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Sustainable soil governance pathways toward zero food gap

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Abstract

Achieving zero food gap has become a strategic global priority in response to increasing pressures from population growth, land degradation, climate change, and resource scarcity. Despite substantial advances in agricultural technologies, persistent disparities between food demand and production highlight the need for integrated approaches that strengthen the natural resource base while improving decision-making and policy implementation. Among these resources, healthy soils constitute the foundation of sustainable food systems, making sustainable soil governance the essential first step toward resilient food production. This review synthesizes recent advances in soil science, Earth observation, artificial intelligence, and decision support systems to develop an integrated conceptual framework—Sustainable Soil Governance Pathways Toward Zero Food Gap. Following the PRISMA 2020 framework, peer-reviewed literature published between 2015 and 2026 was systematically analyzed and organized into four interconnected domains: sustainable soil management, digital soil intelligence, sustainable soil governance, and enabling societal drivers. Rather than treating these domains independently, the review emphasizes their interactions in transforming scientific evidence into coordinated management and policy actions. The proposed framework identifies sustainable soil governance as the central coordinating mechanism that links healthy soils to digital innovation, evidence-based decision-making, and broader environmental, institutional, and socioeconomic conditions influencing food systems. This perspective recognizes that while soil governance is not the sole determinant of food security, it provides the foundation for integrating complementary interventions to advance the long-term vision of zero food gap. The framework offers a practical roadmap for supporting resilient, productive, and sustainable food systems.

Keywords: Soil governance; Zero food gap; Soil health; Earth observation; Artificial intelligence; Food security

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1. Introduction

The increasing imbalance between global food demand and agricultural production has emerged as one of the most pressing societal challenges of the 21st century. Population growth, changing consumption patterns, climate variability, and accelerating land degradation continue to place unprecedented pressure on agricultural systems, threatening long-term food security and sustainable development.[1] Although technological advances have improved agricultural productivity in many regions, substantial gaps persist between food demand and production capacity, particularly where soil degradation, water scarcity, weak governance, and limited institutional capacity constrain sustainable resource management.[2] These interacting pressures make the transformation of food systems a critical priority for achieving sustainable development, particularly because increasing food production alone may not ensure long-term food security when the natural resources and institutional systems supporting production are simultaneously degraded. Reducing the food gap therefore requires more than increasing agricultural production. It demands integrated strategies that strengthen the natural resources supporting food systems while improving the institutions and decision-making processes responsible for their sustainable management.

In this review, *zero food gap* is defined as a broader, sustainability-oriented conceptual vision that extends beyond the conventional quantitative gap between food demand and food supply. It refers to a long-term condition in which food production capacity, food availability, resource sustainability, environmental integrity, and equitable access are sufficiently aligned to support resilient food systems. Thus, zero food gap is not used as a quantitative indicator or as a substitute for the established concept of food security. Food security encompasses the availability, access, utilization, and stability dimensions of food, whereas the Zero Hunger goal (Sustainable Development Goal 2) represents the United Nations' global commitment to ending hunger and achieving food security and improved nutrition while promoting sustainable agriculture. In contrast, the zero food gap concept adopted here provides an integrative framework linking these outcomes to the sustainable management of soil and other natural resources, digital innovation, effective governance, and socioeconomic enabling conditions.

Among these natural resources, soil occupies a unique position because it underpins virtually every terrestrial food production system. Healthy soils regulate nutrient cycling, water availability, carbon sequestration, biodiversity, and numerous ecosystem services that sustain agricultural productivity and environmental resilience. However, nearly one-third of the world's soils have been degraded through erosion, salinization, nutrient depletion, contamination, and declining organic matter, resulting in lower crop productivity and greater vulnerability of food systems.[3] The persistence and interacting nature of these pressures demonstrate that addressing food-system challenges requires coordinated interventions that simultaneously consider production capacity, natural resource sustainability, institutional governance, and social equity. These challenges have elevated sustainable soil management from a field-level practice to a strategic priority for global food security, climate adaptation, and ecosystem sustainability.

Recent advances in Earth observation, digital soil mapping, and artificial intelligence (AI) have transformed the way soil resources are monitored and assessed. Multi-source satellite observations, unmanned aerial vehicles, proximal sensing technologies, and machine learning algorithms now enable continuous monitoring of soil properties, degradation processes, moisture conditions, and agricultural dynamics across multiple spatial and temporal scales.[4,5] These technologies have substantially improved the availability and accuracy of soil information. However, technological progress alone cannot address complex food system challenges unless scientific information is translated into practical management decisions and effective public policies.

This transition highlights the growing importance of soil governance, which extends beyond conventional soil management by integrating scientific knowledge, institutional coordination, stakeholder participation, policy instruments, and decision support systems into a coherent framework for sustainable land stewardship.[6] Within this perspective, soil governance should not be viewed as the sole determinant of food security. Rather, it represents the coordinating mechanism through which soil information, technological innovation, and management practices are coordinated with broader environmental, economic, and societal priorities. Its effectiveness depends on interactions with several enabling factors, including climate adaptation, water resource management, agricultural policies, investment, and socioeconomic conditions.

The societal significance of sustainable soil governance extends well beyond agricultural productivity. Healthy soils contribute to food security, food safety, climate resilience, ecosystem restoration, sustainable cities, and human well-being while supporting progress toward multiple Sustainable Development Goals.[7] Consequently, achieving zero food gap requires an integrated perspective that recognizes soil governance as the connecting interface between healthy soils, digital innovation, policy development, and the wider social and environmental systems that influence food production.

Although substantial progress has been made in soil science, remote sensing, and AI, existing reviews have largely examined these themes independently. Comparatively little attention has been given to how these components interact within an integrated governance perspective capable of supporting resilient food systems. As a result, an important knowledge gap remains between technological innovation and its effective translation into governance strategies that can address the multidimensional drivers of food insecurity.

Therefore, this review develops an integrated conceptual framework entitled Sustainable Soil Governance Pathways Toward Zero Food Gap. The framework is organized around four interconnected domains: (i) sustainable soil management as the biophysical foundation of food systems, (ii) digital soil intelligence derived from Earth observation and AI, (iii) sustainable soil governance as the mechanism that transforms knowledge into evidence-based decisions, and (iv) enabling societal drivers that influence the successful implementation of governance strategies. By integrating these domains, the proposed framework positions sustainable soil governance as an important pathway connecting scientific evidence with coordinated action toward resilient food systems and the broader long-term vision of zero food gap.

2. Review methodology

This review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines.[8] A systematic search was performed in Scopus, Web of Science Core Collection, and ScienceDirect, with additional studies identified through Google Scholar and reference list screening. The search covered publications from January 2015 to June 2026, reflecting the rapid development of sustainable soil management, Earth observation, AI, and digital decision support.

The primary databases were selected to provide multidisciplinary coverage of the four major themes addressed in this review, while Google Scholar and reference-list screening were used as supplementary sources to identify potentially relevant publications that might not have been retrieved through the primary database searches. Publisher-specific platforms, including the Multidisciplinary Digital Publishing Institute (MDPI), were not searched independently; therefore, articles published by MDPI or other publishers were included only when they were retrieved through the predefined databases or supplementary search procedures.

The search strategy was structured around four thematic dimensions corresponding to the objectives of this review: soil sustainability, digital technologies, food systems, and governance. The search combined keywords and Boolean operators related to these four dimensions, including terms describing soil health, soil degradation and restoration, Earth observation, digital soil mapping, AI, soil governance, food systems, food security, climate adaptation, water resources, agricultural policy, and socioeconomic drivers.

