

Review

Reconsidering the Soil–Water–Crops–Energy (SWCE) Nexus Under Climate Complexity—A Critical Review

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Abstract

Nowadays, sustainable agriculture is emerging as a critical framework within which food production, environmental protection and resilience to climate change must go hand in hand. At the core of this framework are the linkages between soil, water, crops, and energy (SWCE). As pressures from climate change, population growth and agricultural land degradation intensify, environmental management strategies are called upon to become more interdisciplinary, targeted and cost-effective. This review article synthesizes recent scientific findings shaping the contemporary understanding of hydro-environmental agriculture and critically examines the conceptual foundation of the SWCE nexus under climate complexity. In addition to reviewing methodological approaches, it highlights both successful global practice examples—such as integrated solar-powered irrigation and conservation-oriented soil–water management systems—and failed or problematic implementations where institutional fragmentation, unsustainable groundwater use, or energy trade-offs undermined outcomes. By analyzing these contrasting experiences, the article identifies key limiting factors and enabling conditions for scaling up nexus-based solutions. Finally, it provides recommendations for future research, integration, and policy-making, emphasizing the importance of adaptive governance, participatory approaches, and cross-sectoral collaboration to enhance the sustainability and resilience of agriculture.

Keywords: agroecosystems; adaptive practices; crop and soil management; irrigation technologies; decision support systems; interdisciplinary knowledge



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1. Introduction

Environmental management and sustainable agriculture are currently at a critical juncture. Increasing climate variability, decreasing water resources and their qualitative degradation require not only technological innovation but also a profound rethinking of the way in which knowledge is produced and applied across scientific fields. Although the relationship among soil, water, crops and energy has been a fundamental axis of agronomic science for decades, contemporary challenges highlight the weakness and failure of fragmented approaches and competing methodologies [1]. In this context, we adopt the concept of climate complexity, which refers to the multi-dimensional and interacting effects of climate change on environmental and agricultural systems. Climate complexity encompasses not only long-term warming trends but also rainfall variability, shifting seasonality, and the rising frequency and intensity of extreme events (e.g., heatwaves, droughts, floods, storms). It also captures indirect effects such as soil erosion, water scarcity, crop stress, and energy demand fluctuations, which together create non-linear, unpredictable dynamics in agroecosystems. Defining climate complexity in this way

provides a quantitative and operational framework for linking observed changes in key variables—such as rainfall distribution, temperature extremes, evapotranspiration rates, and hydrological variability—to agricultural sustainability [2,3] (Figure 1).

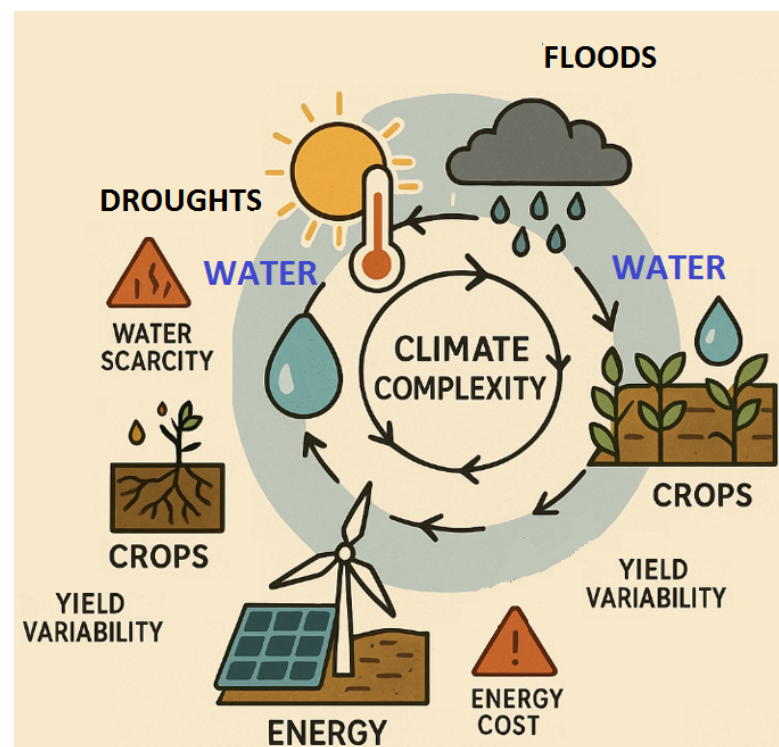


Figure 1. A schematic representation of the key parameters that influence agro-environmental systems under climatic complexity.

In a changing natural environment affected by this climate complexity, qualitative degradation and the scarcity of natural resources, sustainable agriculture has emerged as a major issue for scientists, policymakers and practitioners in the field. Sustainable agriculture is dynamically dependent on soil, water, crops and energy. These four elements are deeply interconnected—through biophysical, economic, and social factors—and must be approached in a holistic and integrated manner. Recent interdisciplinary research has highlighted the importance of this relationship, while revealing shortcomings and failures in dominant models of agro-environmental management [4,5]. Climate change is exacerbating the linkages between key environmental resources, increasing pressure on agriculture, soil health, energy systems and water supply [1,4,5]. Given the interdependencies, especially under conditions of climate variability, the soil–water–crops–energy (SWCE) nexus has gained growing consideration in both academic and policy circles.

Energy is the vital factor that connects soil, water and crops—the fundamental components of sustainable agriculture and food security. Under the influence of climate complexity, which is characterized by more intense and unpredictable patterns of extreme events such as flash or prolonged droughts/floods and soil/water erosion, the linkages between these systems become more breakable and dynamic. The energy demands of agricultural systems are increasing due to the rising need for irrigation, automation of mechanization, agrochemical production and post-harvest processing. At the same time, energy systems themselves are being disrupted by climate instability and resource limitations [4].

Numerous research studies have already examined farmers' preferences for conservation-focused and climate-smart strategies in order to determine their preferences for various agro-environmental climate practices [6,7]. Due to its significant reliance on

natural resources and susceptibility to climate change, there is not much research that examines the connections between climate change and the soil–water–crops–energy (SWCE) nexus in agricultural output. Regarding agricultural production, climate change and the SWCE nexus are strongly related since climate change primarily impacts the nexus's water nodes, which include water supply and water quality. Water supply is directly impacted by variations in rainfall patterns, while water quantity is indirectly impacted by changes in water compartments like surface water or groundwater suitable for agriculture. Climate conditions such as high temperatures and winds may also have an impact on agricultural water demand [8]. While increased precipitation unpredictability and higher temperatures can increase soil moisture and lower agricultural yields, extreme weather events can also induce soil erosion. Changes in atmospheric CO₂ concentration, temperature increases, modified precipitation and transpiration regimes, and an increase in the frequency of extreme water events, pests, and weeds are some of the direct effects of climate change on crops. The latter ones cause more pesticides, herbicides, and insecticides to be applied, which increases pollution. Additionally, the increased demand for irrigation water raises the energy required for irrigation, distribution, and extraction, which raises greenhouse gas emissions even more [8].

