (IAV), Rabat, Morocco
[4] International Centre for Agricultural Research in the Dry Areas (ICARDA), Rabat, Morocco
[5] Institut National de la Recherche Agronomique (INRA), Rabat, Morocco
[6] Plant Ecology Unit, Department of Plant Protection and Environment, National School of Agriculture, Meknes, Morocco
[7] CIHEAM-IAMM, UMR ABSys, 34093 Montpellier, France
[8] ABSys, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, Montpellier, France

Abstract

Smallholder farmers, who mostly engage in low-value agriculture in the drylands of Northern Africa, were the first to have felt the effects of climate change, with threats to their livelihoods and food security. The increasing costs of agricultural production, poor water and energy infrastructure, loss of agricultural land due to urban expansion, fragmented resource management, and unsustainable management practices all contribute to this vulnerability to climate change. This highlights the urgent need for innovative practices in farming systems. Within the framework of the water–energy–food–ecosystem nexus, this paper explores innovative practices in dryland farming systems, by assessing their impact on water, energy, food, and ecosystem through stakeholder perception. In this work, we aim to present a systems approach for assessing the resilience of the water–energy–food–ecosystem nexus in arid and semiarid regions. By using a multi-criteria analysis (MCA) approach, the study—which focuses on the Fès–Meknès region in Morocco—involves local actors to help researchers identify the key variables in order to assist farmers in their adaptation to climate change. The findings revealed different priorities between farmers and other stakeholders regarding the adoption of agricultural innovations. Farmers prioritize innovations that guarantee higher profitability and more market opportunities, such as integrating olive trees with cereal crops, by highlighting the importance of sustainable income sources. Meanwhile, stakeholders, such as researchers, engineers, government officials, and agribusiness entrepreneurs, prioritize innovations that emphasize high water use efficiency, which is crucial for the resilience of dryland farming areas: for instance, rainwater harvesting or the use of drought-resistant crop varieties that directly address the need for water conservation. But in doing so they are overlooking broader aspects within the water–energy–food–ecosystem nexus.

Keywords: Global change, Drylands, North Africa, Multi-criteria decision analysis, Smallholders, Focus group discussion

Introduction

Climate change has become a major concern, and is causing severe problems worldwide, especially for drylands, which are home to over 2 billion people (UNCCD 2017). In drylands, agriculture is particularly affected, which results in low productivity, water depletion, increased irrigation demand, disrupted food availability, droughts, and so on. In addition to climate change, dryland areas are facing a wide range of socioeconomic challenges. There is a growing demand for energy, a decline in agricultural productivity, and an increase in food demand due to population growth, as the drylands are experiencing a high population growth rate worldwide (Feng and Fu 2013; Fan et al. 2020). Such growth presents both challenges and opportunities, which require innovative solutions to ensure the sustainable development and resilience of these regions. In dryland areas, smallholders are primarily engaged in producing low-value crops for home consumption, and a small percentage for selling; they were the first ones to have felt the impacts of these changes (DALRRD 2023; UNESCO and European Commission, 2021; Waha et al. 2017). This makes it difficult for them to maintain their activities, and in some cases, they are forced to switch to other sectors to survive, or to migrate from rural areas (Szaboova 2023). What makes the situation worse is that in these areas, water, energy, food, and ecosystem assets have been managed separately from one another (OECD 2023). This fragmented approach has hindered the sustainable use of water resources, led to the degradation of ecosystems and aquifers, and prevented the recognition of the interlinkages between water, energy, and food security (OECD 2023). The lack of integrated management has also contributed to the vulnerability of small producers in remote drylands, thus further exacerbating the risks of poverty traps and land degradation due to increasing climate shocks (Jobbins and Henley 2015). In addition, the fluctuation in precipitation and water availability is affecting farming systems, which has a significant impact on both the economy and society due to its implications on agricultural productivity (Ahmed et al. 2022; Kee-Tui et al. 2021). Furthermore, current management techniques used by farmers are questionable since they are unsustainable over the long term, especially considering water scarcity, which is exacerbated by climate change (FAO 2014). Losses resulting from the suboptimal management of farming systems, which include all the agricultural practices used in irrigated areas, such as crop selection and rotation, technical packages, etc., are significant.

When it comes to evaluating the stress impact of a scarce resource like water on other sectors such as energy, food production, and ecosystems, new theoretical and methodological approaches such as the nexus approach help to renew the understanding of the trade-offs that regulate agri-food system sustainability (Brunori et al. 2020). According to Ponce Oliva et al. (2021), the nexus framework recognizes the interdependencies and interconnections between multiple sectors that share natural resources and have different management schemes. It is particularly effective for identifying and quantifying trade-offs and synergies, as well as helping to manage the resource competition between urban and agricultural sectors under climatic and demographic stressors. In practice, the adoption of innovative agricultural techniques such as advanced farming processes and technologies by large-scale farmers in the context of the water–energy–food–ecosystem nexus can present both benefits and challenges. These practices offer advantages such as improved water and energy efficiency, enhanced yields, and reduced environmental impacts. However, they also present challenges, including water scarcity (Fitton et al. 2019), soil degradation, and biodiversity loss. The adoption of these techniques is influenced by ownership structures, market dynamics, and regulatory frameworks, with implications for sustainability and resilience within the WEFE nexus (Namany et al. 2023; Nhamo et al. 2020). Nevertheless, innovative techniques play a crucial role in addressing the complex interactions within the WEFE nexus, and can contribute to the promotion of sustainable agriculture, resource efficiency, and environmental conservation (Peña-Torres et al. 2022). Some large-scale farms also use innovative techniques and are well integrated into domestic and foreign markets, and are mostly owned by investors, companies, and large historical landowners (Dugué et al. 2015).

All the pressures faced by agriculture mentioned above—climate, economic, and human pressure—have a direct impact on four crucial elements: food, water, energy, and ecosystems (Karan et al. 2018; El Gafy et al. 2017). Understanding the intertwined relationships between these four elements is crucial for sustainable development and a stable future, starting on a local scale. However, several existing studies (Hamiche et al. 2016; Tan and Zhi 2016; Maftouh et al. 2022; El Azhari and Loudyi 2019) focus only on one or two of these elements. This limited approach may not lead to relevant results as these four elements are strongly interlinked (Bizikova et al. 2013). Therefore, this research explores the innovative practices that can positively impact these four elements directly or indirectly by triggering scenarios in a study area characterized by dryland farming.[1] Applying the water–energy–food–ecosystem nexus approach to quantify resilience is a useful way to identify and describe the characteristics of vulnerable areas of the system, such as drylands, and then target solutions to reduce the impact of resource and asset scarcity (Núñez-López et al. 2022; Tebaldi and Vignali 2023). Furthermore, to increase the consideration of stakeholder and farmer views in the present research, we have involved local actors to help researchers identify the key variables to be taken into account for the climate adaptation of farmers. To the best of our knowledge, and according to previous literature [e.g., (Hoff et al. 2019; UNESCO and European Commission 2021; Jobbins et al. 2015)], there is limited use of multi-criteria WEFE nexus analysis in climate innovation assessment, specifically at farm level, which has not sufficiently been explored in the area.

In the following section, we present an extended literature review of farming in North African drylands, and of the implementation of resilience and WEFE approaches. We then present our methodology based on multi-criteria analysis (MCA) for prioritizing innovations that address the needs of farmers and other stakeholders in combating climate change effects in the Saïss plain in Morocco, while considering their impact on water, energy, food, and the ecosystem. The paper then shows the results obtained regarding the adoption of innovations in the study area. The findings highlight the complex nature of differences in prioritization between stakeholders and farmers concerning the feasibility and impacts of innovations at farm level.

[1] According to Stewart and Thapa (2016), dryland farming is a particular type of rainfed agriculture used in arid and semiarid regions in which annual precipitation represents about 20–35% of potential evapotranspiration.