Studies were screened according to predefined eligibility criteria. Only peer-reviewed journal articles and review papers published in English were considered. Eligible studies addressed at least one of the four thematic dimensions while demonstrating clear relevance to sustainable soil management, governance, or food systems. Publications lacking environmental or management implications, as well as conference abstracts, editorials, and other non-peer-reviewed documents, were excluded. During title and abstract screening, records were excluded when they were clearly outside the scope of the review or lacked substantive relevance to the predefined thematic dimensions. During full-text assessment, reports were excluded when they did not satisfy the thematic eligibility criteria, did not provide sufficient evidence relevant to the objectives of the review, or represented an inappropriate publication type.

The literature selection followed the four stages of PRISMA 2020: identification, screening, eligibility assessment, and inclusion. After duplicate removal, titles and abstracts were screened, followed by full-text evaluation of potentially relevant studies. A total of 420 records were identified from the primary databases and supplementary sources, comprising 245 records from Scopus, 105 from Web of Science Core Collection, 50 from ScienceDirect, and 20 from supplementary sources. After removing 70 duplicate records, 350 records remained for title and abstract screening. A total of 240 records were excluded at this stage, leaving 110 reports for full-text assessment. Following the full-text evaluation, 21 reports were excluded for predefined eligibility criteria, leaving 89 studies for the final evidence synthesis. Thus, the numerical sequence of the study-selection process was: 420 records identified, 350 records screened, 110 full-text reports assessed, and 89 studies included. The corresponding numbers and selection stages are presented in Table 1 and visually summarized in the PRISMA 2020 flow diagram (Figure 1). Relevant information was extracted from the selected publications, including research objectives, study location, methodological approaches, technological tools, governance components, and reported environmental or societal outcomes.

For each included study, the evidence-extraction process also recorded the publication year, thematic domain, methodological approach, soil-related component, digital or Earth observation component, governance dimension, relevance to food-system sustainability, and principal reported findings. A structured evidence-extraction matrix was used to organize these characteristics and support the subsequent thematic synthesis. The distinction between systematically retrieved studies and supplementary contextual literature was maintained during the review process. The predefined systematic search period was January 2015–June 2026; however, a limited number of seminal references published before 2015 were retained where they provided essential conceptual or foundational context for the reviewed themes. These references were not used to extend the predefined database-search period. The five pre-2015 references retained in the manuscript are identified separately in the reference list and are treated as contextual rather than as evidence extending the systematic search period.

The selected studies were synthesized into four core scientific domains supported by cross-cutting enabling drivers, which collectively informed the development of the proposed Sustainable Soil Governance Pathways Toward Zero Food Gap framework. Within this framework, sustainable soil governance is viewed as the coordinating mechanism that integrates scientific knowledge, digital innovation, and evidence-based decision-making while recognizing the complementary roles of environmental, policy, and socioeconomic drivers in advancing the long-term vision of zero food gap.

Artificial intelligence-assisted tools, i.e., Google Gemini (version 1.5 Pro; United States of America), were used only to refine the graphical presentation of selected conceptual figures, including layout organization, visual consistency, typography, and graphical clarity. The scientific concepts, framework structure, interpretation of the literature, relationships among the framework components, and final figure content were developed and determined by the author based on the reviewed evidence.

3. Sustainable soil management: the foundation of food systems

3.1. Soil health and soil functions

Soil is the foundation of agricultural production and one of the Earth's most valuable natural resources. It supports plant growth, regulates ecological processes, and sustains the environmental conditions required for food production. As global demand for food continues to increase while cultivable land becomes increasingly limited, maintaining healthy soils has become essential for ensuring food security and achieving sustainable development. This shift has expanded the role of soil from a production resource to a strategic asset that supports both ecosystem stability and human well-being.[9]

The concept of soil health extends beyond traditional measures of soil fertility. It refers to the capacity of soil to function as a living ecosystem that continuously supports plants, animals, and humans while maintaining its physical structure, chemical balance, and biological activity. A healthy soil promotes efficient nutrient cycling, stores and supplies water, resists degradation, and responds effectively to environmental stress. Because these processes are closely interconnected, changes in one property often influence the overall performance of the soil system, making comprehensive assessment essential for sustainable land management.[10]

Table 1. Literature search strategy and eligibility criteria for the PRISMA 2020–based review

Component	Description
Review framework	PRISMA 2020
Primary databases	Scopus, Web of Science Core Collection, ScienceDirect
Supplementary sources	Google Scholar, reference-list screening
Search period	January 2015–June 2026
Main thematic domains	Sustainable soil management; digital soil intelligence; soil governance; food-system enabling drivers
Search concepts	Soil sustainability, soil degradation, soil restoration, Earth observation, artificial intelligence, digital soil mapping, soil governance, food systems, climate adaptation, water resources, agricultural policy, socioeconomic drivers

Notes: The literature search identified 420 records. After removing 70 duplicate records, 350 records remained for screening. Following title and abstract screening, 240 records were excluded, leaving 110 full-text reports for eligibility assessment. Of these, 21 reports were excluded following full-text assessment, resulting in 89 studies included in the final systematic synthesis.
Abbreviation: PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