A holistic approach to understanding the interconnections between soil, water, crops and energy is crucial to promoting sustainable agricultural intensification and adaptation to climate change. This article reviews current developments in the main fields of environmental management and sustainable agriculture, synthesizing empirical findings and constructively criticizing the assumptions that shape contemporary challenges in this field. This paper explores the role of energy in the soil–water–crop nexus under climate complexity and highlights key challenges that need to be addressed, both now and in the future. Furthermore, it presents successful examples of implementation of the SWCE nexus, as well as a typical failed problematic implementation. Based on this analysis, this article also provides sustainable future directions and vital lessons for the design and governance successful SWCE applications under climate complexity.

2. Soil Health and Agroecological Research

Agroecological frameworks have given particular emphasis to the importance of maintaining soil biodiversity as a mechanism for mitigating climate extremes, contributing significantly to crop productivity [9]. In recent years, the concept of “soil health” has not focused exclusively on soil chemistry and fertility but reflects a more holistic approach that also includes other approaches such as biological activity, structural cohesion and organic matter dynamics. Modern soil research highlights the essential role of soil health not only in enhancing productivity but also in carbon sequestration, biodiversity conservation and maintaining the coherence and stability of the hydrological cycle [10]. A typical example is the transition from models/approaches that study soil exclusively as a chemical substrate, to approaches that recognize its biological complexity. For example, studies in the soil rhizosphere show that microbial load dynamics and microbiome variation play a critical role in nutrient cycling, pathogen suppression and drought tolerance [11]. How can we incorporate microbiome variation and microbial dynamics depending on soil type and climatic conditions into classical agronomic models that focused exclusively on simulating the dynamics of macronutrients and organic matter in the soil? Although advanced molecular techniques such as high-throughput sequencing and metagenomic analysis provide powerful data, their practical application and integration of their potential into soil management strategies remain challenging as microbial biomass is sensitive to land use history and climatic gradients, making it difficult to establish universal application standards [12].

Soil is recognized as a living ecosystem that contributes significantly to nutrient cycling, water storage, and carbon sequestration. Many studies confirm that regenerative agriculture practices, such as organic amendments, cover cropping, reduced tillage, and diversified crop rotations, improve soil structure, enhance microbial activity, and increase drought and erosion resistance of agricultural soils [13]. However, the implementation of these practices in many areas is still limited due to a lack of economic incentives, limited knowledge about their application and/or uncoordinated political interventions that lead to their obsolescence. In addition, precision agriculture technologies, through soil sensors, satellite imaging and artificial intelligence, are valuable tools at the service of farmers and geoscientists which have significantly improved the accuracy, speed of spatiotemporal monitoring and interpretation of soil conditions. However, these technologies are mainly accessible in high-income countries, raising issues of equity in knowledge and dependence on technology [14].

3. Water Governance and Sustainability in Agriculture

Water is both a limiting resource and a key factor for the sustainability of agricultural production. Agriculture consumes more than 70% of global freshwater withdrawals, making irrigation water management the most critical factor for the overall sustainability of our planet. Many studies have shown that integrated water resource management approaches, when implemented through open, participatory and decentralized governance, enhance sustainability and facilitate conflict resolution, while also bringing to the fore creative ideas in the implementation and design of innovative water management services in agriculture [15].

Reduced water resources remain the most important constraint to development in many agricultural areas, especially when exacerbated by climate instability, poor water quality and competition for water use (agricultural, urban/tourism and industrial). In this context, precision irrigation and deficit irrigation strategies are gaining ground as ways to optimize water use efficiency without significant loss in crop yield, and in many cases (when properly implemented) also provide added value to the quality of the products produced [16]. Developments in remote sensing and low-cost artificial intelligence technologies such as IoT allow for real-time irrigation scheduling, which is aligned with crop water needs and climate fluctuations [17]. In recent years, digital irrigation platforms have been created to facilitate these practices, offering personalized suggestions based on meteorological forecasts, crop stages, soil hydraulic properties, and soil moisture data [18–20].

Despite the benefits, critical gaps remain in understanding the socio-hydrological interactions that shape water governance outcomes, especially on small farms where action capacity is weak [21]. One critical issue is that optimizing water use efficiency at farm scale can have inadvertent consequences at the watershed scale. When less water is returned to downstream ecosystems or aquifers, local efficiency improvements may, conversely, lead to regional water stress, a phenomenon often referred to as the “hydrological paradox” [22]. Furthermore, technological solutions to water management often benefit wealthier farmers who can afford to invest in sensors, drip systems or decision support software, deepening social inequalities in the countryside [23]. An emerging body of research calls for the integration of socio-political dimensions into water governance frameworks. These include the recognition of customary rights to water and the promotion of participatory watershed planning. Water governance should be better aligned with the principles of equity, sustainability, and long-term system viability. In this context, the One Water Concept (OWC) promotes an integrated approach to water resources management, emphasizing the interconnectedness of water systems and the need for holistic governance [24].

4. Crop Management Systems in an Era of Unpredictable Climatic and Market Conditions

The necessity to develop crops and products that are resilient to the effects of climatic variability has led to the development of innovative strategies in current farming practices across the production chain as well as in genetic enhancement. Regenerative agricultural practices, such as multiple cropping systems (intercropping), no-till farming, increasing soil organic carbon, smart irrigation, and varieties that are resistant to drought or salinity, have shown promising results in improving resilience and reducing environmental impacts. The levels of adoption of the above regenerative agricultural practices, however, vary significantly depending on the culture, and educational and economic level of farmers, as well as the type of crop [25]. In addition, organic farming strengthens the SWCE nexus by enhancing soil organic matter, which improves fertility, water retention, and carbon storage, making soils more resilient to droughts and floods. Healthier soils reduce irrigation needs and protect water quality by lowering chemical runoff. Through crop diversification, rotations, and the use of resilient varieties, organic systems improve food security under climate stress. At the same time, by minimizing synthetic fertilizer and pesticide use, they reduce fossil fuel dependence and greenhouse gas emissions, lowering the energy footprint of agriculture. Together, these synergies make organic farming a key strategy for building climate-resilient and sustainable food systems [12,26].

It is necessary to understand that the objective of achieving the maximum annual yield as the only criterion of success in the production process does not in any way ensure the sustainability of the crop or the income of the farmer in the future. Although yield remains a crucial indicator, it does not by itself consider all the ecological processes and resilience characteristics required for sustainability. On the contrary, the multifunctionality of the agroecosystem is increasingly promoted as a more comprehensive goal for the sustainability of crops. The loss of biodiversity, the emergence of insect resistance and reductions in soil fertility have been linked to intensive monoculture systems, which are mainly based on chemical inputs and systematic anthropogenic/mechanical interventions. Agroecological models, on the other hand, (a) maintain higher yields in the long term, (b) are more resilient to extreme climatic events, and (c) reduce dependence on external inputs [26]. As far as the production chain is concerned, the combination of green innovation (which seeks to reduce the environmental risks of product production processes) and digital technologies in the supply chain is the means to achieve sustainable development in the manufacturing industry under unstable climatic and marketing conditions. In this context, promoting green technology innovation among companies in a supply chain can break the constraints of time and space, shorten the production chain from the field to the consumer by removing unnecessary intermediaries, promote information exchange and reduce the final cost to the consumer. In addition, obstacles such as poor communication between companies in the supply chain and the mismatch between the supply of products from the farmer's field and the final demand of end consumers can be overcome [27].