Literature review and theoretical background

Dryland farming in North Africa

North African drylands cover approximately 725 million hectares (FAO 2019), including arid, semiarid, hyperarid, and dry subhumid areas. With a population of around 240 million and an annual growth rate of 1.8 percent (FAO 2019; World Bank Data 2022), these regions often face poverty, resource scarcity, and political marginalization (FAO 2022; Hirwa et al. 2022). They are also hotspots for natural disasters, social conflicts, and inequalities (FAO 2015; FAO 2007b). Drylands are characterized by limited water availability (Ribbe and Dehnavi 2020), high temperatures (Daramola and Xu 2021), low and unpredictable rainfall (Bedair et al. 2023; FAO 2018), land degradation and deforestation (FAO 2019), which lead to significant issues such as drought (FAO 2018), and food insecurity (Devkota et al. 2022b). Moreover, the scarcity of water and arable land (FAO 2022), coupled with a limited potential for increasing output without irrigation, has led to a high and growing dependence on international markets for key staple foods (OECD and FAO 2018). The degradation of drylands in the region is also forcing people who can no longer make a living off the land to move to urban areas, which has led to increased pressure on limited water resources (Boshra 2008). Despite having a long history of agriculture (Morales et al. 2013), the agricultural sector in North Africa contributed less than 9% to the regional GDP in 2016 (AFDB 2018). However, it remains a primary source of employment, particularly for women, who make up 55% of the workforce (Kühn 2019) in rural areas (FAO 2018; OECD and FAO 2018). Around 52% of the total population in North Africa, including small-scale farmers and farm workers, live in rural areas, and are among the poorest and most affected by agroecological crises (Sowers et al. 2011). Although they face challenges such as low yields, limited access to quality seeds, and insufficient resources, smallholders play a crucial role in North Africa's agricultural sector. They contribute significantly to food production and are essential for ensuring food security in the region (FAO 2024).

Drylands in North Africa have witnessed a sharp increase in rural poverty, malnutrition, and social inequalities (FAO 2015; FAO 2007b). The challenges relating to climate change and the vulnerability in coping with these changes have directly affected food security (Schilling et al. 2012), and posed significant issues for farming systems and the livelihoods of inhabitants of the drylands. The main type of farming system is the irrigated farming system, which is of crucial importance in generating much of the region's agricultural output. It contains both large- and small-scale irrigation schemes, with the large-scale system consisting of irrigated cropland and an agricultural population. The second most important type, the dryland mixed farming system, covers a significant area and contains a large agricultural population (FAO 2001). It is primarily dependent on wheat and barley production, with strong interaction with small livestock, primarily sheep (Alary and Frija 2022). Crop production relies heavily on rainfall, and the whole system is vulnerable to inter-annual and seasonal variability. The risk of drought is high, and considerable food insecurity exists within this system (FAO 2001). The third type is the rainfed mixed farming system, which is characterized by the cultivation of rainfed crops such as wheat, barley, legumes, olives, grapes, fruit, and vegetables. Livestock, mainly sheep and goats, are an important feature of this system. The prevalence of poverty within this system is moderate, but would be higher without extensive off-farm income from seasonal labor migration (Hirwa et al. 2022; Ryan 2011; FAO 2001). Also, the location of farms in North African drylands, particularly in Morocco, can be categorized into both remote rural and peri-urban contexts. Remote rural farms are often isolated with limited market access, poor infrastructure, and significant challenges such as water scarcity and poor soil fertility. They rely on subsistence farming and face high vulnerability to climate change (Kmoch et al. 2018). In contrast, peri-urban farms benefit from proximity to urban centers, and offer better market access, infrastructure, and diversified agricultural activities. However, they face threats of urban encroachment and pollution (El Hassani and Laziri 2022).

The concept of resilience in dryland farming systems

In the agricultural context, resilience refers to the ability of farming systems to withstand and recover from various challenges, such as climate change (Baffour-Ata et al. 2023), market fluctuations, and natural disasters, while continuing to maintain productivity and adapt to changing circumstances (Martin et al. 2019; Cabell and Oelofse 2012; Darnhofer et al. 2010a; OECD 2020). This approach considers the interconnectedness of various components, such as ecological, social, and economic factors, to understand the system's capacity to withstand and recover from disturbances (Meuwissen et al. 2019; Tebaldi and Vignali 2023). In other words, resilient agriculture is not just about the ability of farms to cope; it is about their ability to transform, be robust and innovative, and adapt to the increasing environmental, economic, social, and institutional challenges of today's world (OECD and FAO 2021). However, resilience does not mean that the agricultural system and the farm itself need to react only when the challenges occur, as in some cases this might be too late. Resilience also involves the importance of building the capacity of the agricultural sector to prepare for risks under a wide range of future scenarios. Several studies (Robinson et al. 2015; Jellason et al. 2022; Meyer 2020; Ephraim et al. 2023; Devkota et al. 2022a) on resilience in agriculture have made significant contributions to the understanding of the resilience of farming systems and farmers in drylands. These studies have emphasized the importance of agricultural resilience in ensuring that management actions do not push the surrounding landscape beyond its limits, that future opportunities to produce goods or income are not lost, and that new opportunities are created to allow producers to market, learn, innovate, and adapt when shocks occur. Furthermore, these studies have underlined the significance of persistence, adaptability, and the ability to transform as key factors in enhancing the resilience of farming systems and farmers in drylands (Coulibaly 2023). Various studies provide valuable insights into the perceptions and practices of smallholder farmers in different regions of Morocco, such as the Fès–Meknèss and Marrakesh-Safi areas, regarding the potential for resilience and adaptation in the face of challenges (Boutagayout et al. 2023). Additionally, research has been conducted to assess the resilience of farming systems in the Saïss plain in Morocco, by focusing on farmer knowledge, existing agricultural production systems, and agricultural practices in the region (Hossard et al. 2021). Furthermore, a study has explored the heterogeneity of resilience in pastoral and agro-pastoral farming systems in semiarid to arid rural areas of Morocco, thus providing a comprehensive understanding of the resilience of livelihood strategies in these regions (Alary et al. 2022). These studies Robinson et al. (2015), Jellason et al. (2022), Hossard et al.

(2021), Meyer (2020), Ephraim et al. (2023), Devkota et al. (2022a), Amede and Tsegaye (2016), Boutagayout et al. (2023), Alary et al. (2022202220222022) have shed light on the factors influencing agricultural resilience, including persistence, adaptability, and the ability to transform, and have emphasized the importance of building robust and adaptable farming systems to cope with environmental, economic, and social challenges. Therefore, they contribute to the development of sustainable and adaptive agricultural practices in the country.

The water–energy–food–ecosystem nexus applied to dryland farming

The growing recognition of the interdependencies between water, energy, food, and ecosystem highlights the importance of innovations in fostering resilience and adaptation (Pérez 2023). Brunori et al. (2020) outlined the importance of innovative policies that should not rely on outdated knowledge, by proposing four approaches that could be used by the scientific community. Firstly, systems approaches analyze the interconnectedness between activities, stakeholders, and outcomes in food systems within changing environments. This involves analyzing the interactions and dynamics within the farming system as a whole. Secondly, nexus approaches, which are at the core of this system, mean that intervening in one sector will have impacts on others (Brunori et al. 2020). Thirdly, future-oriented approaches involve acknowledging that past trends may not dictate future events, and considering the unintended consequences of choices, from consumption to technology (Brunori et al. 2020). This involves assessing the resilience and sustainability of farming systems by considering future scenarios and potential impacts. This approach helps to identify strategies for developing alternative systems, and to assess their compatibility with projected exogenous factors, thereby guiding decision-making toward more adaptive and resilient farming practices (Paas et al. 2021). Lastly, inter- and trans-disciplinary approaches embrace collaboration and synergies with other disciplines to tackle complex issues in agriculture and food studies (Brunori et al. 2020), by facilitating a deeper understanding of interactions within farming systems and the development of integrated strategies for resilience and sustainability (van der Lee et al. 2022). In line with the nexus approach advocated by Brunori et al. (2020), this methodology is best suited for assessing the resilience of farming systems due to its focus on the interconnected nature of water, energy, and food systems within farming systems. This approach seeks to reconcile the interdependencies between water, energy, food, and natural ecosystems, by providing a more targeted assessment of the specific relationships and interactions that influence the resilience of farming systems. Recent studies have further expanded the nexus framework, such as Ponce Oliva et al. (2021), who highlighted the importance of incorporating urban water use within the nexus framework to better understand the economic interdependencies between agriculture and urban sectors. Their research demonstrates how nexus thinking can reveal the compatibilities and divergence between food production and urban water use under different climatic and demographic stressors. This perspective highlights the need to integrate economic dimensions, such as household welfare and agricultural income, into the nexus analysis, by providing a comprehensive approach to resource management at basin level. By considering these factors, we can develop more effective strategies for enhancing resilience and sustainability in dryland farming systems.

The concept of the WEFE nexus has evolved since the decision to add "Ecosystem" to the WEF nexus (Hoff 2011). The WEFE nexus has transitioned from a focus on resource security to a more comprehensive approach that considers interconnections and integration to achieve sustainable development goals. The goal of the water–energy–food–ecosystem nexus approach is to demonstrate that food and energy production are dependent on water resources. They must be studied together, and multidimensional interventions are needed to identify optimized and adequate management and technical solutions. In light of these considerations, understanding the consequences of shortages of water, energy, food, and ecosystem services is crucial for comprehensively addressing the challenges faced by farming systems (Muthee et al. 2021).