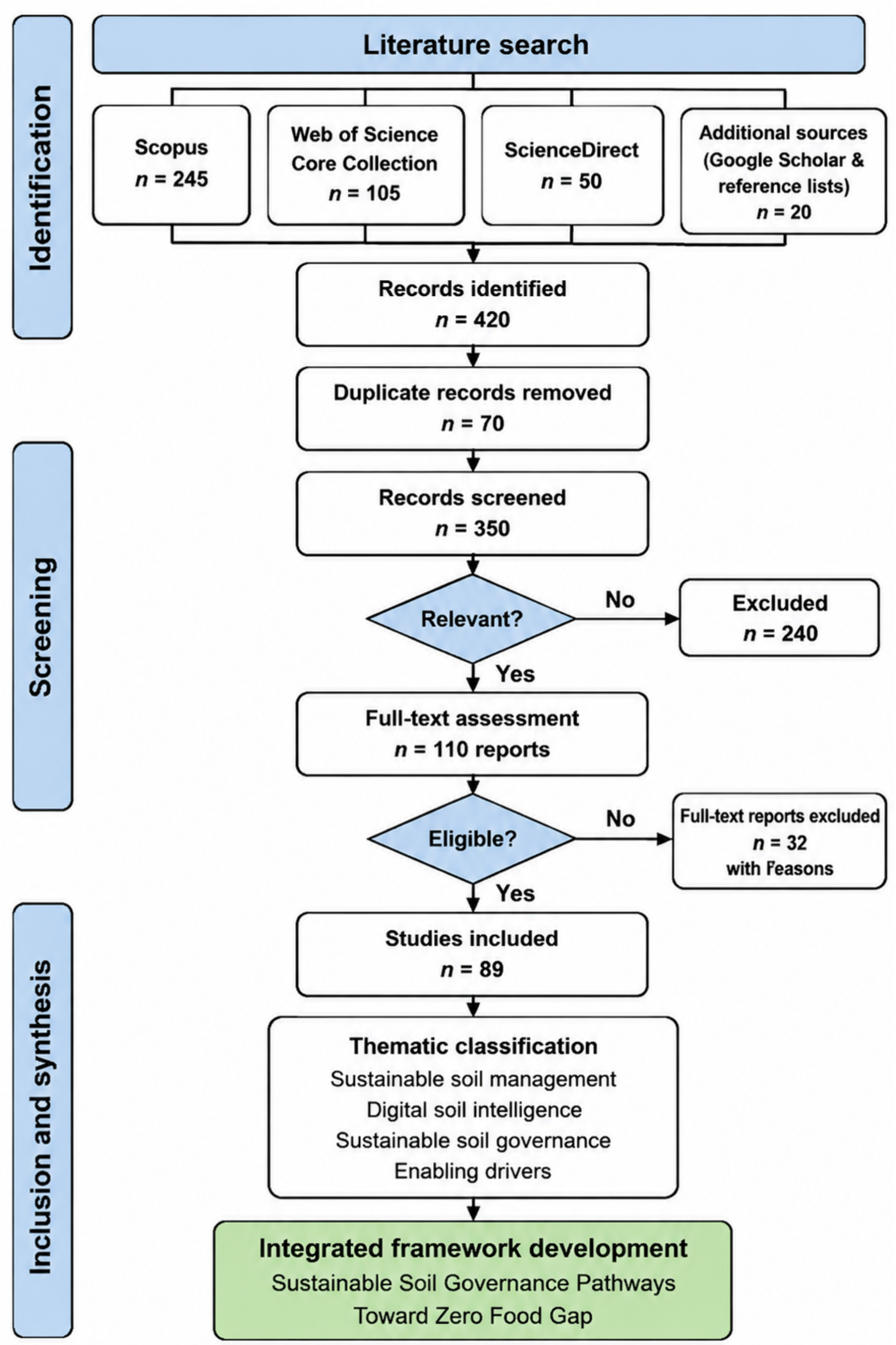

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020–based workflow for literature identification, screening, and thematic synthesis. Image refined with Google Gemini (version 1.5 Pro). Search period: January 2015–June 2026. Five seminal references published before 2015 were retained for conceptual/contextual support and were not used to extend the predefined database-search period.

Soil functions represent the fundamental processes through which soils support agricultural productivity, regulate environmental processes, and provide essential ecosystem services. Beyond their role as a medium for plant growth, healthy soils contribute to nutrient cycling, water regulation, carbon sequestration, biodiversity maintenance, and climate regulation. Understanding these functions is essential for evaluating soil health and designing sustainable management strategies. The major soil functions, their associated ecosystem services, key indicators, and contributions to sustainable food systems are illustrated in Table 2.

The importance of healthy soil also lies in the wide range of ecosystem services that it provides. These services include water regulation, carbon storage, nutrient transformation, contaminant filtration, and the maintenance of biological productivity. Together, they improve agricultural performance while reducing environmental risks associated with land degradation and climate change. From this perspective, sustainable soil management is not limited to increasing crop yields. It also seeks to preserve the ecological functions that sustain productive landscapes over time and support resilient food systems under changing environmental conditions.[11]

Biological diversity is another defining characteristic of healthy soil. Billions of microorganisms, along with earthworms, fungi, and other soil organisms, regulate decomposition, recycle nutrients, and maintain soil fertility through complex ecological interactions. These biological communities improve soil structure, increase nutrient availability, and suppress many soil-borne diseases that threaten agricultural productivity. Recent research indicates that conserving soil biodiversity can strengthen ecosystem functioning and support sustainable agricultural production, with potential benefits for crop health and food quality, as well as broader implications for human health through interconnected soil–plant–food–health pathways.[12] Healthy soils constitute the biophysical foundation upon which sustainable food systems depend. Their capacity to regulate ecosystem processes, sustain agricultural productivity, and provide essential ecosystem services establishes the scientific basis for sustainable soil management. However, these functions are increasingly threatened by multiple forms of degradation that reduce soil resilience and compromise food production. Understanding the nature and consequences of soil degradation is therefore essential for identifying effective management strategies, as discussed in the following section.

3.2. Soil degradation and agricultural productivity

Soil degradation has become one of the most significant constraints on global agricultural sustainability, reducing the productive capacity of land and increasing the vulnerability of food systems. Physical, chemical, and biological degradation processes often occur simultaneously, resulting in declining soil fertility, impaired ecosystem functioning, and reduced resilience to environmental stress. As agricultural production becomes increasingly dependent on marginal lands, the consequences of soil degradation extend beyond crop yields to encompass food security, rural livelihoods, and environmental sustainability.[13]

Among the major degradation processes, soil erosion remains the most widespread threat to agricultural productivity. The removal of fertile topsoil diminishes nutrient availability, weakens soil structure, reduces water infiltration, and accelerates organic carbon losses. These impacts not only decrease crop yields but also increase the demand for external agricultural inputs, thereby reducing the long-term sustainability and economic viability of farming systems.[14]

Chemical degradation, including salinization, acidification, nutrient imbalance, and contamination by heavy metals or emerging pollutants, further constrains soil productivity. These processes alter soil physicochemical properties, reduce nutrient use efficiency, and adversely affect soil microbial communities responsible for essential biogeochemical functions. In irrigated and arid environments, secondary salinization has become an increasingly important challenge under climate change and water scarcity, threatening agricultural production in many food-insecure regions.[15]

Biological degradation is receiving growing attention because soil biodiversity underpins nutrient cycling, organic matter decomposition, disease suppression, and ecosystem resilience. Declining microbial diversity and reduced biological activity impair the capacity of soils to recover from environmental disturbances, thereby weakening the long-term stability of agroecosystems. Protecting soil biological integrity has therefore emerged as a key component of sustainable soil management strategies designed to maintain resilient food production under changing environmental conditions.[16]

Soil degradation represents a multidimensional challenge that directly limits agricultural productivity while reducing the ecological functions required for resilient food systems. Preventing further degradation is therefore essential, but it is insufficient to meet future food demands. Long-term food security requires proactive restoration strategies capable of rebuilding soil functions, enhancing ecosystem resilience, and sustaining agricultural production. These restoration approaches are discussed in Section 3.3.

Table 2. Major soil functions and their contributions to sustainable food systems

Soil function	Main ecosystem services	Key indicators	Contribution to sustainable food systems
Primary production support	Crop growth and biomass production	Soil organic carbon, nutrient availability, pH, cation exchange capacity, nutrient balance	Maintains soil fertility and supports stable agricultural productivity
Nutrient cycling	Transformation and supply of essential nutrients	Microbial biomass, enzyme activity, nitrogen and phosphorus availability, soil respiration	Enhances nutrient use efficiency and reduces dependence on external inputs
Water regulation	Water storage, infiltration, and filtration	Soil texture, bulk density, hydraulic conductivity, available water capacity	Improves drought resilience and supports efficient irrigation management
Carbon storage and climate regulation	Carbon sequestration and greenhouse gas regulation	Soil organic carbon stocks, carbon fractions, CO_2 fluxes	Mitigates climate change and improves soil resilience
Habitat and biodiversity support	Maintenance of soil organisms and ecological interactions	Microbial diversity, nematode abundance, biological activity indices	Strengthens ecosystem stability and natural regulation processes
Soil protection and structural stability	Resistance to erosion and degradation	Aggregate stability, erosion rate, soil compaction indicators, infiltration rate	Reduces land degradation and preserves long-term agricultural capacity
Contaminant regulation	Immobilization and degradation of pollutants	Heavy metals, pesticide residues, microbial degradation capacity	Protects food safety and ecosystem health

3.3. Soil restoration and regenerative practices

Soil restoration has become a central component of sustainable food system transformation, particularly as the expansion of agricultural production increasingly depends on soils affected by degradation processes. Restoration aims not only to recover soil productivity but also to rebuild the ecological functions that regulate nutrient cycling, water availability, carbon storage, and ecosystem resilience. Unlike conventional approaches focused primarily on maintaining crop yields through external inputs, modern restoration strategies emphasize the recovery of intrinsic soil processes and the enhancement of soil multifunctionality through regenerative management practices.[17]

Regenerative agriculture encompasses a range of context-dependent principles and practices aimed at restoring soil health and ecosystem functions, although no universally accepted definition currently exists. Commonly reported practices include reduced soil disturbance, cover cropping, crop diversification, organic amendments, and agroforestry.[18] Evidence indicates that these practices can improve selected components of soil health, including soil organic carbon, nutrient cycling, microbial activity, and soil structure.[19,20] Regenerative practices may also contribute to improved biodiversity, ecosystem functioning, and climate-related environmental outcomes, although the magnitude and consistency of these effects vary among practices and environmental contexts.[21]