Plant breeding is another rapidly growing field. Advances in gene editing technology and genomic selection are accelerating the development of varieties resistant to pathogens/insects as well as water/environmental stress, ensuring high yields [28]. However, critics of these technologies raise concerns about the long-term ecological impacts of genetically modified products, such as gene transfer to wild species and unintended metabolic interactions. Agroecological researchers argue that resistance is not simply a trait introduced into the genetic material, but a property that emerges and interacts with the entire system, including soil structure, biodiversity, and agricultural practices. In any case, the integration of genomic data with agronomic and environmental data remains a contemporary challenge, as it requires the development of interoperable databases, machine

learning algorithms, and long-term field trials to understand genotype–environment interactions in order to draw reliable conclusions that will lead to correct and evidence-based cultivation protocols [29,30].

5. Energy in the Soil–Water–Crops Nexus

Energy plays a crucial role at every phase of the agricultural value chain, including land preparation, harvesting, storage, and distribution. It impacts both the volume and quality of water and soil resources used for food production, as well as their sustainable management.

Most modern irrigation systems require some form of energy input, mainly for pumping water from the ground and distributing it [31]. In India, where more than 60% of the irrigated area is based on groundwater, more than 20% of national electricity production is used to pump groundwater with heavily subsidized electricity costs [5]; diesel pumps are common in sub-Saharan Africa, resulting in greenhouse gas emissions and higher irrigation costs for farmers. As a result, renewable energy solutions (e.g., solar-power) are being adopted as a means to decrease operational costs, reduce emissions, and improve irrigation reliability; however, they can also lead to over-extraction of groundwater if not regulated or paired with smart irrigation management tools [32].

Energy-intensive agricultural practices such as deep tillage, plowing, and use of synthetic fertilizers and pesticides degrade soil health by depleting nutrients, increasing erosion, and decreasing the amount of organic matter in the soil. Conservation agriculture techniques like no-till farming, cover cropping, and organic fertilization minimize energy inputs while improving water retention, soil organic matter, and resilience to climate extremes [33]. Fertilizer production (and especially nitrogen synthesis by the Haber–Bosch process) is one of the most energy-intensive industrial processes. A more efficient nutrient cycle based on organic amendments, biofertilizers, and integrated nutrient management systems is urgently needed to reduce fossil energy use and environmental pollution [34].

Energy plays a crucial role in post-harvest activities such as drying, cooling, storage, and transportation. In developing areas, nearly 40% of perishable food is wasted due to insufficient cold storage and processing facilities, frequently associated with unreliable energy supply [35]. Innovations like solar-powered cold storage units and decentralized energy solutions are demonstrating effectiveness in prolonging the freshness of goods, minimizing waste, and enhancing market accessibility.

Climate adaptation strategies in agriculture are centered on energy access and resilience. Climate complexity, characterized by rising variability and more frequent extreme weather events, poses challenges to traditional farming practices and infrastructure. Decentralized renewable energy systems offer flexibility and robustness, for instance, micro-hydropower and biogas digesters embedded into farming systems can generate clean energy while enhancing waste management and nutrient recycling [35]. Energy-enabling innovations such as automated irrigation, precision agriculture, and sensor-based monitoring systems may enhance the efficiency of water and fertilizer use, making farming more responsive to climatic fluctuations. Nevertheless, their deployment is not uniform in areas where institutional capacity or financial resources are weak. Therefore, efforts are needed to ensure that all have access to clean energy at affordable prices.

6. Global Good Practice Examples of the SWCE Nexus

Ten recent and successful large-scale global applications of the soil–water–crops–energy (SWCE) nexus are briefly presented below.

6.1. Morocco: Solar-Powered Drip Irrigation in Semi-Arid Zones

Morocco is a country with areas suffering from drought, high temperatures and limited water resources. Many of the rural areas, especially in the semi-arid regions of the south and center, rely on groundwater to irrigate crops. However, pumping this water requires energy. To address these problems, an initiative was developed that combines the use of solar energy with efficient drip irrigation systems [36]. The program was piloted by the National Agency for Rural Development and involved small and medium-sized farmers. The basic idea was to replace diesel pumps with solar pumping systems, which feed drip irrigation networks. This technology allowed the transformation of traditional, water-wasting irrigation methods into an efficient and sustainable system. The initiative had multiple benefits. Farmers saved water—up to 60% compared to traditional methods—and drastically reduced fuel costs. At the same time, solar energy eliminated the need for an electrical connection or the use of diesel, reducing carbon dioxide emissions. The soil benefited from targeted moisture, while its degradation due to over-irrigation or runoff was avoided. This strategy has improved citrus fruit, almond, and olive yields, while lowering labor and energy costs, revitalizing more than 100,000 hectares of farmland and empowering smallholder farmers, especially women [37]. The example of Morocco is typical of how, in conditions of climate stress and poverty, practical solutions that combine solar energy with water saving and soil protection can be implemented.

6.2. India (Telangana): Integrated Watershed Management in Telangana

Telangana, a state in the central south of India, is a region that faced severe challenges due to land degradation, water scarcity and poverty of rural communities. Continued deforestation, overgrazing and poor water management had led to severe soil erosion and low agricultural yields. To address this situation, a major Integrated Watershed Management Programme (IWMP) was implemented, initiated by the Government of India in collaboration with international organizations and local communities [38,39]. The Telangana IWDP in India is a prime example of a comprehensive strategy that links agricultural diversification, energy efficiency, water harvesting, and soil conservation. The basic idea was simple: to improve land and water resources naturally, with the participation of local people. Small dams, terraces, water collection wells and reforestation were created at strategic points so that rainwater remained in the landscape and fed the aquifer. At the same time, infrastructure was built to store water and supply it to crops through drip or rotary irrigation. Soil management was carried out with practices such as the use of organic matter, limited tillage and plant cover with endemic species. This helped to stabilize the soil, prevent erosion and restore productivity. Farmers were also trained in alternative crops that consume less water and are of high value, such as chickpeas and millet, while the use of renewable energy (mainly solar) for water pumping and lighting was strengthened. The program was implemented in hundreds of communities and covered more than 810,000 hectares. The results were spectacular: groundwater levels rose, fields regained vegetation, and crop yields doubled in many cases. In addition, there was an increase in farmers' income and a reduction in rural–urban migration [39]. The Telangana example is a model of how collaboration between the state, local communities, and scientific institutions can reverse the degradation of natural resources and bring about sustainable development. The combination of soil, water, crop, and energy management through participatory and tailored solutions is one of the most successful examples of the nexus in practice.