In order to grasp the complexity of the WEFE nexus in drylands, and to identify key and innovative solutions for farmers to better manage water, energy, ecosystem resources, and food production, different approaches have been adopted by academics. Several studies have used spatial analysis (Raya Tapia et al. 2023; Liang et al. 2020; Wang et al. 2018), Geographic Information Systems (GIS) (Lin et al. 2019), participatory approaches (Ghafoori Kharanagh et al. 2021), or sector-based resource management approaches (De Andrade Guerra et al. 2021) to analyze the water–energy–food–ecosystem nexus in various contexts, including drylands. Azzam et al. (2023) introduced a developed WEF nexus framework based on Geographic Information Systems (GIS), which aims to assess the interlinkages between water, energy, and food on a spatial scale. Moreover, sector-based resource management approaches fail to recognize the interconnectedness of water, energy, and food resources, thus leading to insecurities within each sector (Taguta et al. 2022). Among the strong efforts of bio-economic modeling that are applied to the NEXUS approach [e.g., (Correa et al. 2022; Ngammuangtueng et al. 2023; Bazilian et al. 2011)], farmer and stakeholder opinions and views are not sufficiently taken into account when it comes to selecting and identifying the key variables which are needed for the assessment and identification of the best adaptation strategies for farmers. Previous bio-economic modeling approaches (Akinsete et al. 2022; Vahabzadeh et al. 2023) applied to the NEXUS approach often prioritized economic factors such as crop yields and market prices, while overlooking technical and environmental considerations such as local knowledge and ecosystem services. Moreover, the combination of qualitative actor-based data with quantitative methodologies such as bio-economic modeling is strongly recommended for improving research on the sustainability of agri-food systems and climate adaptation (Cammarano et al. 2023; Jennings et al. 2024).

WEFE-based innovations in dryland farming systems

Innovation in agriculture is essential for addressing the complex challenges facing the global food system and achieving the sustainable development goals, especially in countries where agriculture is an important field of the economy (Markovic et al. 2020). By using the power of technology, science, and collaboration, we can unlock the potential of agriculture to feed people, protect the planet from different hazards such as climate change, and build prosperous and resilient communities for future generations (Vyas and Singh 2022; Masi et al. 2022; Gremmen et al. 2019; El Bakali et al. 2023b). The concept of innovation in farming systems encompasses the introduction of new strategies, methods, and practices aimed at improving four elements: water, energy, food, and ecosystem. Implementing innovations in farming systems not only depends on willingness for development and resilience, but there are also barriers that limit these innovations, such as the size and type of farms, their technological advancement and financial resources, as well as the experience and educational attainment level of farmers (Diederen et al. 2003). Innovations in the water–energy–food–ecosystem nexus in farming systems are crucial for achieving sustainable and resilient agricultural practices (Ansari et al. 2023). Based on the needs of farmers in these areas, these innovations should encompass diverse approaches aimed at enhancing the resilience, productivity, and sustainability of farming systems while mitigating their impacts on water, energy, food, and the ecosystem. Key WEFE-related innovations implemented in dryland farming involve the adoption of minimum tillage methods, which aim to reduce soil disturbance and erosion while preserving soil moisture and fertility (Singh et al. 2023). In addition to tillage practices, the use of organic fertilizers, such as compost and manure, provides multiple benefits for the environment. These natural inputs enhance soil fertility and structure, thus reducing the need for synthetic fertilizers and minimizing nutrient runoff into water bodies (Zhou et al. 2022). Furthermore, smallholders implement the integration of drought-resistant crop varieties, which helps to mitigate the impacts of water scarcity on agricultural production. Reducing fertilizer use in agriculture is an innovation that is generally not accepted by farmers, as to them it involves sacrificing food; however, it may be feasible in some cases (Yuan et al. 2023). The adoption of drip irrigation technologies enables precise water delivery to crops, thus minimizing water losses through evaporation and runoff (Yang et al. 2023). Intercropping, rainwater harvesting, and agroforestry practices, such as the integration of olives trees with cereals crops, further contribute to water conservation, energy efficiency, and environmental sustainability in farming systems (Stott et al. 2023; Reddy et al. 2023; Tamagnone et al. 2020; Ouali et al. 2022; Daoui and Fatemi 2014). Concerning the financial aspect, subsidies and support mechanisms can encourage farmers to adopt water-saving technologies (Burt et al. 2023). Moreover, the financial incentives of revolving loans for women can be a means of supporting women in agriculture.

Innovations impacting the WEFE nexus for smallholders

When examining the studies conducted on WEFE in Morocco, we found only limited literature. The studies mostly focus on the relationship between water and energy (Humphrey et al. 2022; Almulla et al. 2022; Maftouh et al. 2022; El Azhari and Loudyi 2019), and reflect the fact that Morocco is a net energy-importing country that is heavily reliant on imported coal, oil, and gas to meet its energy needs (Almulla et al. 2022). At the same time, the country faces water scarcity, and the study by Siddiqi and Anadon (2011) demonstrates the interdependence of energy and water. Furthermore, Ouassissou et al. (2022) incorporated water and energy in irrigated agriculture, thus finding that farming systems in Morocco are characterized as water-intensive and energy-inefficient, and that this situation is caused by government subsidies. Other studies explore the relationship between water, energy, and food (Zarkik and Ouhnini 2022; Meir et al. 2022; Sang-Hyun et al. 2020; El Youssfi et al. 2020), but without including the environment, and not at farm level. One key observation highlighted in the review paper by El Youssfi et al. (2020) is the lack of consideration for interdependencies within the WEF nexus in Morocco, as

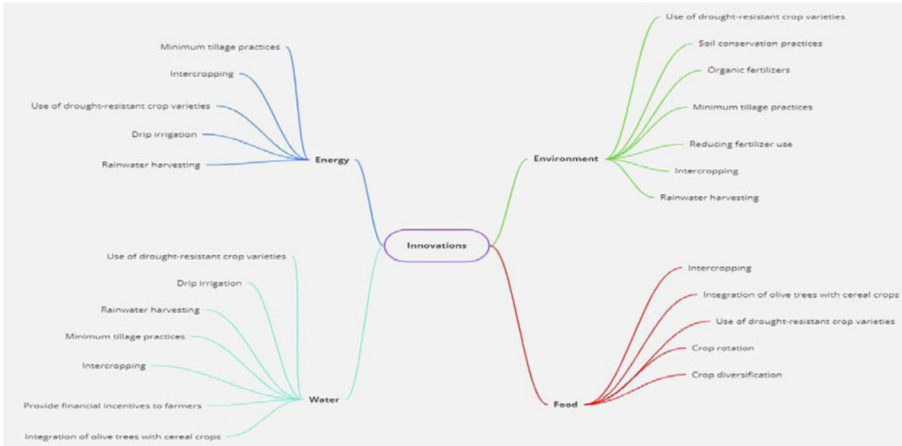

Fig. 1 The potential direct or indirect impact of innovations on WEFE (water, energy, food, and ecosystem). *Source*: Authors' own elaboration

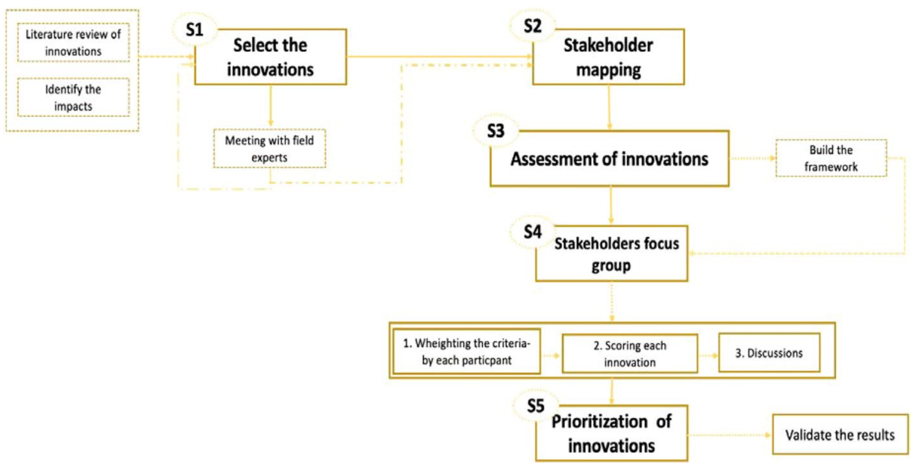

Fig. 2 Method used to assess innovations for smallholdings' adaptation to climate change in drylands

well as the absence of comprehensive policies that address all components of the nexus. Some of the challenges faced by dryland farmers, including those in Morocco, are water scarcity, soil erosion, land degradation, and food security. Innovations in the water–energy–food–ecosystem nexus in farming systems are crucial for achieving sustainable and resilient agricultural practices (Ansari et al. 2023). These innovations should encompass diverse approaches aimed at enhancing the resilience, productivity, and sustainability of farming systems while mitigating their impacts on water, energy, food, and the ecosystem, based on the characteristics of the area. The elaboration of innovations focuses on agro-ecology, conservation agriculture (CA), and financial incentives (Fig. 1).