A major pathway for soil restoration is the enhancement of soil organic carbon, which represents one of the most important indicators of soil functionality and resilience. Increasing soil organic carbon improves soil physical properties, including aggregate stability, porosity, and water-holding capacity, while supporting microbial activity and nutrient availability. Carbon-focused soil management practices, including organic amendments, compost application, biochar incorporation, and improved residue management, have gained increasing attention as strategies for restoring degraded soils and mitigating climate change through carbon sequestration.[22]

Biochar application has attracted particular scientific interest due to its potential to improve degraded soil conditions through long-term carbon stabilization and modification of soil physicochemical properties. Depending on feedstock characteristics and production conditions, biochar can enhance nutrient retention, improve water availability, increase microbial habitat, and reduce nutrient losses. However, its effectiveness varies considerably among soil types, climatic conditions, and management contexts, highlighting the importance of site-specific evaluation before large-scale implementation.[23]

Integrated soil fertility management provides another important pathway for restoring soil productivity, particularly in regions where nutrient depletion represents a major limitation to agricultural development. Integrated soil fertility management combines the efficient use of mineral fertilizers with organic nutrient sources, improved crop varieties, biological inputs, and locally adapted management practices. This integrated approach improves nutrient use efficiency while reducing environmental impacts associated with excessive fertilizer application, supporting sustainable intensification of agricultural systems.[24]

Beyond agricultural management practices, ecosystem-based restoration approaches are increasingly recognized as essential components of sustainable land management. Restoration of degraded landscapes through agroforestry, vegetation recovery, and nature-based solutions can improve soil protection, enhance biodiversity, regulate hydrological processes, and reduce land degradation risks. These approaches are particularly relevant in drylands and vulnerable regions where soil degradation interacts with climate variability, water scarcity, and socioeconomic pressures.[25]

Recent field evidence further indicates that the restorative effects of conservation-oriented tillage depend not only on the overall reduction of soil disturbance but also on the location, geometry, and intensity of mechanical treatment. Geometry-optimized strip tillage can improve physical conditions and hydraulic functioning within the root zone while limiting unnecessary disturbance of inter-row soil, particularly in semi-arid production systems.[26] Conversely, conventional mouldboard tillage may contribute to the development of dense subsurface layers and increased penetration resistance, particularly in compacted soils.[27] Localized soil loosening provides an alternative approach by concentrating mechanical disturbance where it is most needed and has been associated with more favorable soil moisture conditions and improved soybean productivity compared with conventional plowing.[28] Mechanical restoration can further be complemented by biological and resource-efficient inputs. Nitrogen-fixing microorganisms and humic substances derived from agricultural waste can support nutrient cycling, biological nitrogen fixation, and soil fertility while potentially reducing dependence on synthetic inputs.[29] Moreover, optimization of combined strip-tillage systems can improve the control and spatial localization of soil preparation, demonstrating the potential for integrating engineering design with conservation-oriented soil management.[30] Collectively, these findings indicate that sustainable soil restoration should consider not only the degree of disturbance but also its spatial distribution, physical effects, and integration with biological inputs.

Figure 2 illustrates how complementary regenerative management practices, including conservation agriculture, cover crops, organic amendments, crop diversification, water-smart management, and precision soil management, collectively restore soil health and enhance key soil functions. Improvements in soil fertility, nutrient cycling, water regulation, and biodiversity strengthen agroecosystem performance, increase agricultural productivity and resilience, and ultimately contribute to sustainable food systems and the achievement of

4. Digital soil intelligence for sustainable soil governance

4.1. Earth observation technologies

The increasing complexity and spatial variability of soil conditions require monitoring approaches capable of providing consistent, repeated, and large-scale information on soil properties and degradation processes. Traditional soil surveys and field-based measurements remain essential for accurate characterization; however, their application is often constrained by high costs, limited spatial coverage, and difficulties in capturing temporal changes. Earth observation technologies have therefore emerged as a fundamental component of digital soil intelligence by enabling repeated assessment of soil conditions through multi-source remote sensing data, geographic information systems (GIS), and advanced spatial analysis techniques.[31]

Satellite-based remote sensing provides unprecedented opportunities for monitoring soil-related variables at regional and global scales. Multispectral sensors, such as those on board the Sentinel-2 and Landsat missions, enable the characterization of soil surface conditions through spectral responses associated with mineral composition, moisture status, vegetation cover, and land degradation processes. Spectral indices derived from visible, near-infrared, and shortwave infrared bands have been widely applied to identify exposed soils, assess soil degradation risk, estimate soil moisture dynamics, and support digital soil mapping activities.[32]

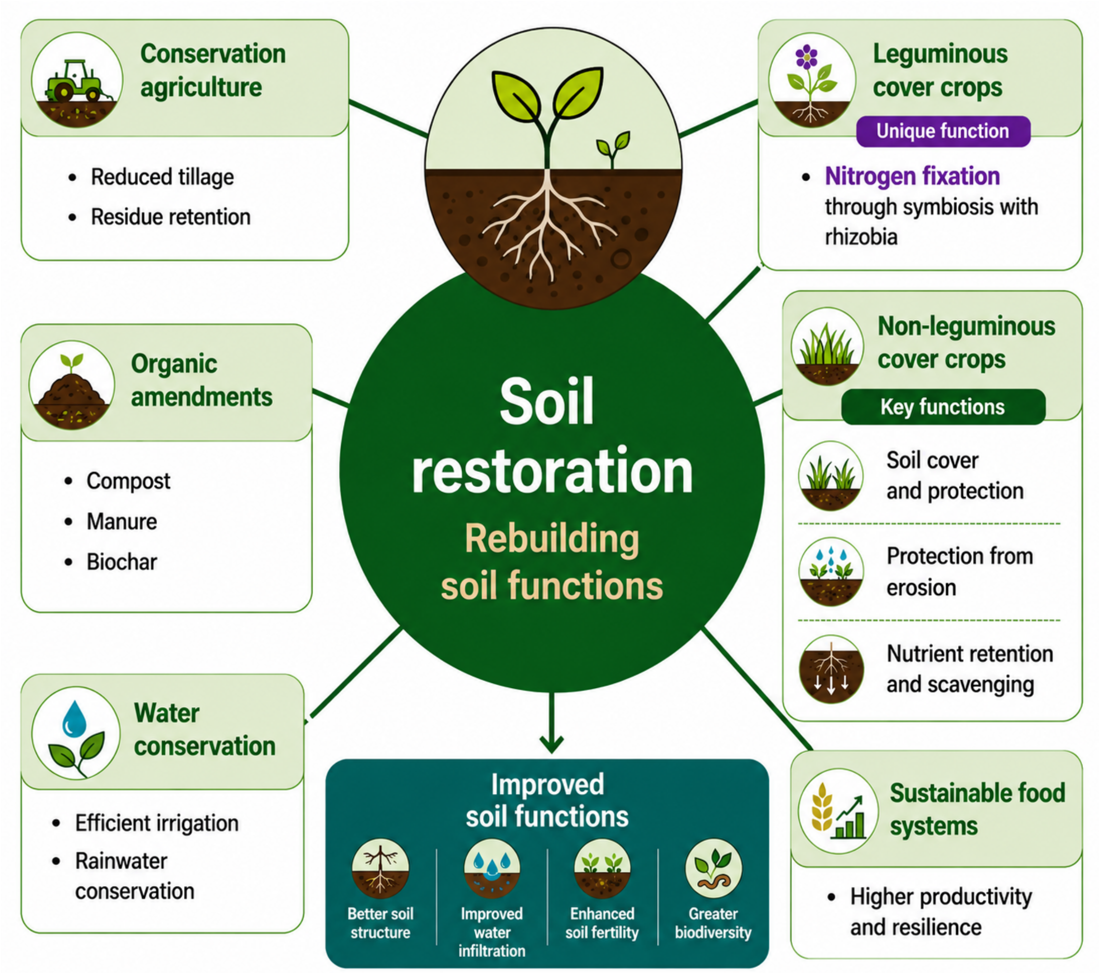

Figure 2. Conceptual framework illustrating how regenerative soil management strengthens soil functions and supports resilient food systems. Image refined with Google Gemini (version 1.5 Pro).