6.3. USA: Precision Agriculture in the Corn Belt

In the United States, the so-called 'Corn Belt'—which includes states such as Iowa, Illinois, Indiana and Ohio—is one of the most productive agricultural regions in the world,

mainly for corn and soybeans. Extensive and intensive agriculture in these areas creates challenges for soil management, water and energy consumption, and has environmental impacts, such as nitrate runoff into rivers and soil degradation [40]. To address these issues, many producers have turned to ‘precision agriculture’—a combination of technology and data-driven management practices. At the heart of precision agriculture is the use of sensors, satellite imagery, GPS, drones and special software to map fields. Farmers can accurately identify which areas have lower humidity, where the soil has less organic matter, and which zones need more or less fertilizer or water. Based on this data, cultivation care (irrigation, fertilization, plant protection) is applied in a targeted manner and not uniformly across the field. This leads to water savings—since unnecessary watering is avoided—and to a reduction in fertilization and energy costs. At the same time, the environment is protected from excessive runoff of nitrates and other chemicals. Some producers have integrated renewable energy sources to power these systems, such as photovoltaics that power monitoring or water pumping equipment. Adoption of precision agriculture in the Corn Belt has spread rapidly, with thousands of producers implementing technologies such as variable fertilization, telemetry in machines, and cloud platforms for data analysis. Many producers are working with agronomists and data scientists to interpret the results and make better decisions [40,41]. This example shows how technology can be combined with natural resource management to enhance efficiency and reduce the ecological footprint. By combining soil management (with analysis and variable interventions), water (with sensors and smart irrigation), crops (adapted practices by zone), and energy (with efficient and renewable means), agriculture in the Corn Belt is a model for applying the soil–water–crop–energy nexus in developed agricultural systems.

6.4. China (Hebei): Eco-Agricultural Parks

Hebei Province in northern China is a region with intense agricultural activity but also serious environmental challenges. Due to the excessive use of chemical fertilizers and pesticides, water pollution and soil degradation, many areas have faced declining productivity and public health problems. As a solution, the Ministry of Agriculture and Rural Affairs in China encourages the development of eco-agricultural parks that incorporate solar-powered greenhouses, organic composting, biogas energy from animal waste, and water-efficient irrigation [42,43]. Ecological parks are designed as farms where all components of production operate in a circular and cooperative manner. Organic residues from crops and livestock are used to produce compost and biogas. The biogas produced is used for heating, cooking or electricity, reducing the need for fossil fuels. The organic fertilizer returns to the soil, improving its structure and fertility. In the water sector, the parks have rainwater collection tanks, modern drip irrigation systems and artificial wetlands to clean waste. Water is reused in multiple phases, reducing overall consumption. Crops are selected based on their resistance to local climatic conditions and their ability to effectively utilize available nutrient and water reserves. Energy in the parks is mainly covered by renewable sources: photovoltaics on the roofs, small wind turbines, and biogas plants. The greenhouses utilize solar energy and semi-autonomous control systems to optimize the microclimate. A central monitoring system oversees water, energy, and production usage in real time. To date, more than 50 ecological agricultural parks have been established in Hebei Province, covering thousands of hectares and integrating thousands of farming families. The results show increased productivity, reduced costs, improved soil and water quality, and strengthened local economies. This model is considered an example of the application of a circular and sustainable agricultural economy [43]. The Hebei example shows how a rural area can be transformed into an ecosystem that produces food, energy, and prosperity, by responsibly managing soil, water, and crops. It is a model for the application of the

soil–water–crop–energy nexus, aiming not only for efficiency, but also for the harmonious coexistence of people and the environment.

6.5. Brazil: No-Till Farming and Bioenergy Integration

Brazil is now a world leader in the integration of bioenergy and conservation agriculture. To protect the soil, reduce emissions and maintain productivity, the country has adopted the technique of ‘no-till farming’ on a large scale, while also integrating bioenergy production into its agricultural sector. No-till farming is based on the principle that the soil should remain covered with plant residues and not be disturbed by deep tilling. Instead of tilling, seeds are placed directly into the soil with special machinery [44,45]. This reduces erosion, conserves moisture, protects soil microorganisms and reduces carbon dioxide emissions. In conjunction with this practice, Brazilian farmers have begun to grow energy crops such as sugarcane and soybeans, which are used to produce ethanol and biodiesel. Many farms have integrated bioenergy plants, using agricultural residues, organic waste or even animal waste. In this way, they ensure energy self-sufficiency for irrigation, processing or transportation. This system has been supported by incentive policies from the Brazilian government and by farmer training programs. In states such as Paraná and Mato Grosso, no-till farming now covers more than 25 million hectares. The results include up to a 70% reduction in erosion, an increase in soil organic carbon, a reduction in fuel use and an increase in yields due to better soil health. This example is a model application of the soil–water–crop–energy nexus: the soil is kept healthy, water is used more efficiently due to the moisture retained, crops adapt to new conditions, and energy is produced endogenously and cleanly [44,45]. In addition, the system supports sustainable rural development and reduces the ecological footprint of agriculture globally.

6.6. Ethiopia (Highlands): Climate-Smart Agriculture

The Ethiopian Highlands are the heart of the country’s agricultural production, with millions of smallholder farmers depending on agriculture for their livelihoods. However, these regions face significant challenges due to climate change such as irregular rainfall, loss of fertile soil, water scarcity and depletion of natural resources. To address these problems, FAO-supported projects in the Ethiopian highlands have implemented climate-smart agricultural practices [46]. Climate-smart agriculture in the Ethiopian highlands includes techniques such as building terraces to slow water runoff and retain soil, collecting rainwater in small tanks, incorporating drought-tolerant crops, and using organic fertilizers to enhance soil fertility. Farmers were also trained in micro-irrigation with drip or furrow irrigation to make better use of the limited water resources available. At the same time, the use of agroforestry systems, where crops are combined with the planting of trees that provide shade, organic matter and soil retention, was strengthened. Energy for community needs (e.g., water pumping and processing) is gradually being covered by small solar units, while the use of efficient wood stoves is being promoted to reduce deforestation [47]. The program was piloted in dozens of areas, in collaboration with the Ministry of Agriculture and is already showing positive results: erosion reduction of up to 50%, increased yields, greater resilience to droughts, and significant involvement of women in new agricultural practices. Social cohesion was strengthened, as the measures were adopted through participatory processes [46]. The case of the Ethiopian highlands highlights how the combined management of soil, water, crops and energy can transform vulnerable areas into sustainable and productive zones, adapted to climate instability. This example has inspired similar interventions in Sub-Saharan Africa and beyond.