Methodological approach and case study description

The methodological flow is illustrated in Fig. 2, and consists of five main steps: (i) innovation selection that combined a literature review with expert validation; (ii) stakeholder mapping with experts, which aims to ensure the diverse representation of farmers, government officials, researchers, engineers, and agribusiness entrepreneurs; (iii) the assessment of innovations by building the framework which served as a structured guide for stakeholder interactions and evaluations; (iv) a stakeholder focus group which allowed for dynamic discussions and evaluations of criteria and innovations by participants; (v) the prioritization of innovations by synthesizing stakeholder input and multi-criteria analysis findings to identify the most suitable innovations for the study area.

Assessment method

This research is initially supported by a literature review that identified many innovations related to the issue identified (climate change), all of which have already been implemented, or whose implementation feasibility has been identified for dryland areas. From this initial list, only measures adapted to the drylands that could have an impact on water, energy, food, and ecosystem were kept and further analyzed. These innovations were then validated as part of a focus group discussion by a small team of local experts working closely with farmers in Morocco, in particular in the Fès–Meknès area.

A multi-criteria analysis can also be useful in WEFE-related climate innovation assessment: it makes it possible to identify the most suitable climate innovations to be implemented in farming systems, due to its ability to provide a structured approach for evaluating and comparing various innovations (Champion et al. 2023), and by considering a wide range of indicators—for instance, economic, environmental, and technical—and including various stakeholders (USAID 2013). In addition, it can facilitate the integration of expert judgment and local knowledge, thus making it a valuable tool for assessing climate adaptation and mitigation strategies, especially at farm level (Houngue et al. 2022; Setyantho et al. 2021). Therefore, careful consideration of the criteria, stakeholder engagement, and transparency is essential to ensure the credibility of the MCA results. The research undertakes a thorough evaluation of adaptation strategies based on the multi-criteria analysis methodology. The MCA methodology stands out with its stakeholder-inclusive approach, and not only incorporates normative judgment but also integrates technical expertise, thus providing a nuanced and comprehensive assessment process (De Brucker et al. 2013). By using MCA, the framework designed facilitates the identification and prioritization of innovations, by strategically aligning them with the critical needs of farmers following the adverse effects of climate change. This strategic combination ensures a robust and thorough evaluation, attuned to the dynamic nature of climate change and responsive to the different needs of vulnerable communities (USAID 2013). By embedding these methods within our research, we aim to contribute to a more effective and tailored approach to climate change adaptation in drylands. The primary objective is to conduct an initial evaluation of innovative strategies from the perspective of local farmers and experts. This assessment, which addresses the challenges posed by evolving risks in the context of climate change, employs a qualitative multi-criteria analysis methodology.

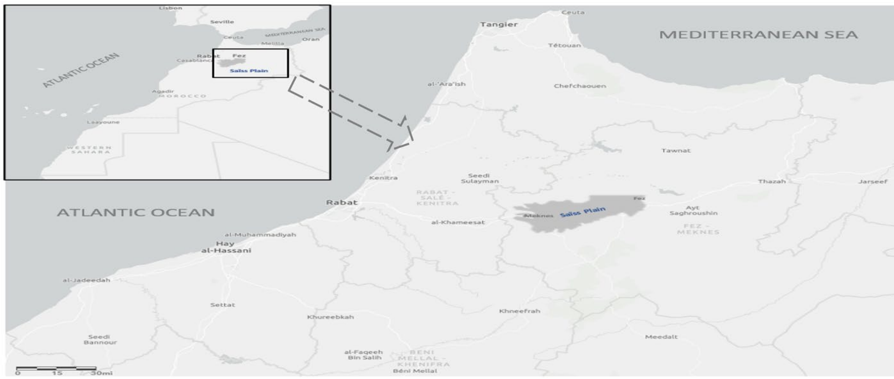

Fig. 3 Location of the "Saïss plain" study area

Regional context and case study description

The Saïss plain in Morocco is a vast and fertile plain with semiarid climate whose average annual rainfall ranges from 207 to 677 mm. The plain is located between the Rif and the Middle Atlas mountain range, and covers a land area of about 2200 km^2 in northern Morocco (El Ansari et al. 2023), of which 1910 km^2 are used for agriculture, thus making it an important agricultural region (Ameur et al. 2020; Bossenbroek et al. 2015). It is traditionally oriented toward rainfed crops (cereal crops, grain legumes, fodder) (Hossard et al. 2021; El Ansari et al. 2020; Baccar et al. 2017; Dugué et al. 2015). The smallholdings in this area are family-owned, and present homogenous production systems with limited access to market, services, and production factors (Baccar et al. 2017), which makes them less likely to adopt innovations in their farming practices (Harmanny and Malek 2019). Moreover, the cultivation area for these small farms is less than 20 ha, and they are equipped with minimal agricultural machinery (Dugué et al. 2015) (Fig. 3).

The resilience of this area is in jeopardy due to many issues caused by climate change or human pressures. In the region, the inefficient adoption of agricultural practices such as organic agriculture (slow progress (El Ghmari et al. 2022), limited access to improved seeds (Irhza et al. 2023; Yigezu et al. 2021)) has led to market limitations. Water scarcity and decreased and irregular rainfall have forced farmers to turn to costly coping mechanisms such as digging wells or abandoning plots of land (Meddi and Eslamian 2021). The depletion of the Saïss aquifer directly threatens agriculture, as over 82% of the water from the Sebou-Saïss basin is used for agriculture. Furthermore, the cost of agricultural production has been increasing (El Ansari et al. 2023; Ameur et al. 2020; El Ansari et al. 2020; Quarouch et al. 2014), for instance, the price of seeds (Sahnouni 2023), energy (Rahhali 2022), and fertilizers; a strong drop in grain production has also been observed (Meddi and Eslamian 2021). Additionally, poor water and electricity infrastructure, as well as the loss of agricultural land to urban expansion (Soulard et al. 2017) are considered key challenges for local farmers. Within this complex and challenging context for farmers, efforts have been made to improve the climate resilience of agricultural systems in the plain, in order to address these challenges by switching from unsustainable practices to sustainable ones, and implementing climate-resilient infrastructure. The 2020–2030 Green Generation Plan (GGP) is working toward improved and more sustainable agricultural development in Morocco, to transition from resource-intensive agriculture to climate-resilient practices (Hossard et al. 2021; Ameur et al. 2020). The Fès–Meknès region has been identified as a priority zone by the GGP, with the specific objective to convert 200,000 hectares to conservation agriculture as part of the 1 million hectare initiative (Essiari and Fadlaoui 2023). However, concerns have been noted, starting with the Green Morocco Plan: these issues are mainly related to investment climate reforms, water and land resource pressure, missing links between its goals and implementation, and outdated data used for its assessment (Faysse 2015).

Data collection

Scenario design

The meeting was set up in January 2023, initially to validate the study area and potential innovations, then later to identify the stakeholders. After considerable deliberations with local stakeholders, a consensus was reached that innovations would take several forms, but they would concern Conservation Agriculture[2] and agroecological practices, followed by financial incentives which would impact four elements directly or indirectly: water, energy, food, and ecosystem. In such a context, several innovations expressed as adaptation strategies were put forward for more eco-efficient agricultural systems, better-balanced food production, and a sustainable provision of ecosystem services. These strategies were often considered with a relative degree of interest by stakeholders (including farmers) due to the specificity of the challenges posed and the diversity of agricultural systems at a territorial level. The meeting was divided into four main stages: (i) first, a presentation highlighting the study area and objectives; (ii) a discussion concerning the proposed innovations from the literature review with stakeholders (iii) a general discussion aimed at identifying the impacts of innovations on WEFE, (iv) the creation of a list of potential stakeholders.

Stakeholder mapping

(ii) Once the innovations had been validated, together with local experts, we went through the list of potential stakeholders and mapped them based on their operational level: local, regional, and national. Active participation from farmers, government officials, researchers, engineers, and agribusiness entrepreneurs was sought to foster a well-rounded understanding of the potential impacts and effectiveness of the innovations. This approach not only enriches the assessment process but also makes sure that the perspectives of key stakeholders are adequately represented, thus contributing to a more informed evaluation (Table 1).