The integration of optical remote sensing with synthetic aperture radar (SAR) observations has significantly improved soil monitoring capabilities, particularly under conditions where cloud cover or vegetation dynamics limit the availability of optical imagery. SAR systems, including Sentinel-1, provide information on surface roughness, dielectric properties, and soil moisture conditions, allowing more reliable assessment of soil hydrological status and land degradation processes. The complementary characteristics of optical and radar observations have facilitated the development of multi-sensor approaches for improved soil characterization and environmental monitoring.[33]

Remote sensing has also become increasingly important for estimating soil organic carbon, one of the most critical indicators of soil health and climate regulation. By integrating satellite observations with field measurements and environmental covariates, Earth observation-based models can support spatial prediction of soil organic carbon stocks over large areas. These approaches are particularly valuable for monitoring carbon sequestration initiatives, assessing land restoration outcomes, and supporting climate-smart soil management strategies.[34]

In agricultural landscapes, Earth observation technologies provide essential information for evaluating soil–vegetation interactions and detecting early signs of degradation. Time-series analysis of vegetation dynamics, crop productivity trends, and surface conditions enables identification of areas affected by erosion, salinity, nutrient limitations, and water stress. The integration of remote sensing-derived indicators with climate and terrain datasets has improved the capacity to develop spatially explicit assessments of soil vulnerability and agricultural resilience.[35]

Earth observation technologies provide essential spatial and temporal information for assessing soil conditions, monitoring degradation processes, and supporting sustainable soil management decisions. Different sensing platforms offer complementary capabilities for characterizing soil properties, environmental conditions, and land surface dynamics. The major Earth observation and AI applications relevant to sustainable soil management, including their data sources, analytical approaches, advantages, and limitations, are presented in Table 3.

The effective application of Earth observation for soil governance requires addressing several challenges, including limited direct observation of subsurface soil properties, uncertainty associated with model predictions, and the need for calibration using reliable field observations. Consequently, future soil intelligence systems increasingly rely on integrating remote sensing with AI, digital soil mapping frameworks, and decision-support platforms to transform observations into actionable management strategies.

Earth observation technologies have fundamentally transformed soil monitoring by providing continuous, spatially explicit information on soil conditions across multiple scales. Nevertheless, the growing volume and complexity of Earth observation datasets require advanced analytical methods capable of extracting reliable and actionable knowledge. AI has therefore emerged as the key enabling technology for transforming remotely sensed observations into quantitative soil information.

Despite these advantages, Earth observation approaches differ substantially in spatial and temporal resolution, spectral sensitivity, data availability, and scalability. Optical sensors provide rich spectral information but are affected by cloud cover and atmospheric conditions, whereas SAR observations can provide complementary information under cloudy conditions but may require more complex interpretation. Hyperspectral observations offer greater potential for detecting specific soil properties but generally involve higher data-processing requirements and more limited operational coverage. Consequently, the choice of Earth observation data should be determined by the target soil property, spatial scale, temporal requirements, and validation capacity. The operational value of Earth observation-derived products also depends on appropriate preprocessing, calibration, uncertainty assessment, and field validation.

4.2. Artificial intelligence and digital soil mapping

The rapid expansion of Earth observation technologies has generated unprecedented volumes of spatial and temporal data describing soil conditions, environmental processes, and agricultural landscapes. However, extracting meaningful information from these heterogeneous datasets requires analytical approaches capable of identifying complex, nonlinear relationships among multiple environmental variables. AI has therefore become an important component of digital soil intelligence by enabling the prediction, classification, and spatial modeling of soil properties across multiple scales. However, the predictive performance of AI models depends strongly on the quality, representativeness, and spatial coverage of training data, as well as model selection and validation procedures.[36]

Digital soil mapping represents one of the most significant applications of AI in soil science. It combines field observations with remotely sensed information, terrain attributes, climatic variables, geological data, and environmental covariates to generate continuous spatial predictions of soil properties. Compared with conventional soil surveys, digital soil mapping offers advantages in spatial resolution, scalability, reproducibility, and the ability to update soil information as new observations become available. However, these advantages depend on adequate sampling density, representative environmental covariates, appropriate model calibration, and independent validation. Consequently, digital soil mapping has become an essential tool for national soil inventories, precision agriculture, land evaluation, and sustainable resource management.[37]

Figure 3 shows that multi-source environmental data, including satellite imagery, SAR, hyperspectral observations, digital elevation models, climate variables, and field measurements, are integrated using AI and machine learning to generate digital soil maps and predict key soil properties. These spatial products support precision agriculture, land-use planning, soil restoration, climate adaptation, and evidence-based soil governance through repeated monitoring and adaptive decision-making.

Machine learning algorithms can improve the predictive performance of digital soil mapping by modeling complex interactions among environmental variables without requiring predefined mathematical relationships. Nevertheless, reported model performance is strongly dependent on the characteristics of the training dataset, validation strategy, spatial sampling design, and environmental conditions represented in the calibration data. Ensemble learning approaches, including random forest, gradient boosting machines, and extreme gradient boosting (XGBoost), are widely recognized for their robustness, computational efficiency, and high predictive accuracy. These algorithms have demonstrated promising predictive performance for estimating soil organic carbon,

Table 3. Earth observation technologies and digital approaches for sustainable soil management

Technology/ Approach	Data sources	Analytical methods	Main applications	Advantages	Limitations
Multispectral remote sensing	Sentinel-2, Landsat, MODIS	Spectral indices, machine learning models	Soil moisture, salinity, vegetation–soil interactions, degradation assessment	Free access, extensive coverage, repeated observations	Cloud effects, indirect soil property estimation
Synthetic aperture radar (SAR)	Sentinel-1, ALOS PALSAR	Backscatter analysis, time-series modeling	Soil moisture, surface roughness, erosion monitoring	All-weather capability	Complex interpretation
Hyperspectral sensing	Airborne and satellite hyperspectral data	Spectral modeling, deep learning	Soil mineralogy, organic carbon, nutrient assessment	High spectral resolution	Limited availability and high data complexity
Digital soil mapping	Earth observation data, DEM, climate and field observations	Random forest, regression models, AI algorithms	Spatial prediction of soil organic carbon, texture, pH, salinity	Provides spatial soil information	Requires high-quality training datasets
AI-based soil assessment	Multi-source environmental datasets	Machine learning, deep learning	Soil property prediction and risk mapping	Captures nonlinear relationships	Requires calibration and validation

Abbreviations: AI: Artificial intelligence; DEM: Digital elevation model.

texture, pH, bulk density, salinity, nutrient availability, and erosion susceptibility across diverse environmental conditions.[38] However, high validation accuracy within a calibration domain does not necessarily guarantee reliable predictions when models are transferred to environments that differ significantly.