6.7. Australia (Murray–Darling): Managed Aquifer Recharge and Solar Energy

The Murray–Darling Basin is one of Australia’s most important agricultural regions, providing over 40% of the country’s agricultural production. At the same time, it is a region that faces serious challenges due to water scarcity, climate variability and over-pumping of groundwater. To address these problems, initiatives have been developed that combine the artificial enrichment of groundwater aquifers with renewable energy sources, mainly solar. Artificial enrichment is implemented by collecting excess surface water (e.g., from floods or seasonal flows), which is filtered through artificial lakes or boreholes and directed to underground aquifers. In this way, water is stored for future use during periods of drought [48,49]. The system is controlled by sensors and infrastructure to monitor the quality and level of groundwater, to ensure the sustainability and safety of drinking and irrigation water. Water pumping and re-channeling require energy, which more and more farmers and operators are choosing to obtain from photovoltaic systems [48]. Solar energy is used to operate pumps, sensors and automatic irrigation systems, thereby reducing gas emissions and operating costs. Many farms combine managed aquifer recharge applications with high-efficiency irrigation networks, such as drip or subsurface irrigation, reducing losses. The program was piloted in South Australia and Victoria, in collaboration with local authorities, agricultural organizations and research institutions. The results are impressive: increased crop resilience to drought, improved water quality, reduced energy consumption, and recharge of groundwater reserves. At the same time, biodiversity has been observed to increase in restoration areas [49]. The example of the Murray–Darling Basin highlights the role of integrated natural resource management: water storage and management, energy autonomy, sustainable agriculture, and ecosystem protection. The combination of artificial enrichment, renewable energy sources and smart irrigation is a modern application of the soil–water–crop–energy nexus.

6.8. China (Yunnan): Greenhouses with Sun and Water

Yunnan province in southwestern China is known for its large production of vegetables and flowers, with a multitude of greenhouses covering thousands of hectares. However, the constant use of energy for lighting, heating and irrigation in the greenhouses, combined with increasing water scarcity, was creating significant sustainability problems [50,51]. To address this challenge, a large-scale project was implemented with the installation of translucent photovoltaic panels on the roofs of the greenhouses. These panels allow light to pass through to crops but, at the same time, produce electricity to power the greenhouses [50]. This significantly reduced dependence on the electricity grid or diesel generators. On many farms, solar energy covers up to 70% of daily consumption. At the same time, rainwater collection tanks and water recycling systems were installed inside the greenhouses. Water that is not absorbed by the plants is collected, filtered and reused for irrigation. Also, by using sensors and automation, farmers water the plants only when really needed, saving water and reducing losses. The soil was improved by using organic fertilizers, and plant cover around the plant rows reduces evaporation and retains moisture. In addition, crop rotation and mixed planting practices were implemented to enhance the resilience and productivity of the greenhouses. The program was piloted on an area of more than 2,000 hectares. The results were very encouraging: up to a 50% reduction in grid energy consumption, a 40% reduction in water use, and a 20% increase in production for some vegetables. Farmers reported significant reductions in operating costs and greater stability in yields, even during periods of heatwaves or water scarcity [51]. The Yunnan example shows how greenhouses can become smarter and more sustainable when solar energy and water reuse technologies are integrated, combined with care for the soil and

crops. It is a practical application of the soil–water–crop–energy nexus model, which strengthens the resilience of the agricultural economy and protects natural resources.

6.9. USA (California): Almonds and Resource Conservation

California in the USA is one of the world's largest almond producers, but at the same time, a region that faces serious challenges of water scarcity, soil degradation and increased energy needs for irrigation. In recent years, in an effort to make agriculture more sustainable and resilient, many almond producers have implemented an integrated natural resource management system, combining soil, water, crop and energy [52]. Thus, the installation of photovoltaic systems on farm land, generates sufficient energy to cover the needs of irrigation systems and pumps, significantly reducing production costs and emissions. In addition, producers use advanced soil moisture monitoring systems. By measuring moisture at different depths with sensors, they are able to irrigate only when absolutely necessary, reducing water consumption by up to 30%. The soil is protected with plant cover and by using organic fertilizers, improving its structure and increasing its water retention capacity [53]. At the same time, biodiversity in the orchards is enhanced, attracting beneficial insects and reducing the need for pesticides. This approach has been applied to an area of more than 50,000 hectares, mainly in the Central Valley of California, where large agricultural enterprises but also smaller producers operate [53]. The results are impressive: increased energy independence, reduced irrigation costs, stabilized yields and a significant reduction in the environmental footprint. The California example shows that, with the right know-how and support from policies and investments, it is possible to transform resource-dependent agriculture into a smart, resilient and sustainable system.

6.10. Greece (Crete): Smart Irrigation and Appropriate Water-Soil Agricultural Practices

Another example is a successful holistic irrigation advisory scheme, accompanied by well-established good agricultural practices (GAPs) related to water and soil (including irrigation according to crop needs, no-tillage, cover crops, winter/summer pruning, mowing weeds only during spring and summer, mulching of pruning residues, application of spray compounds to reduce canopy transpiration, appropriate fertilization, application of compost and introducing natural barriers to reduce water runoff and erosion in sloping areas), which has been implemented in the island of Crete in Greece by the Hellenic Agricultural Organization (ELGO DIMITRA) and which is well adapted to the different needs of farmers and water management bodies [18,54]. The irrigation advisory scheme consists of three different components/levels depending on the spatial scale of application and the needs of end-users. The first level consists of free weekly irrigation bulletins in the main rural areas of the island that aim to inform farmers and local water managers about the irrigation needs of crops. The second level comprises an open-access innovative digital online platform for the precise determination of the irrigation needs of crops in Crete at the parcel level as well as information on the best strategies for adapting crops to climate change. The third level of the proposed irrigation advisory includes an Internet of Things (IoT) energy-independent smart irrigation system [18,55]. This three-level advisory approach provides farmers with specialized information regarding the automated irrigation system and the optimization of the use of irrigation water, saving time and energy for farmers. Indicative results from the application of the above holistic irrigation advisory scheme in many olive, citrus and avocado parcels in the whole island of Crete, demonstrates how this approach can positively affect the quantity and quality of the production compared to traditional irrigation. Specifically, olive production was increased up to 58%, water use efficiency was improved by 39%, and olive oil quality was increased (20% more polyphenols, 33% lower acidity). Regarding citrus fields, fruit production and water use efficiency were improved

by 10% and 34%, respectively. Also, regarding citrus fruit quality, phenols, fruit weight and vitamin C increased by 21%, 4% and 14%, respectively. Finally, in avocado parcels, fruit production and water use efficiency were improved by 14% and 23%, respectively. Also, regarding avocado fruit quality, dry matter, fruit weight and oil content increased by 9%, 12% and 17%, respectively. These data came from quantitative and qualitative crop production measurements throughout Crete, which have been published in the local and national press (printed and electronic) for direct and popular dissemination of information to farmers and management bodies [56]. Also, a portion of these results has already been published in international scientific journals [18,54].

Furthermore, it is estimated that the above smart irrigation approaches, if implemented by all farmers in Crete, could reduce the carbon footprint by almost 3,000 tons of CO₂ on an annual basis, due to reductions in the required travel (use of transport) for irrigation, and could also result in significant savings in man-hours of work due to reduced travel by farmers for irrigation [18,57].

Below, a summary Table 1 of the main points from the 10 case studies related to the soil–water–crops–energy (SWCE) nexus is presented.

Table 1. Summaries the main points from the 10 case studies related to the soil–water–crops–energy (SWCE) nexus.