Defining the criteria for assessing the feasibility of innovations

(iii) These criteria play the most important role in ensuring a comprehensive evaluation of the innovations. Despite suggestions from prior studies that a simplified approach might be more practical (Baills et al. 2020; Boruff et al. 2005), ten criteria were defined to

[2] Conservation agriculture consists in conserving and improving soil properties, conserving moisture, stabilizing and increasing crop yields (Hobbs et al. 2008; FAO 2022). Conservation agriculture relies on three principles: (a) minimization of soil disturbance by using methods such as no-tillage (NT), minimum tillage (MT), or strip tillage (ST); (b) continuous maintenance of soil cover which includes crop residues and cover crops; (c) implementing practices such as crop rotation, combination, or diversification within the field to optimize agricultural output and ecological balance (Marenya et al. 2017; El Bakali et al. 2023a).

Table 1 List of the stakeholders consulted

Stakeholder profiles		Power scale
Four smallholder farmers		Local
	Decision-maker	Regional
	Decision-maker	Regional
Extension services	Extension services (private)	Regional
	Extension services (public)	Regional
Researchers	Researcher	Local
	Researcher	Regional
	Researcher	National

assess the innovations in this study. The chosen criteria were categorized into three main groups: technical, economic, and environmental (Table 2).

Criteria weighting and scoring

(iv) The fourth step aimed to include technical expertise in the assessment process, and focused on the involvement of stakeholders through a focus group discussion as well as on criteria weighting and innovation scoring. The judgments of experts were crucial for the assessment of innovations by mobilizing a technical, economic, and environmental nexus analysis.

Criteria weighting was at the heart of group discussions, as it could ultimately change the ranking of innovations. Each criterion was evaluated independently by each stakeholder using their knowledge and experience of the suggested innovations. In this step, the stakeholders decided which criteria should be given more or less weight with respect to others based on their interest. The criteria were ranked from most important to least important, where the most important (first ranked) criterion was rated as 1, the second most important criterion as 2, the third one as 3, and so on.

To calculate the weight of each criterion, we used the following formula:

$$\text{Weight of criteria} = \left(\text{Value} \,/ \sum \text{Values}\right) \times 100 \tag{1}$$

where the *Value* is the number given by the stakeholder from 10 to 100, the $\sum Values$ is the sum of all values given to each criterion by the stakeholder.

Prioritization of options

(v) In the fifth step, innovation scoring is followed by a second stage called standardization of scoring values, which involves neutralizing the influence of different criteria on ranking results, thus ensuring a fair and unbiased assessment, and allowing for a more accurate and meaningful overall ranking. Consider a scenario where the stakeholder rates the “technical capacity” as 5, which means that a specific innovation needs a very high level of technical capacity, and this is a barrier for the innovation to be implemented: despite the fact that the total score will contribute to a better ranking. To address this, we applied standardization, by assigning a standardized value, in this case of 1, to the original score of 5 (Table 3). The criteria subjected to scoring standardization

Table 2 Explanation of criteria

Groups	Criteria	Explanation
Technical capacity	*Technical capacity*[1]	This refers to the infrastructure, equipment, and resources available for farming. It encompasses buildings and facilities, equipment, road network, and labor (Meuwissen et al. 2019)
	Social complexity[2]	Refers to the acceptance of farmers of the innovation strategies suggested, as well as to the consensus between the parties concerned, their views, and cooperation (Darnhofer et al. 2010b; Hall and Clark 2010; Asayehegn et al. 2017) *Specific questions included:* How willing are you to adopt the proposed innovations? How would you describe the level of consensus among various stakeholders (e.g., farmers, government officials, researchers) regarding the proposed innovations? Do these innovations consider cultural norms? How would you rate the level of cooperation among farmers regarding the adoption of these innovations? What are the main challenges you foresee in implementing these innovations, also those arising from cultural and institutional barriers?
	Institutional complexity	Refers to any barrier from institutions, both public (e.g., government agencies, regulatory bodies) and private (e.g., banks, financial institutions), such as bureaucratic procedures to go through, not providing financial support for the farmers, etc. (Darnhofer et al. 2010b; Hall and Clark 2010; Asayehegn et al. 2017)
Economic	*Profitability*[3]	How much profit will farmers gain from this strategy? (Fadina and Barjolle 2018)
	Cost of action	These opportunities arise from changes in market trends, shifts in consumer preferences, new technologies, and emerging markets. (Fadina and Barjolle 2018; Burrell 2010)
	Market opportunities[4]	Potential revenue streams and access to value-added markets through innovations (Feenstra and Lewis 1999)
	Transaction costs[5]	Includes uncertainty (related to market conditions, weather variability, and the performance of new technologies), frequency (how often transactions occur), and asset specificity associated with technology adoption. (Obińska-Wajda 2016)
Environment	*Water use efficiency*[6]	The extent to which the adaptation strategy can help conserve water resources
	Energy use efficiency[7]	The extent to which the adaptation strategy can help save the energy
	Environmental emergency	How soon does the option need to be implemented due to environmental emergency? (FAO 2007a)

[1] Assessing technical capacity is essential for understanding the resources and capabilities of a farming system (Meuwissen et al. 2019)

[2] It is essential to recognize that farmers are at the core of innovation adaptation. Their willingness to adopt innovations significantly impacts the feasibility and success of implementation efforts (Darnhofer et al. 2010b; Hall and Clark 2010; Asayehegn et al. 2017)

[3] Burrell (2010) emphasizes that if farmers are to take action, they need to see that the benefits of adaptation outweigh the costs

[4] Understanding market dynamics enables farmers to align their adaptation efforts with market demands and opportunities for economic growth. If there is no market for what is produced on the farm with the help of the adapted innovation, then the innovation can be considered as not feasible (Feenstra and Lewis 1999)

[5] This comprehensive view aligns with the neo-institutional school of thought

[6] A crucial criterion to be considered in the drylands due to water scarcity for innovation assessment is water use efficiency

[7] Energy plays a significant role in agricultural operations, from powering machinery and equipment to processing and transportation. Assessing energy use efficiency involves the identification of opportunities to reduce energy consumption (Burrell 2010)

Table 3 Scoring standardization

Criteria to be standardized	Initial scoring	Standardization
Technical capacity	1	5
Social complexity	2	4
Institutional complexity	3	3
Costs	4	2
Transaction costs	5	1

are: technical capacity, social complexity, institutional complexity, costs, and transaction costs.

The last step involved the prioritization of options, where innovations were ranked based on the final weighted scores. The formula for weighted scores considered the weight of each criterion and the score of each option in relation to that criterion. The stakeholders assigned numerical scores from 1 to 5 to each option against specific criterion.

The following Eq. (2) was used to calculate the value of attribute score (x_i) for each criterion multiplied by the weights (w_i), thus giving the weighted sum (S) for each innovation criterion.

$$S = \Sigma w_i * x_i; \tag{2}$$

To calculate the total of all the criteria for each innovation option, we used the following formula:

$$S_1 = \Sigma w_1 * x_1 + w_2 * x_2 + w_3 * x_3 \ldots w_n * x_n \tag{3}$$

Findings

WEFE weighting criteria obtained from farmers and other stakeholders

Farmers and stakeholders taking part in the focus group discussion ranked a list of ten criteria based on the importance accorded to their objectives.

According to Dessart et al. (2019), if resources are abundant and farmers perceive an immediate threat, they may prioritize the environmental criteria in their decision-making process. This is applicable in the study area, where there is a scarcity of resources. Although it is unclear to what extent farmers perceive this scarcity as a threat, they are aware of it. Despite this awareness, they do not prioritize environmental criteria when selecting innovations. The results showed that there is a consensus among farmers regarding the crucial role of profitability and the cost of action when it comes to adopting innovations in farming practices (Table 4).

Both the mean and median values indicate a strong consensus and highlight a unanimous agreement on the significance of these factors. However, the reasoning behind this choice goes beyond farmers simply wanting to minimize costs and maximize profits. We must consider various factors that influence their decision-making process. These include educational and awareness levels (Ben Khadda et al. 2021; Moinina et al. 2018; Berni et al. 2016), previous experience with innovations, economic considerations, limited resources, risk management, and market dynamics. Additionally, the high level of

Table 4 Criteria weighting by farmers

Farmers								
		S1	S2	S3	S4			
Category of criteria	Criteria	W (%)	W (%)	W (%)	W (%)	Mean (%)	Median (%)	St deviation (%)
Feasibility	Technical capacity required	11.8	9.7	13.8	9.9	11.3	10.8	1.9
Feasibility	Social complexity	2.0	4.8	4.6	11.3	5.7	4.7	4.0
Feasibility	Institutional complexity	3.9	6.5	4.6	11.3	6.6	5.5	3.3
Economic	**Profitability**	**19.6**	**16.1**	**13.8**	**12.7**	**15.6**	**15.0**	**3.1**
Economic	**Cost of action**	**17.6**	**14.5**	**15.4**	**12.7**	**15.1**	**15.0**	**2.1**
Economic	Market opportunities	5.9	11.3	10.8	11.3	9.8	11.0	2.6
Economic	Transaction costs	7.8	8.1	10.8	4.2	7.7	8.0	2.7
Environmental	Water use efficiency	13.7	11.3	9.2	14.1	12.1	12.5	2.3
Environmental	Energy use efficiency	11.8	9.7	9.2	5.6	9.1	9.5	2.5
Environmental	Environmental emergency	5.9	8.1	0.08	7.0	7.2	7.4	1.0

S—stakeholder, V—values given by farmer from 10 to 100, W—weights, the bold indicates the criterion ranked as the highest

cooperation among farmers in the study area, which leads to shared interests, is another reason for this choice. However, these choices can also be impacted by family composition and farmers' life cycle stage. For instance, larger families may have more labor available, while younger farmers might be more open to adopting new technologies. This approach may influence their preferences and priorities differently compared to older or smaller family units.