Recent advances in deep learning have further expanded the analytical capabilities of digital soil intelligence. Convolutional neural networks (CNNs), recurrent neural networks, and hybrid deep learning architectures can automatically extract hierarchical spatial features from satellite imagery and multi-source geospatial datasets, reducing the need for manual feature engineering. These approaches have shown considerable potential for improving prediction accuracy, particularly when large training datasets and high-resolution Earth observation products are available. Their performance, however, remains dependent on the availability and representativeness of sufficiently large training datasets. Deep-learning models may also be sensitive to domain shifts between training and application areas, and their apparent predictive performance can decline when applied to conditions poorly represented in the training data.[39]

The integration of AI with cloud computing platforms has fundamentally transformed large-scale soil assessment. Cloud-based geospatial platforms, such as Google Earth Engine, provide access to extensive Earth observation archives and high-performance parallel computing capabilities, enabling large-scale processing and analysis of geospatial data without requiring local high-performance computing infrastructure. These capabilities facilitate the integration of machine learning algorithms with environmental datasets and spatial modeling workflows and have supported applications in environmental monitoring, land-cover assessment, drought analysis, water management, and climate monitoring. Consequently, cloud-based platforms can enhance the operational capacity of digital soil intelligence and evidence-based soil governance.[40,41]

However, the predictive performance of AI-based digital soil mapping depends strongly on the quality, representativeness, and spatial distribution of the training data. Appropriate validation strategies are therefore essential because conventional validation may not adequately reflect model performance when predictions are transferred to different environmental or geographic domains.[42] Model transferability and extrapolation should be explicitly evaluated, particularly when the target area contains environmental conditions or combinations of soil-forming factors that are poorly represented in the training dataset. Recent evidence indicates that models showing satisfactory cross-validation performance may nevertheless exhibit reduced predictive accuracy under spatial extrapolation, emphasizing the importance of independent validation, training-data representativeness, and assessment of extrapolation conditions.[43]

The relative performance of AI methods should not be evaluated solely on reported prediction accuracy. Random forests and other ensemble approaches offer advantages in robustness, computational efficiency, and applicability to heterogeneous environmental covariates, whereas deep learning approaches may provide greater capacity to extract complex spatial features but generally require larger and more representative training datasets and greater computational resources. Model performance can also vary substantially with spatial resolution, sampling density, environmental heterogeneity, and validation strategy. High accuracy within a calibration area does not necessarily indicate reliable transferability to environmentally different regions. Therefore, model selection should consider predictive performance together with uncertainty, computational requirements, data availability, transferability, and the feasibility of independent ground validation.

Artificial intelligence-based soil mapping still faces significant challenges in data quality, model transferability, interpretability, and uncertainty quantification. Training data may contain spatial bias, uneven sampling density, measurement inconsistencies, or insufficient representation of environmental variability, which can affect model generalization. Reliable prediction therefore requires representative field observations, harmonized soil databases, appropriate cross-validation, and independent ground validation to assess model performance under the intended application conditions. Model extrapolation beyond the environmental range represented in the training data should also be explicitly assessed and reported. Consequently, future developments increasingly emphasize explainable AI, uncertainty assessment, and hybrid modeling frameworks that combine process-based knowledge with data-driven learning to improve the credibility of soil information products.

Artificial intelligence has significantly improved the accuracy and efficiency of digital soil mapping by enabling robust prediction of soil properties from heterogeneous environmental datasets. However, predictive models alone are insufficient unless their outputs can support practical management decisions. Consequently, digital decision support systems have become essential for translating AI-derived soil intelligence into sustainable land management strategies.

Overall, the integration of Earth observation and AI offers considerable potential for scalable digital soil intelligence, but no single sensor, spatial resolution, or modeling approach is universally optimal. Effective implementation requires matching data and algorithms to the target soil property and decision scale while explicitly accounting for uncertainty, transferability, validation requirements, computational capacity, and institutional implementation barriers.

4.3. Digital decision support

The use of AI-derived soil information in decision support systems should account for prediction uncertainty, spatial transferability, and the reliability of the underlying validation data, particularly when recommendations are extended beyond the environmental conditions represented in model training. Earth observation technologies and AI have substantially improved the capacity to characterize soil conditions and predict their spatial and temporal dynamics. Accurate predictions alone do not guarantee sustainable soil management unless they are translated into practical recommendations that support evidence-based decision-making. Digital decision support systems bridge this gap by integrating geospatial information, predictive models, environmental monitoring, and management scenarios into interactive platforms that assist stakeholders in selecting appropriate interventions under varying environmental and socioeconomic conditions.[44]

Modern digital decision support systems combine multi-source datasets, including satellite observations, digital soil maps, climate records, field measurements, and socioeconomic information, to generate comprehensive assessments of soil conditions and agricultural risks. Their ability to synthesize heterogeneous information enables the identification of priority areas for soil restoration, optimization of land-use planning, evaluation of degradation risks, and assessment of alternative management strategies. Consequently, decision support systems have become indispensable tools for precision agriculture, sustainable land management, and national soil monitoring programs.[45]

Geographic information systems constitute the spatial backbone of digital decision support by facilitating the integration, visualization, and analysis of multiple geospatial datasets. GIS-based spatial decision support systems enable the production of suitability maps, erosion risk assessments, salinity distribution models, carbon sequestration potential maps, and land degradation vulnerability analyses. These spatial products improve communication between scientists, land managers, and policymakers by converting complex analytical outputs into interpretable decision-support information.[46]

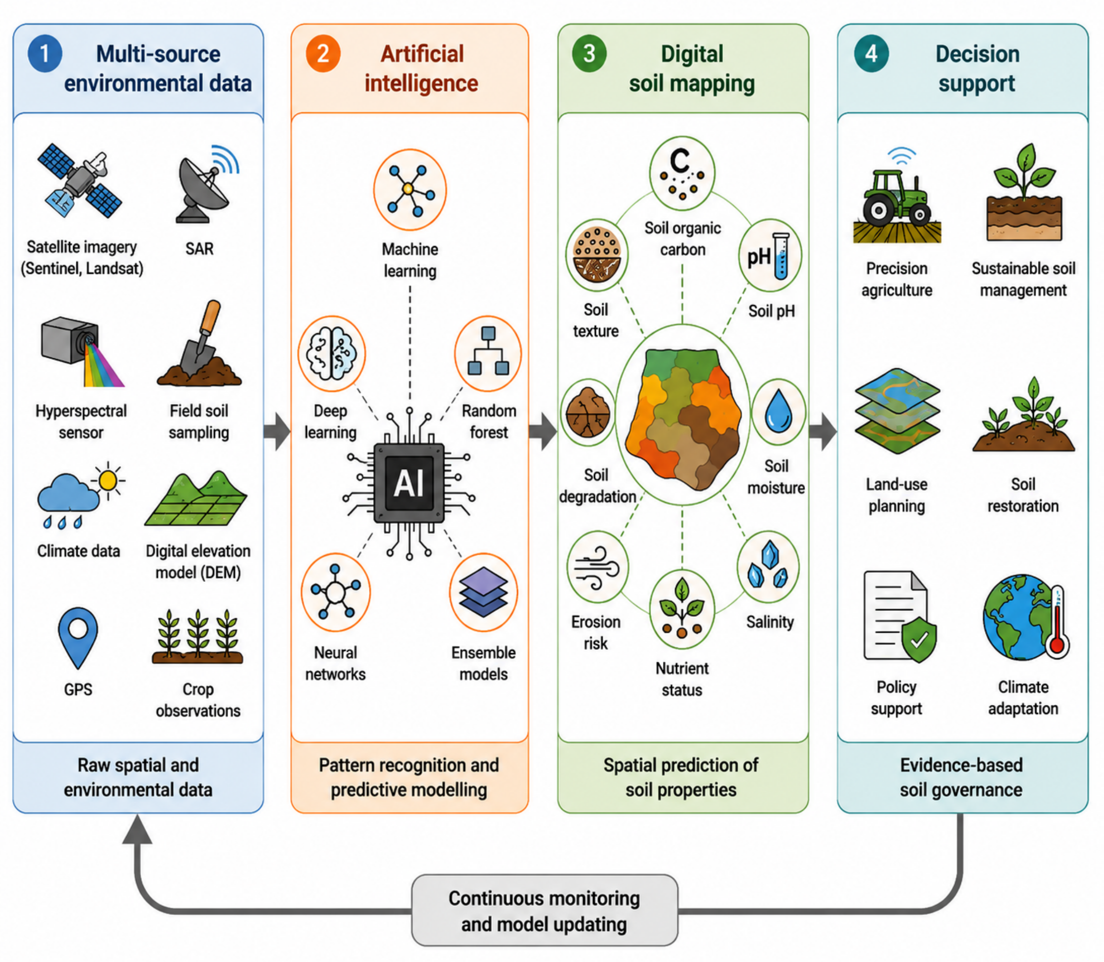

Figure 3. Artificial intelligence (AI) and digital soil mapping framework for sustainable soil governance. Image refined with Google Gemini (version 1.5 Pro). Conceptual framework proposed by the author based on the synthesis of the reviewed literature. Directional arrows indicate proposed conceptual linkages and should not be interpreted as experimentally demonstrated causal relationships.
Abbreviation: SAR: Synthetic aperture radar.