Location	Main Challenges	Key Interventions	Main Crops	Benefits Achieved
Morocco	Drought, energy costs, inefficient irrigation	Solar-powered drip irrigation replacing diesel	Citrus, almonds, olives	60% water savings, fuel cost reduction, CO ₂ reduction
India (Telangana)	Soil erosion, water scarcity, rural poverty	Integrated watershed management and micro-irrigation	Chickpeas, millet, various rainfed crops	Yield increase, water retention, aquifer recharge, income boost
USA (Corn Belt)	Soil degradation, nitrate runoff, high energy use	Precision agriculture with sensors, drones, variable-rate input	Corn, soybeans	Reduced runoff and inputs, higher efficiency, lower costs
China (Hebei)	Water pollution, soil degradation, chemical overuse	Eco-agricultural parks with solar, biogas, and recycling	Vegetables, fruits, mixed cropping in eco-parks	Reduced emissions, soil health, circular farming benefits
Brazil	Erosion, GHG emissions, energy dependence	No-till farming and bioenergy from residues	Soybeans, sugarcane, cereals	70% erosion reduction, increased soil carbon and yields
Ethiopia (Highlands)	Soil loss, water scarcity, climate vulnerability	Terracing, agroforestry, micro-irrigation, solar energy	Cereals, legumes, enset, local varieties	50% erosion reduction, better resilience, women's involvement
Australia (Murray–Darling)	Water scarcity, groundwater depletion, energy cost	Managed aquifer recharge, solar pumping	Various horticultural and cereal crops	Water quality and storage improved, energy and biodiversity gains
China (Yunnan)	High energy demand in greenhouses, water scarcity	Solar PV on greenhouses, water reuse, sensors	Vegetables, flowers	50% energy and 40% water reduction, 20% yield boost
USA (California)	Water scarcity, soil degradation, high irrigation cost	Soil sensors, cover crops, solar-powered pumps	Almonds	30% less water, improved soil and biodiversity, lower costs
Greece (Crete)	Inefficient irrigation, fragmented farmer support	Three-tier advisory: bulletins, platform, IoT systems	Olives, citrus, avocados	39% higher water efficiency, quality improvements

6.11. Spain (Axarquía Region): A Failed or Problematic Implementation of the SWCE Nexus

While the above examples demonstrate the promise of the soil–water–crops–energy (SWCE) nexus in enhancing agricultural sustainability, it is equally important to recognize cases where such integration has faced systemic challenges. The case of hydrological

collapse in southern Spain's Axarquía Region is an example focusing on a recent, large-scale, and problematic implementation relevant to the SWCE nexus. The case revolves around the expansion of irrigated avocado and mango farming in the Axarquía region of southern Spain, which has led to a hydrological collapse that clearly demonstrates the interplay—and faults—between soil, water, crops and the energy system [58]. The Axarquía region in southern Spain has experienced a sharp increase in irrigated avocado and mango plantations, positioning it as the largest producer of these subtropical fruits in Europe. This agricultural intensification was intended to strengthen rural economies and align with the SWCE link by synergistically exploiting the potential of soil, water, crops and energy. However, instead of ensuring resilience, the push led to a hydrological collapse between 2019 and 2024. During this period, reservoirs that covered both irrigation and urban water needs were almost exhausted. Groundwater levels have dropped sharply—falling to sea level in many areas—raising serious concerns about seawater intrusion and long-term water quality degradation. These dynamics caused immediate crop losses and threatened the economic viability of the agricultural sector in the region. An analysis of the causal factors reveals several critical constraints to the implementation of the SWCE network [59,60]:

1. Exceeding structural water demand: The rapid expansion of export-oriented avocado and mango cultivation did not adequately match the region's water resources capacity. The imbalance was systemic—it was due to uncontrolled water extraction without regard to recharge rates or broader hydrological constraints.
2. Seasonal drought as a trigger: The system was not designed to include continuous meteorological drought events that served as direct stressors. Thus, overuse and mismanagement of water resources under climate variability has put the system on a collision course, waiting only for the right climatic disturbance to collapse.
3. Governance and regulatory failures: Authorities failed to enforce existing water quotas. There was no adaptive regulatory mechanism to restrict or reallocate water use responsively amid declining resources. These governance shortcomings prevented proactive, equitable balancing of water allocations among agricultural, urban, and environmental needs.
4. Overlooked energy–water–crop trade-offs: While the primary issue related to water, the energy dimension—such as increased pumping costs as groundwater depths declined—magnified vulnerabilities. Increased energy needs for irrigation can intensify pressure on both water and operational budgets, yet this feedback was underappreciated in planning models.
5. Consequences for soil and land system: Although not yet fully documented, the challenges of over-pumping and soil wetting/drying cycles increase the risks of soil salinization, nutrient depletion and land degradation—further weakening the foundations for sustainable crop production in the region.

In summary, the hydrological collapse of Axarquía is an example of a high-stakes failure to implement the SWCE nexus. Despite the promise of irrigated tropical fruit agriculture, the system collapsed due to unbalanced water exploitation, lack of regulatory adaptability, and insufficient appreciation of inter-sectoral feedback.

7. The Need for Interdisciplinarity and the Redesign of the Research Agenda

One of the most important challenges in environmental management and sustainable agriculture is the interaction and constructive integration of knowledge between scientific disciplines. In the agricultural sector, soil scientists, hydrologists, geneticists, economists and social scientists often work autonomously, using different terminology and

methodological standards. For example, agronomists focus mainly on yield optimization, hydrologists on water balances and soil scientists on the dynamics of soil nutrients and microbes. Few frameworks effectively bridge these scientific fields. The emergence of contemporary scientific fields concerned with modeling coupled human–natural agricultural systems has offered promising avenues for bridging scientific gaps. These approaches aim to consider both ecological and social dynamics but still face significant difficulties in integrating and analyzing qualitative knowledge [61].

Policy initiatives such as the FAO’s “One Water-One Health” approach highlight the need for integrated modeling platforms and interdisciplinary research teams in the agricultural sector. However, implementing this vision in practice is challenging. Interdisciplinary efforts often stumble on methodological incompatibility, for example, aligning probabilistic simulations with regulatory frameworks and community priorities [62]. Furthermore, reward systems in research institutions continue to prioritize publications in specific scientific fields, which discourages the time-consuming work of collaborative synthesis and cross-sectoral learning. These structural barriers often act as a brake on the creation of the research teams needed to address the complexity of agro-environmental systems. Based on this, there is a need for interdisciplinary approaches that combine natural sciences, social sciences and local knowledge systems [63]. In addition, scholars are increasingly advocating the use of participatory modeling tools (which are gaining increasing recognition in both academia and the field of practice/producers) that can facilitate dialogue. Examples include shared geospatial dashboards and collaborative scenario-building workshops that allow for both expert input and stakeholder participation [64].