Technical capacity emerges as a key concern for farmers, with a consensus and minimal divergence in viewpoints, as it directly affects their ability to adopt and successfully integrate new practices into their existing farming practices. Farmers in the Fès–Meknès region recognize the need to enhance their technical capacity not only to remain competitive, but also to adapt to climate change.

In this case, farmers are likely to change their priorities in response to government interventions, subsidies, and other support programs (Taramuel et al. 2023).

The importance placed on water and energy use efficiency, as well as environmental emergency, by other stakeholders is highlighted in Table 5. This consensus among them is driven by government policies and incentives such as the 2020–2030 Green Generation Plan, vulnerability to climate change, and the increase in energy consumption despite policy efforts (Fragkos 2023).

Experts recognize a connection between the environment and economic criteria, where sustainable resource use, specifically water, and energy efficiency, contribute to long-term cost savings and enhance the overall economic viability of the agricultural sector. While social complexity was given less weight compared to other criteria, this does not imply that it is negligible (Table 5). Rather, it reflects the perspective that farmers and other stakeholders will not be a barrier to the adoption of these innovations.

Table 5 Criteria weighting by other stakeholders

Other stakeholders											
	S5	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**				
Category of criteria	**Criteria**	**W (%)**	**W (%)**	**W (%)**	**W (%)**	**W (%)**	**W (%)**	**W (%)**	**Mean (%)**	**Median (%)**	**St deviation (%)**
Feasibility	Technical capacity required	2.08	12.90	10.94	10.17	11.67	9.84	7.8	9.34	10.17	3.57
Feasibility	Social complexity	4.17	6.45	7.81	3.39	1.67	6.56	6.3	5.18	6.25	2.17
Feasibility	Institutional complexity	4.17	4.84	7.81	3.39	3.33	9.84	9.4	6.11	4.84	2.83
Economic	Profitability	10.42	12.90	10.94	10.17	15.00	8.20	9.4	11.00	10.42	2.28
Economic	Cost of action	6.25	11.29	7.81	11.86	8.33	9.84	12.5	9.70	9.84	2.32
Economic	Market opportunities	10.42	4.84	6.25	10.17	6.67	8.20	6.3	7.54	6.67	2.12
Economic	Transaction costs	6.25	1.61	4.69	3.39	3.33	1.64	4.7	3.66	3.39	1.70
Environmental	**Water use efficiency**	**18.75**	**16.13**	**15.63**	**16.95**	**16.67**	**14.75**	**14.1**	**16.13**	**16.13**	**1.54**
Environmental	**Energy use efficiency**	**18.75**	**14.52**	**14.06**	**15.25**	**16.67**	**16.39**	**15.6**	**15.90**	**15.63**	**1.57**
Environmental	**Environmental emergency**	**18.75**	**14.52**	**14.06**	**15.25**	**16.67**	**14.75**	**14.1**	**15.44**	**14.75**	**1.71**

S—stakeholder, W—weights, the bold indicates the criterion ranked as the highest

Additionally, technical capacity is acknowledged as an important criterion, but they assigned it a moderate weight to avoid the risk of not capturing the broader challenges and considerations that impact implementation feasibility and success.

Prioritization of WEFE innovations

Based on the findings of the MCA assessment, the two groups of stakeholders that took part in the focus group discussion made different choices regarding the innovations to be adopted in the study area (as shown in Tables 6, 7). The proposed innovations were generally well aligned with local cultural and traditional farming practices, as well as local characteristics, which are key drivers of decision-making when adopting innovations. However, the group of stakeholders believed that some of the innovations put forward, such as the loan initiatives for women, did not fit the local context. This misalignment underlines the importance of tailoring innovations to the specific needs and conditions of the target area to ensure their successful implementation.

These findings collectively demonstrate the complex and multifaceted nature of the differences in prioritization of innovations in terms of their impacts on WEFE, and their implementation feasibility at the farm level.

The group of other stakeholders considers drought-resistant crop varieties to be crucial innovations in the area due to their high water use efficiency and resistance to crop yield losses in drought-prone areas (Table 6), while the analysis of social complexity revealed that other stakeholders showed a high willingness to adopt drought-resistant crop varieties due to their potential to mitigate crop yield losses in drought-prone areas. This strategy scored notably high in water use efficiency (0.78) and environmental emergency (0.76). Overall, the group stated that addressing water scarcity and promoting the economic viability of drought-resistant crops make this strategy a comprehensive choice for sustainable agriculture in the Fès–Meknès area. Likewise, intercropping secured the second position in the prioritization process among other stakeholders, thus highlighting its importance in addressing water scarcity, just like drought-resistant crop varieties. It is worth noting that intercropping has a moderate level of technical complexity (0.45), yet according to local experts, in order to successfully implement it, farmers need to have a certain level of technical knowledge, including understanding the compatibility of different crops, their growth patterns, and nutrient requirements. Additionally, intercropping is compatible with existing market systems and has the potential to improve market access (0.32), which makes it accessible and profitable as an agricultural innovation.

Rainwater harvesting is considered crucial for improving water resources and offering farmers an alternative to expensive external water sources such as groundwater or municipal supplies. This translates into cost savings, particularly in areas with water scarcity. On the social front, the level of social complexity is low (0.27), which highlights the need for community awareness, education, and, in some cases, collaborative efforts. The success of rainwater harvesting initiatives not only depends on the technology itself but also on effective communication and community engagement. Given that the level of cooperation among farmers is generally high in the study area, this creates a positive environment for collective action in adopting innovations and addressing resource scarcity issues, especially for practices that provide clear mutual benefits, such as rainwater harvesting. However, unlike other strategies, the

Table 6 Weighted scores—other stakeholders

Options	Technical capacity required	Social complexity	Institutional complexity	Profitability	Cost of action	Market opportunities	Transaction costs	Water use efficiency	Energy	Environmental emergency	Final score	Ranking
Weights	0.09	0.05	0.06	0.11	0.10	0.08	0.04	0.16	0.16	0.15	1.00	
Minimum tillage practices	0.19	0.10	0.31	0.33	0.10	0.38	0.04	0.81	0.16	0.77	3.17	10
Organic fertilizers such as compost and manure	0.47	0.26	0.31	0.22	0.19	0.08	0.04	0.81	0.64	0.77	3.77	6
Use of drought-resistant crop varieties	**0.47**	**0.26**	**0.31**	**0.55**	**0.48**	**0.38**	**0.18**	**0.81**	**0.16**	**0.77**	**4.36**	**1**
Drip irrigation	0.09	0.26	0.06	0.44	0.19	0.30	0.07	0.65	0.48	0.62	3.16	11
Intercropping	**0.47**	**0.26**	**0.31**	**0.55**	**0.48**	**0.30**	**0.15**	**0.65**	**0.16**	**0.77**	**4.09**	**2**
Rainwater harvesting	**0.47**	**0.26**	**0.31**	**0.55**	**0.48**	**0.08**	**0.18**	**0.65**	**0.16**	**0.77**	**3.90**	**4**
Integration of olive trees with cereal crops	**0.47**	**0.26**	**0.31**	**0.55**	**0.48**	**0.30**	**0.18**	**0.65**	**0.16**	**0.62**	**3.97**	**3**
Production of alternative livestock fodder	0.47	0.26	0.31	0.55	0.29	0.38	0.18	0.16	0.64	0.15	3.38	8
Providing financial incentives to farmers who adopt water conservation practices	**0.09**	**0.26**	**0.31**	**0.55**	**0.48**	**0.08**	**0.11**	**0.65**	**0.64**	**0.62**	**3.78**	**5**
Establishing schemes for revolving loans with a focus on women	0.47	0.26	0.31	0.33	0.10	0.08	0.11	0.16	0.16	0.15	2.12	14
Crop rotation	0.19	0.10	0.31	0.55	0.19	0.38	0.15	0.65	0.64	0.62	3.76	7
Integration of livestock and crop production	0.09	0.10	0.31	0.22	0.19	0.23	0.18	0.32	0.32	0.15	2.12	13
Crop diversification	0.09	0.05	0.31	0.44	0.10	0.38	0.07	0.48	0.48	0.31	2.71	12
Soil conservation practices	0.09	0.10	0.31	0.44	0.10	0.38	0.04	0.81	0.16	0.77	3.19	9