The integration of multi-criteria decision analysis (MCDA) has further strengthened digital decision-support capabilities by enabling multiple environmental, economic, and social criteria to be evaluated simultaneously within a structured decision-making framework. Common MCDA approaches include the analytic hierarchy process, fuzzy-based methods, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and weighted linear combination, which can support the evaluation and prioritization of alternatives under multiple and potentially conflicting criteria.[47]

Recent advances in cloud computing have expanded the operational capacity of digital soil intelligence by enabling large-scale processing of Earth observation data and real-time environmental monitoring. Cloud-based platforms facilitate continuous updating of digital soil information, rapid assessment of degradation trends, and implementation of early-warning systems for drought, salinization, erosion, and desertification. These developments have substantially improved the scalability and accessibility of digital decision support systems for regional and national soil governance initiatives.[48,49]

Digital decision support systems represent the operational interface between scientific knowledge and sustainable soil management by integrating spatial information, predictive analytics, and management scenarios to produce evidence-based recommendations. Their successful implementation provides the technological foundation for broader governance frameworks to coordinate policies, institutional actions, and stakeholder participation. Section 5 therefore examines the transition from digital soil management to sustainable soil governance.

5. Sustainable soil governance

5.1. From soil management to soil governance

For decades, sustainable soil management has primarily focused on improving soil quality through field-level interventions, including conservation agriculture, nutrient management, erosion control, and soil restoration practices. While these approaches have substantially enhanced agricultural productivity and environmental sustainability, they generally address soil-related challenges at the farm or landscape scale without adequately considering the broader institutional, economic, and policy dimensions that determine long-term sustainability.[38]

The increasing complexity of global food systems, climate change, land degradation, population growth, and competing demands for land resources has expanded the scope of soil management beyond agronomic practices alone. Sustainable management now requires coordinated actions among governmental institutions, scientific organizations, private stakeholders, and local communities to protect soil resources while simultaneously supporting food production, ecosystem services, and climate resilience.[50]

However, soil management and governance should be considered as important contributing components of food-system resilience rather than as sufficient solutions to food insecurity, which is also shaped by wider economic, social, institutional, and food-system conditions.

Soil governance has consequently emerged as a comprehensive framework that integrates scientific knowledge, policy instruments, institutional arrangements, and stakeholder participation to guide sustainable soil use across multiple spatial and administrative scales. Unlike conventional soil management, which primarily emphasizes technical interventions, soil governance addresses how decisions are formulated, implemented, monitored, and evaluated within social, economic, and political contexts. This broader perspective recognizes soil as a strategic natural asset whose sustainable management can contribute to food-system resilience and food security outcomes, in interaction with environmental, economic, institutional, and policy conditions.[51] Its contribution to food security outcomes, however, depends on interactions with other determinants, including agricultural productivity, resource availability, food affordability and distribution, market access, trade, food loss and waste, infrastructure, and political and socioeconomic stability.

Effective soil governance also depends on transparent institutional coordination and clearly defined responsibilities among governmental agencies, research institutions, agricultural extension services, and land users. Multi-level governance mechanisms facilitate the integration of national strategies with regional implementation plans while encouraging collaboration across different sectors responsible for agriculture, water resources, environmental protection, and climate adaptation. Such coordination improves policy coherence and reduces conflicts arising from fragmented management approaches.[52]

These mechanisms can therefore strengthen the capacity of agricultural and food systems to respond to environmental and socioeconomic pressures, but they do not, in and of themselves, determine food security outcomes.

International initiatives have further accelerated the transition toward soil governance by emphasizing harmonized monitoring systems, standardized soil indicators, and evidence-based policy development. Global frameworks addressing land degradation neutrality, climate mitigation, sustainable agriculture, and ecosystem restoration increasingly recognize healthy soils as a prerequisite for achieving multiple Sustainable Development Goals. Consequently, soil governance has become a strategic component of integrated environmental governance rather than a discipline confined solely to agricultural management.[53]

The transition from soil management to soil governance reflects a fundamental shift from implementing isolated technical practices toward coordinating scientific evidence, institutional arrangements, and policy interventions within integrated decision-making frameworks. Within the broader zero food gap perspective adopted in this review, soil governance is therefore proposed as one coordinating pathway that can support sustainable production capacity and food-system resilience, rather than as a direct or sufficient mechanism for eliminating food deficits. However, effective governance requires clear guiding principles that balance agricultural productivity, environmental sustainability, and socioeconomic development. These governance principles provide the conceptual foundation for integrating soil protection into national and international policy frameworks, while recognizing the broader food system conditions that influence food security outcomes, as discussed in Section 5.2.

In this review, soil governance is therefore considered a coordinating and integrative mechanism rather than a quantitatively demonstrated dominant driver of food security outcomes. Its effectiveness depends on its interactions with climate conditions, water availability, agricultural policies, economic resources, institutional capacity, and broader food system factors.

5.2. Governance principles and policy integration

Effective soil governance requires a set of integrated principles that move beyond fragmented management approaches toward coordinated, transparent, and adaptive decision-making systems. Because soils are dynamic resources influenced by ecological processes, socioeconomic conditions, and institutional structures, governance frameworks must recognize soils as strategic natural capital rather than merely agricultural production inputs. This perspective emphasizes long-term stewardship, intergenerational equity, and the integration of environmental, economic, and social objectives within soil-related policies.[54]

One of the fundamental principles of sustainable soil governance is policy coherence, which requires alignment among agricultural, environmental, climate, water, and land-use policies. Historically, soil protection has often been addressed indirectly through separate policies related to erosion control, agricultural productivity, biodiversity conservation, or climate mitigation. Such fragmented approaches may result in conflicting objectives and inefficient resource allocation. Integrated policy frameworks are therefore essential to ensure that soil conservation contributes simultaneously to food security, climate adaptation, ecosystem protection, and sustainable development goals.[55]

A second key principle is evidence-based governance, which relies on reliable soil information, standardized indicators, and monitoring systems to support policy formulation and evaluation. The increasing availability of digital soil information, Earth observation products, and advanced modeling approaches provides new opportunities to establish science-based governance mechanisms. These tools enable governments to identify vulnerable areas, prioritize restoration interventions, evaluate policy effectiveness, and monitor progress toward national and international sustainability targets.[56]

Stakeholder participation and inclusiveness represent another essential component of effective soil governance. Since soil-related decisions directly affect farmers, land managers, local communities, industries, and governmental institutions, successful implementation requires participatory approaches that incorporate local knowledge and stakeholder priorities. Participatory governance improves policy acceptance, strengthens implementation capacity, and ensures that soil protection measures are compatible with local environmental and socioeconomic conditions.[57]

The integration of soil governance into international sustainability frameworks has gained increasing attention through initiatives addressing climate change mitigation, land degradation neutrality, biodiversity conservation, and sustainable food systems. The recognition of soils as a critical component of ecosystem services and climate regulation has encouraged the development of policy mechanisms that connect soil management with broader environmental commitments. Such integration enhances the visibility of soil protection within national strategies and facilitates coordinated actions across sectors.[58]

Adaptive governance is particularly important under changing environmental conditions. Climate change introduces new uncertainties related to drought frequency, extreme rainfall events, soil carbon dynamics, and agricultural productivity. Therefore, governance systems must be flexible enough to incorporate emerging scientific knowledge, updated monitoring information, and changing societal priorities. Adaptive approaches allow continuous improvement of policies through feedback mechanisms, evaluation, and iterative decision-making.