Also, the research agenda should be redesigned based on energy supply disruptions due to climate variability. Climate variability impacts not only water or crop production but also energy generation: hydropower (about 60% of all renewable electricity globally) is susceptible to droughts and glacial retreat [31], while extreme heatwaves raise demand for cooling which can stress electricity grids, leading to increased fossil fuel consumption during peak loads. Strategies to build climate-resilient energy infrastructure with battery storage and hybrid systems incorporating solar, wind, and bioenergy are important, as are demand-side energy efficiency measures such as LED lighting, energy-smart pumps, and improved insulation for cold storage.

Integrating energy into the soil–water–crops nexus introduces trade-offs, especially for land and water use [34], which means that expanding bioenergy crops may compete with food crops and increase land degradation or deforestation, while long-term groundwater depletion from over-pumping of aquifers using solar-powered systems is another risk calling for more robust monitoring systems and regulatory frameworks to ensure resource sustainability. Life cycle assessment (LCA) and strategic environmental assessment (SEA) can be used to measure and minimize the negative externalities. Based on the above, Figure 2 depicts the main interdisciplinary challenges in agro-environmental research.

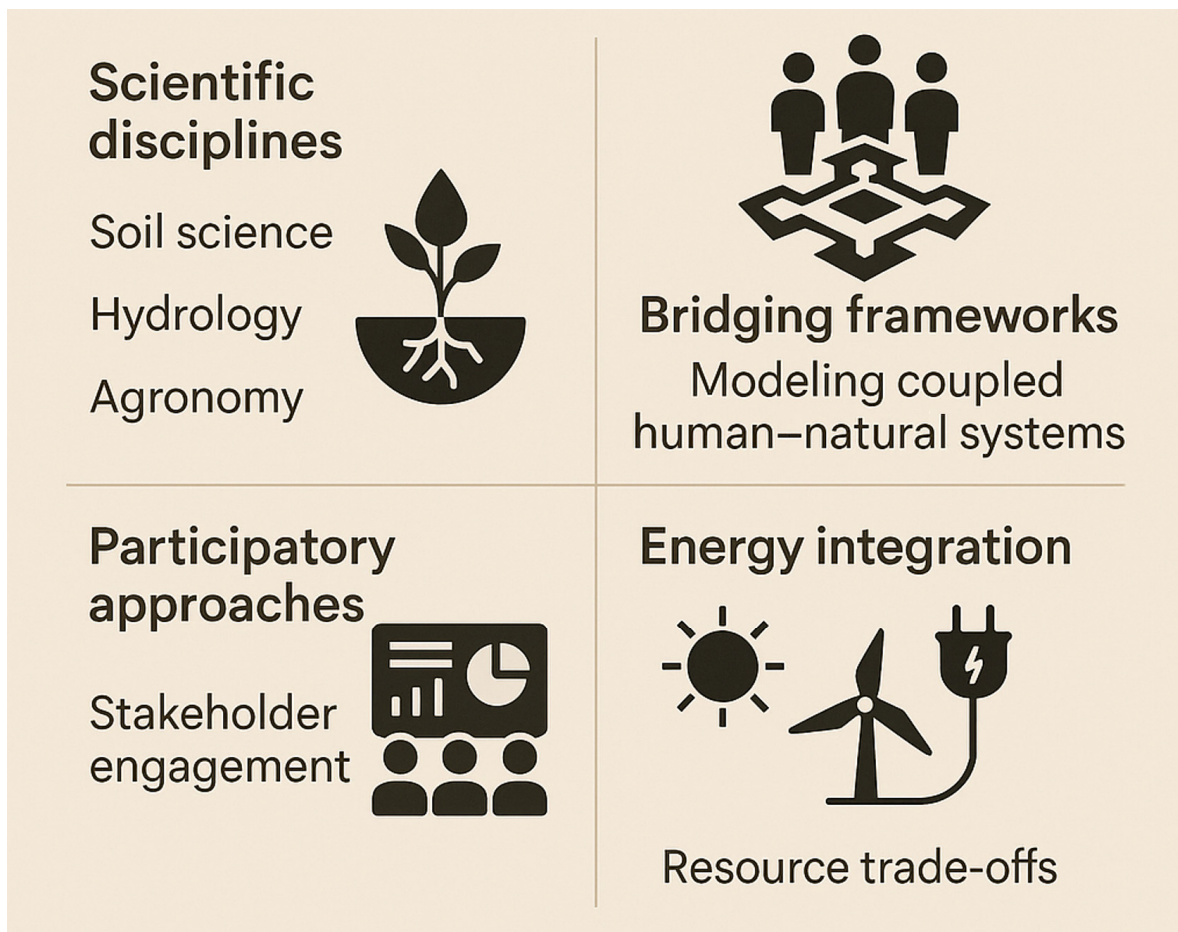


Figure 2. The main interdisciplinary challenges in agro-environmental research.

8. Critical Thinking and Future Directions

While the soil–water–crops–energy (SWCE) nexus approach holds great promise, it faces a multitude of interrelated scientific, technological, institutional, and socio-political challenges, especially in the face of climate complexity [11].

As climate and global instability exert unpredictable and ongoing pressures that are testing and reshaping the boundaries of sustainable development, the need for proactive and flexible governance policies in the agricultural sector is an urgent priority. These should include not only collecting more data, but also re-evaluating the forms of knowledge that we have so far recognized as valuable. Based on this, in many cases, local rural communities possess deep knowledge about the interactions among soil, water, crops and energy, which has been shaped through generations of empirical adaptation. However, this kind of knowledge is often underestimated by the scientific community and remains outside of scientific assessments and decision-making processes [62,65]. Some directions that require special attention from agricultural scientists are the following:

- (a) *The need for epistemological pluralism and social equities.* Beyond the dominance of technocratic logics, knowledge of local conditions and farmers' experiences should be incorporated into research and policy-making. Marginalized communities often do not have decision-making power over water or land management, so outcomes can be inequitable without their participation or with projects that ignore local knowledge, gender dynamics, and indigenous practices, which may also result in community resistance [5].