Bold: Indicates the innovation ranked as a top priority in the area

Table 7 Weighted scores—Farmers

Options	Technical capacity required	Social complexity	Institutional complexity	Profitability	Cost of action	Market opportunities	Transaction costs	Water use efficiency	Energy	Environmental emergency	Final score	Ranking
Weights	0.11	0.06	0.07	0.16	0.15	0.10	0.08	0.12	0.09	0.07	1.00	
Minimum tillage practices	**0.34**	**0.28**	**0.33**	**0.47**	**0.15**	**0.10**	**0.31**	**0.48**	**0.45**	**0.36**	**3.27**	**5**
Organic fertilizers such as compost and manure	**0.23**	**0.28**	**0.33**	**0.62**	**0.45**	**0.10**	**0.31**	**0.48**	**0.36**	**0.36**	**3.52**	**2**
Use of drought-resistant crop varieties	0.23	0.28	0.33	0.62	0.30	0.10	0.31	0.48	0.09	0.36	3.10	8
Drip irrigation	**0.34**	**0.28**	**0.33**	**0.62**	**0.30**	**0.10**	**0.31**	**0.60**	**0.27**	**0.36**	**3.52**	**3**
Intercropping	0.34	0.17	0.33	0.47	0.45	0.10	0.31	0.48	0.18	0.36	3.19	6
Rainwater harvesting	0.34	0.28	0.33	0.47	0.30	0.10	0.31	0.48	0.09	0.36	3.06	9
Integration of olive trees with cereal crops	**0.56**	**0.28**	**0.33**	**0.62**	**0.60**	**0.10**	**0.39**	**0.48**	**0.27**	**0.36**	**4.00**	**1**
Production of alternative livestock fodder	0.23	0.06	0.07	0.47	0.45	0.10	0.08	0.24	0.27	0.36	2.31	14
Providing financial incentives to farmers who adopt water conservation practices	0.56	0.28	0.26	0.47	0.15	0.39	0.15	0.36	0.09	0.29	3.01	10
Establishing schemes for revolving loans with a focus on women	0.45	0.23	0.07	0.47	0.15	0.39	0.15	0.12	0.09	0.22	2.33	13
Crop rotation	0.34	0.06	0.07	0.47	0.30	0.29	0.15	0.36	0.18	0.36	2.58	12
Integration of livestock and crop production	0.34	0.06	0.07	0.62	0.45	0.29	0.15	0.12	0.18	0.36	2.64	11
Crop diversification	0.56	0.06	0.07	0.62	0.45	0.29	0.15	0.36	0.18	0.36	3.11	7
Soil conservation practices	**0.45**	**0.06**	**0.07**	**0.62**	**0.60**	**0.29**	**0.15**	**0.48**	**0.36**	**0.36**	**3.45**	**4**

Bold: Indicates the innovation ranked as a top priority in the area implementation costs of rainwater harvesting are not low. Once the infrastructure is in place, maintenance involves routine checks and simple repairs, which leads to sustainable and cost-efficient water management, and results in a positive return on investment.

Lastly, the implementation of financial incentives to encourage farmers to adopt water conservation practices highlights the complex social and institutional factors involved. This suggests that financial incentives can be crucial in engaging farmers. Nonetheless, it is important to recognize that this strategy also carries the risk of becoming a maladaptation, based on past experiences. It is common for farmers to prioritize planting cash crops, such as vegetables, when they have ample water resources for crop production. This choice is driven by the desire to maximize profits, as these cash crops typically yield higher returns. However, it is crucial to note that such crops also require more water, thus creating a trade-off between profitability and water consumption. This trade-off goes against the original purpose of suggesting this innovation in the first place.

Meanwhile, the ranking carried out by farmers is influenced by the different perceptions and priorities of farmers, as well as by their experience, local concerns, and interactions within the farming community. Based on farmer choices, it becomes evident that economic incentives outweigh the environmental benefits of innovations (Table 7). Farmers argue that the adoption of certain practices is not solely determined by their willingness, but rather requires favorable conditions, such as soil type, water availability, farmer experience, and cultural context, to be met beforehand.

Integrating olive trees with cereal crops is ranked as one of the top five priorities for both "other stakeholders" (in the third position) and farmers (in the first position). The preference of farmers for this integration reflects a localized understanding of the high economic benefits that come with diversified agroforestry. This understanding may be influenced by historical agricultural practices in the region and the demands of local markets. For instance, in the 2020–2021 agricultural year, the production of olives was 623,539 t (Idrissi 2021). The scoring patterns among farmers indicate an increasing recognition of agroforestry as a multifaceted solution within sustainable agriculture. Practical experiences and challenges related to water scarcity in the region further reinforce the importance of technologies such as drip irrigation. This aligns with the findings of Elouadi et al. (2020), which highlight the positive impact of drip irrigation on crop water use efficiency and overall farm productivity. The high profitability score (0.62) emphasizes the economic attractiveness of drip irrigation. This choice aligns with the global trend of precision agriculture, which prioritizes resource-efficient practices.

Furthermore, regarding organic fertilizers, farmers still see their use as profitable (0.62), especially because they can obtain manure from their own livestock without incurring additional costs (0.45). While they are open to incorporating organic fertilizers into their farming practices and recognize their benefits, they still prefer fertilizers that provide higher yields. As for pest control, only a small number of farms in the Fès–Meknès region use more sustainable methods. This finding is supported by a study conducted by Ben Khadda et al. (2021), which revealed that 85.6% of farmers rely solely on chemical methods. Nonetheless, the acceptance of the adoption of more sustainable practices indicates that awareness-raising efforts have been effective in this area.

Table 8 Prioritization of adaptation options—Other stakeholders & Farmers

Other stakeholders			Farmers		
Options	**Total**	**Ranking**	**Options**	**Total**	**Ranking**
Use of drought-resistant crop varieties	4.36	1	Integration of olive trees with cereal crops	4	1
Intercropping	4.09	2	Drip irrigation	3.52	2
Integration of olive trees with cereal crops	3.97	3	Organic fertilizers such as compost and manure	3.52	3
Rainwater harvesting	3.90	4	Soil conservation practices	3.45	4
Providing financial incentives to farmers who adopt water conservation practices	3.78	5	Minimum tillage practices	3.27	5

Lastly, it is worth mentioning that farmers ranking soil conservation and minimum tillage practices as their fourth and fifth preferences are in line with the objectives of the Green Generation Plan. This demonstrates that the government's active promotion of and education in sustainable agriculture have likely played a role in influencing farmers to prioritize methods that align with national policy.

Moreover, the increasing awareness of environmental issues and the economic viability of these practices among farmers also contributes to their selection. They are also inspired by success stories from other farmers, known as farmer leaders in the region, who have successfully implemented these practices. Additionally, access to resources and government support further influence the decisions of farmers.

Discussions

Both groups of stakeholders (farmers and other stakeholders) prioritize strategies with high water use efficiency, which aligns with the study of Rejekiningrum et al. (2022), who emphasize the importance of maximizing water efficiency in dryland farming areas for resilience. Innovations such as drip irrigation and crop rotation directly address this need by conserving water resources, thereby helping farmers withstand periods of drought and water scarcity. However, while other stakeholders place a stronger emphasis on environmental considerations, farmers prioritize economic viability and market opportunities. For instance, integrating olive trees with cereal crops, thus ensuring a sustainable source of income: this innovation not only enhances economic resilience but also promotes ecological benefits, such as improved soil health and biodiversity, and contributes to the overall resilience of dryland farming ecosystems (Table 8). Studies by Waha et al. (2017) and Szaboova (2023) also highlight the economic considerations of smallholders in adopting new agricultural practices.

Findings by Fadina and Barjolle (2018) and Burt et al. (2023) highlighted that financial support mechanisms are critical for the adoption of sustainable practices. Our study adds a layer of complexity by discussing the unintended consequences of financial incentives, such as the prioritization of high water use cash crops. These insights suggest that while financial mechanisms can drive the adoption of sustainable practices, they must be carefully designed to avoid promoting unsustainable agricultural choices. It is essential to integrate these perspectives in order to develop sustainable water management policies that align with both ecological imperatives and the economic realities of local agriculture in the Fès-Meknes region. The collaborative identification of strategies that balance technical feasibility, economic viability, and environmental emergency is crucial for the successful implementation of innovations. Based on this work, we observed a gap in the perception of the impact of innovations between the two groups, even though some farmers in the area adopted several practices suggested in the WEFE assessment. This finding indicates that the impacts of these practices were not significant enough to be widely acknowledged. By comparing indicators, we observed that the same strategies scored better in terms of impacts on water use efficiency, energy efficiency, and the environment, for instance, crop rotation or drip irrigation, and in the farmers' group these same strategies received moderate scores in terms of these impacts.

There are several potential reasons for this perception gap. One of them is the lack of knowledge and awareness of certain practices, which influences their perception and ranking of the impacts of these practices. Smallholders in the region have a low level of education and rely mostly on their own experience or unreliable sources. Furthermore, we have observed skepticism among farmers about certain innovations, as some of the farmers tried to implement these practices but did not achieve satisfactory production, and perceived yield impact plays a role in decision-making as well. Given that the farmers who took part in this study were men, the strategy we put forward to involve women in providing loans for farm investments was rejected by both the group of farmers and that of other stakeholders (Tables 6, 7). This indicates that cultural influence remains strong in Morocco. This is primarily due to the limited cases of women being in charge of farms: they cannot be head of the family even when the latter includes no men. According to cultural norms, another male relative will take responsibility for managing the family and the farm in such cases. These factors contribute to the gap in the perception of the impacts of agricultural innovations, which highlights the complex interplay of knowledge, experience, cultural dynamics, and perceived yield impact in shaping the attitudes and decision-making of farmers in the Saïss Plain. Addressing these challenges requires tailored approaches that consider the educational, cultural, and gender dynamics within the farming community.

A key result of the Multi-Criteria Assessment revealed that other stakeholders do not prioritize Conservation Agriculture practices within their top five rankings. This is surprising not only due to its important role in enhancing the resilience of dryland farming within the WEFE nexus, but also since Morocco has made significant efforts in recent years for the extension of CA. In 2008, the implementation of no-tillage practices was limited to only 4000 ha (Kassam and Friedrich 2010), whereas the current plan is to convert 1 million hectares, and 200 k ha out of these are planned for the Fès–Meknès region alone. Farmers rated CA higher than other stakeholders, even though the difference in scoring is very small and they still rank these practices in the 4th and 5th places rather than in their top three priorities. This could be explained by the proximity of these farmers to other leading farmers currently practicing CA. This can also be attributed to the country's commitment to sustainable agricultural innovations. The Moroccan government has prioritized sustainable agriculture and food production as part of its economic and social development, thus recognizing the role of agriculture in achieving broad-based economic growth and reducing poverty. Furthermore, the promotion of CA practices, and the commitment to water-saving technologies have helped

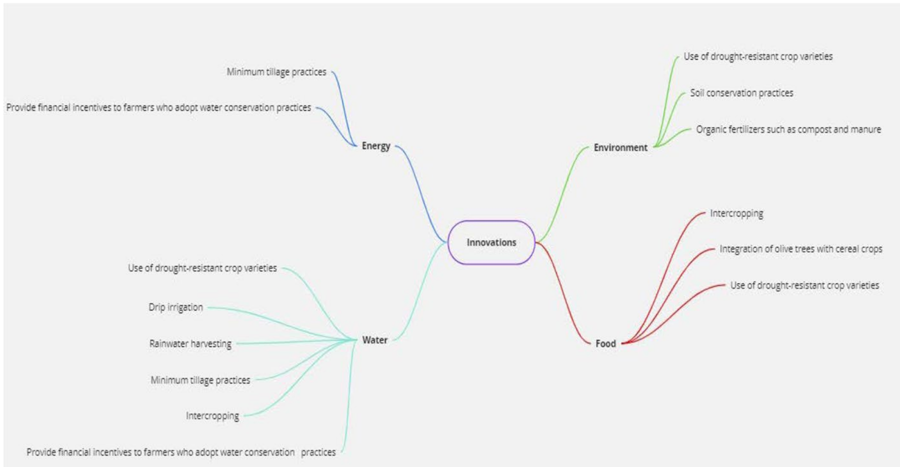

Fig. 4 The potential impacts of innovations on WEFE (water, energy, food, and ecosystem) (according to stakeholders)

to strengthen resilience to drought and increased water scarcity due to climate change. These efforts and commitments create a conducive environment for the acceptance of CA practices by farmers in Morocco, nevertheless not enough to motivate them to be part of the implementation yet.

As shown in the literature review (see Fig. 1), studies not only examine the direct impacts that certain innovations will have on the WEFE nexus, but also consider the indirect impacts. According to the literature, one innovation can somehow affect the entire WEFE nexus, either directly or indirectly. Meanwhile, in our case, stakeholders' perspectives on the impacts of innovations on the farming system mainly focus on the immediate effects on water, often neglecting the broader aspects (Fig. 4). Nevertheless, the identified innovations (Fig. 4) are related to water–food–energy–ecosystem, and are closely linked to the resilience of dryland farming, by addressing water scarcity (through innovations such as drip irrigation, rainwater harvesting, use of drought-tolerant varieties), promoting environmental sustainability (through soil conservation practices and the use of organic fertilizers), improving energy efficiency (through minimum tillage), as well as improving economic viability, which is in the interest of farmers (such as intercropping).

Overall, stakeholders' perspectives on the impacts of innovations are shaped by a combination of interests, economic priorities, knowledge gaps, and communication dynamics within the agricultural sector. This is influenced by various factors; firstly, stakeholders, in this case farmers, tend to prioritize issues with direct and immediate consequences, such as water scarcity and energy efficiency, due to their tangible impacts on production costs and resource availability. For instance, as minimum tillage practices directly affect water usage and energy consumption, they are more inclined to focus on these aspects, which they perceive as more immediately relevant to their operations. Consequently, the broader environmental implications of minimum tillage practices, such as soil health and biodiversity, may be overlooked in favor of more immediate economic concerns. Similarly, financial incentives provided to farmers for adopting water conservation practices are perceived differently by academics and stakeholders. While studies suggest that such incentives primarily impact water resources and their management, both group of stakeholders considered the impact on energy consumption. Moreover, farmers may possess limited awareness or understanding of the multifaceted impacts of agricultural practices. This lack of comprehensive knowledge can result in a narrowed focus on the relationship between water, energy, food, and ecosystem. Additionally, there may be a communication gap between farmers, researchers, and policymakers, regarding the impacts that these innovations have on farming.

Conclusions

This work has developed a systems approach for assessing the resilience of the water–energy–food–ecosystem nexus in arid and semiarid regions, by exploring innovative practices in dryland farming systems, and assessing their impact on water, energy, food, and ecosystem through stakeholder perceptions. In this study, we observed that farmers and local experts in dryland farming systems have differing priorities with regard to the impact of innovative practices on WEFE nexus resources. By identifying and prioritizing innovations that directly or indirectly impact the WEFE nexus in farming systems, this study emphasizes the significance of taking into account stakeholder perspectives, including those of farmers, when implementing innovation strategies in agriculture. Unlike previous literature that examined both the direct and indirect impacts of innovations on the WEFE nexus, in the research case presented in this paper, stakeholder perspectives on the impacts of innovations on farming systems mainly focus on immediate effects on water, often neglecting the broader aspects of the WEFE approach. A deeper examination of stakeholder opinions makes it possible to further explore more systemic impacts of innovations on WEFE resources, beyond the positive effects on water scarcity, such as environmental sustainability, energy efficiency, and farm economic viability, all of which contribute to the resilience of dryland farming systems.

While the adoption of innovations is rising, there is still a long way to go. There seems to be a knowledge gap both at farm and extension service levels, as well as among policymakers, which requires more tailored advice to know which innovations should be encouraged, and where. Future research should focus on including socioeconomic analysis to design appropriate incentives for the adoption of innovations by farmers. Furthermore, as the Moroccan government is working toward more sustainable farming innovations, there is a need to work on information programs, not only designed for farmers but also for extension services and policymakers.

Abbreviations

CA	Conservation agriculture
GGP	Green Generation Plan
GIS	Geographic Information Systems
MT	Minimum tillage
MCA	Multi-criteria analysis
NT	No-tillage
ST	Strip tillage
WEFE	Water, energy, food, and ecosystem

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Author contributions

EK, PP, and HB were involved in study conception and design. EK, PP, RH, RM, GE, and HB helped in review and acquisition of data/material. EK, PP, RH, RM, GE, and HB contributed to analysis and interpretation. EK helped in drafting of manuscript. Review and comments were done by PP, RH, RM, GE, and HB. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets generated and analyzed during the current study are not publicly available as they were obtained from a workshop but are available from the corresponding author on reasonable request.

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