- (b) *Data Gaps and Monitoring Limitations in decision-making.* Most agronomic and hydrological indicators are based on seasonal or annual totals, while climate change and land degradation evolve over a time horizon of decades or centuries. It is, therefore, necessary to redesign agronomic management systems that take into account such long-term feedback phenomena. Also, in developing countries, data on soil conditions, groundwater levels, crop responses, and energy use may be inaccurate, lacking disaggregation, or nonexistent; remote sensing and Internet of Things (IoT)-based technologies are underutilized or unaffordable; and without good data, it is challenging to develop adaptive strategies [16,55].
- (c) *Moral principles in science.* As genetically modified crops, water commercialization and artificial intelligence farming become increasingly common, it is important to consider not only what is technically feasible as an achievement, but also what is desirable and for whom [66].
- (d) *Institutional and governmental interventions.* Bridging the gap between science and policy requires institutions that promote legitimacy, transparency and participation. Consultation forums, farmer groups and open data platforms can enhance collaboration, reduce production costs and open new horizons in profitability and product promotion (e.g., new markets). Most countries treat water, energy, and agriculture through distinct ministries or agencies; this lack of coordination between policies and investments results in fragmented governance and siloed institutions that often do not share data platforms or inter-ministerial communication [5,14].
- (e) *Economic and Technological Barriers.* High initial costs for integrated systems (e.g., solar irrigation, drip lines, soil sensors), as well as lack of access to credit, prevent widespread adoption of integrated systems; farmers may not have the technical training to maintain or optimize nexus systems in many regions where digital literacy is low and extension services are inadequate [5,55].
- (f) *Fragmented Policy and Institutional Frameworks.* Another challenge in integrating energy into the soil–water–crop nexus is institutional fragmentation. Water, energy, and agriculture are frequently managed by different government agencies with varying mandates and funding priorities, resulting in a siloed approach that hinders coordinated investments [5,67]. Cross-cutting governance models like “nexus committees” or inter-ministerial platforms can be useful to align energy strategies with agricultural and environmental policies. Policy coherence will help scale up renewable energy technologies for farming and design incentive structures that promote more efficient use of resources.
- (g) *Inequitable Access to Clean Energy.* While access to electricity has improved worldwide in recent years, about 675 million people still do not have access to power, with rural agricultural communities most affected [68]. Smallholder farmers, especially in developing countries, can face barrier due to the high cost of installing and maintaining renewable energy systems. Targeted financing mechanisms such as microcredit, green subsidies, and blended finance models are important enablers for the uptake of sustainable energy solutions, while local capacity-building programs and technical training must accompany technological deployment to ensure long-term sustainability [69].

These directions are not instant solutions, but indicate the need for a more thoughtful, participatory, and holistic model of sustainable agriculture, which can be based on a complex and dynamic interaction between ecological, social, technological and energy systems (Figure 3).

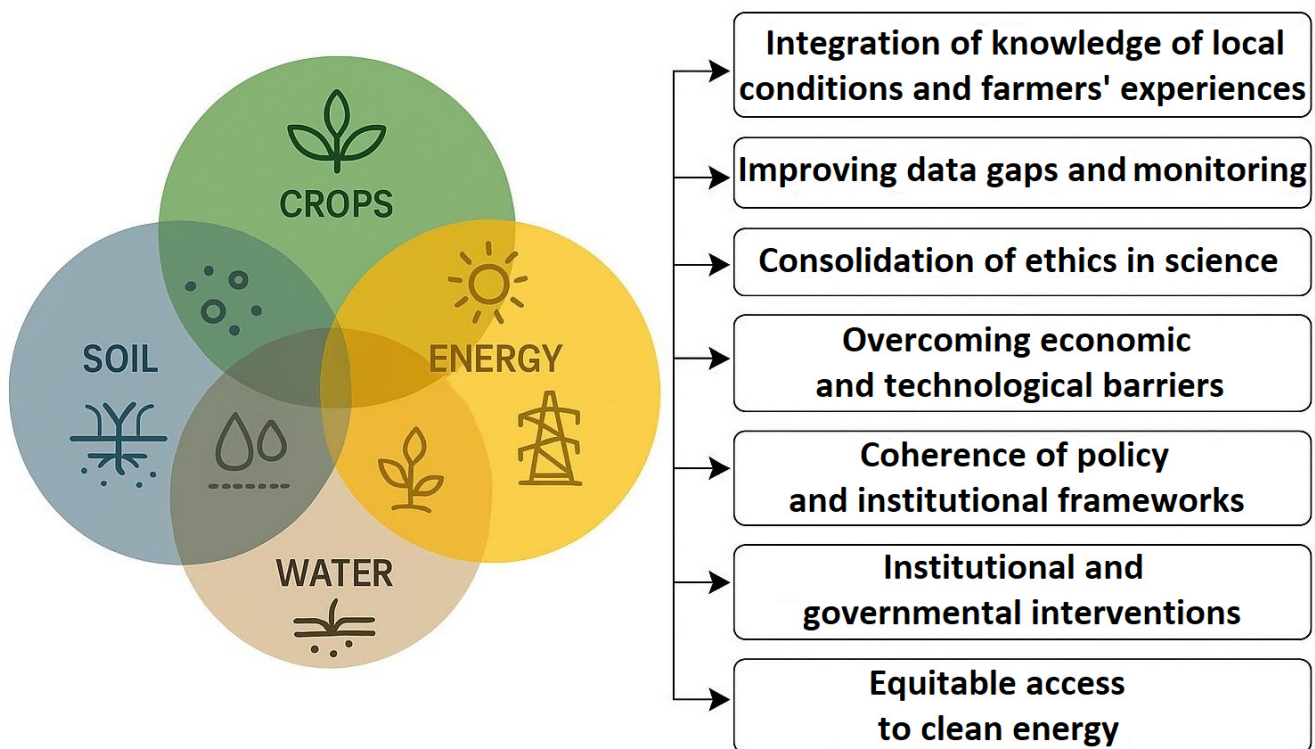


Figure 3. A schematic representation of the SWCE nexus and the future directions that should be prioritized for sustainable agriculture.

9. Conclusions

Sustainable agriculture today is the result of a complex and dynamic interaction between ecological, social and technological systems. Managing soil, water, crops and energy in this context requires more than the application of “good practices” or innovative tools. It requires an integrated, critically reflective approach to science, policy and practice. While recent developments in microbial ecology, precision irrigation, crop genomics and energy systems provide powerful new tools, they also reveal scientific gaps and contradictions, often resulting from the marginalization of local knowledge and the difficulties in synthesizing quantitative and qualitative data. To shape a more equitable and resilient path towards agro-environmental sustainability, it is essential to approach the complexity of agricultural systems methodically rather than with a logic of simplification. This means recognizing and valuing the multiple forms of knowledge that emerge from different social and agro-environmental processes as well as promoting collaboration between sciences and local institutions. The original contribution of this article lies in proposing a policy-oriented framework that reinterprets the soil–water–crops–energy (SWCE) nexus under climate complexity. By synthesizing recent scientific insights and highlighting critical shortcomings in dominant models of agro-environmental management, the paper advances a conceptual framework that links soil, water, crops, and energy, not as isolated resources, but as dynamically interdependent systems shaped by climate variability and governance structures. In agriculture, energy is a cross-cutting enabler that connects and transforms soil, water, and crop systems; under climate complexity it will play a crucial role as a driver of resilient, adaptive, low-carbon agricultural pathways, but only if we can navigate institutional fragmentation, achieve equitable access to energy, and address emerging trade-offs through informed governance.

From this analysis, several vital lessons for the design and governance of future SWCE applications can be drawn. Agricultural strategies must account for hydrological

thresholds and recharge dynamics rather than focusing solely on short-term yield gains, while governance structures need to remain flexible enough to reallocate resources and enact restrictions as conditions shift. A holistic understanding of energy costs and soil health trajectories becomes increasingly necessary when scaling water-intensive agriculture, and effective crisis prevention requires foresight into systemic pressures, with attention not only to reactive responses to climatic triggers but also to the long-term sustainability of resource balances. By framing the SWCE nexus as both a scientific synthesis and a governance challenge, this work contributes a methodological and policy-oriented perspective that can guide future research, cross-sectoral collaboration, and sustainable agricultural transitions.

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