The effectiveness of soil governance depends on the ability to integrate scientific evidence, institutional coordination, stakeholder participation, and adaptive policy mechanisms. While these principles provide the foundation for sustainable soil stewardship, their practical implementation requires operational frameworks that translate governance objectives into measurable actions and management decisions. Section 5.3 therefore explores the role of decision-support approaches in enabling effective soil governance.

5.3. Decision support for soil governance

The increasing availability of soil information, Earth observation products, and advanced analytical models has created new opportunities to develop evidence-based governance systems capable of addressing complex soil challenges. However, the practical value of scientific knowledge depends largely on the ability to transform data and assessments into actionable decisions. Decision-support approaches provide the operational link between soil information, governance objectives, and management interventions by enabling stakeholders to evaluate risks, prioritize actions, and assess alternative policy scenarios.[59]

Decision support for soil governance requires integrating multiple dimensions, including biophysical conditions, environmental risks, economic constraints, institutional priorities, and stakeholder objectives. Unlike conventional management tools that focus primarily on field-scale recommendations, governance-oriented decision support systems operate across multiple spatial and administrative levels. They assist decision-makers in identifying vulnerable landscapes, allocating restoration resources, evaluating land-use alternatives, and monitoring progress toward sustainability targets.[60]

Geospatial decision support systems have become particularly valuable for soil governance because soil-related challenges are inherently spatially variable. By integrating digital soil maps, remote sensing observations, climate information, and socioeconomic datasets, spatial decision-support platforms can generate vulnerability assessments and priority maps for soil conservation, restoration, and sustainable land-use planning. These systems support regional planning by identifying areas where interventions can produce the greatest environmental and socioeconomic benefits.[61]

Multi-criteria decision analysis provides an important methodological framework for addressing the complexity of soil governance decisions. Soil-related decisions often involve trade-offs among competing objectives, such as increasing agricultural productivity while minimizing erosion, preserving biodiversity, conserving water resources, and reducing greenhouse gas emissions. MCDA approaches allow the integration of diverse indicators and stakeholder preferences, enabling transparent evaluation of alternative management strategies under different environmental and policy scenarios.[62]

The emergence of digital twins and dynamic modeling approaches represents a further advancement in decision-support capabilities. Digital twins enable continuous representation of soil systems by integrating real-time observations, predictive models, and scenario simulations. Although still developing in soil applications, these approaches offer significant potential for evaluating future climate impacts, testing management interventions, and supporting adaptive governance strategies under uncertain environmental conditions.[63]

Effective implementation of decision support systems requires more than technological capacity. Institutional readiness, data accessibility, interoperability standards, and stakeholder engagement are essential for ensuring that decision-support outputs are trusted and incorporated into governance processes. Furthermore, decision support systems must provide transparent and interpretable information to avoid creating technological barriers among scientific communities, policymakers, and land users.

Decision support systems represent the practical interface between digital soil intelligence and sustainable governance by transforming complex environmental information into strategic actions (Figure 4). Their integration within institutional frameworks enables more adaptive, transparent, and evidence-based soil policies. However, these systems should be viewed as decision-enabling mechanisms rather than direct determinants of food security outcomes. Their contribution to the broader zero food gap vision depends on how effectively their outputs are translated into sustainable management and policy actions, and on how these actions interact with broader food system conditions, including resource availability, affordability, distribution, market access, trade, and socioeconomic stability. Building on this foundation, Section 6 explores the broader enabling drivers, including climate adaptation, water management, agricultural policies, and socioeconomic factors that influence the capacity of these pathways to contribute to resilient and sustainable food systems and the broader zero food gap vision.

6. Enabling drivers toward zero food gap

Achieving a zero food gap requires more than increasing agricultural production; it depends on the capacity of food systems to remain productive, resilient, and sustainable under rapidly changing environmental and socioeconomic conditions. Although sustainable soil management and digital soil governance provide essential foundations for maintaining land productivity, their effectiveness is strongly influenced by external drivers, including climate variability, water availability, agricultural policies, and socioeconomic conditions. These interconnected drivers determine the capacity of agricultural systems to adapt to future pressures while ensuring food availability, accessibility, and long-term environmental sustainability.[64]

Progress toward zero food gap is influenced by broader food system conditions beyond soil and agricultural production. These include food affordability and distribution, market access, trade, dietary patterns, food loss and waste, infrastructure, and social and political stability. Accordingly, the enabling drivers considered in this review should be understood as complementary conditions that influence the capacity of soil governance and sustainable agricultural practices to contribute to resilient food systems.

The concept of the zero food gap extends beyond closing the difference between food demand and supply. It requires a transformation toward resilient food systems that maintain productivity while reducing environmental degradation and improving resource-use efficiency.

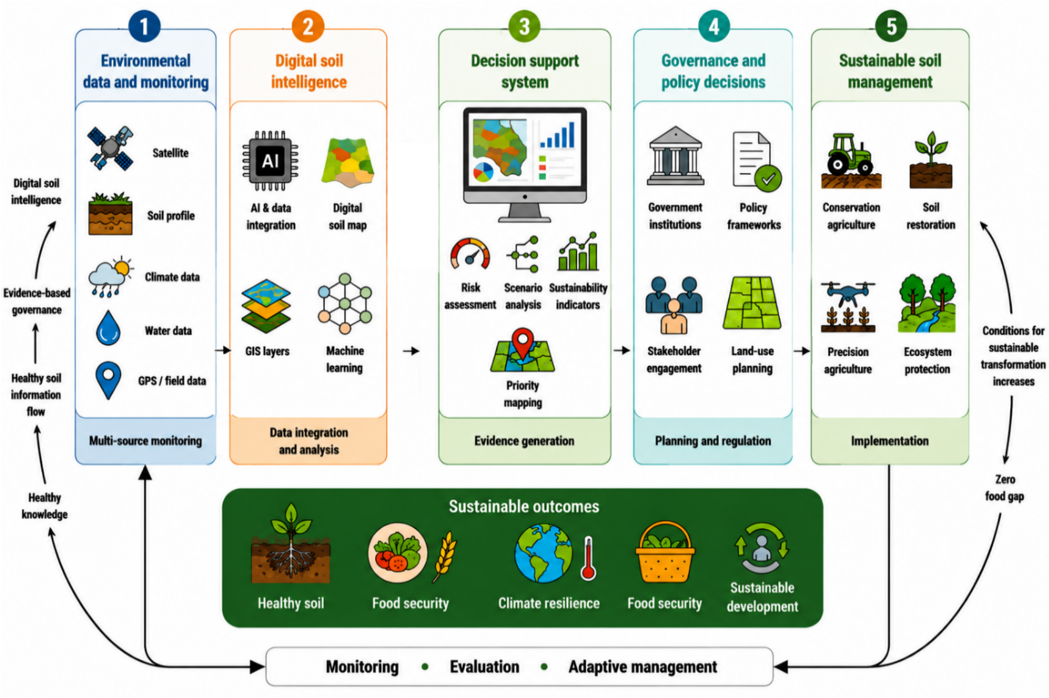

Figure 4. Decision support framework for sustainable soil governance. Image refined with Google Gemini (version 1.5 Pro). Conceptual framework proposed by the author based on the synthesis of the reviewed literature. Directional arrows indicate proposed conceptual linkages and should not be interpreted as experimentally demonstrated causal relationships.
Abbreviations: AI: Artificial intelligence; GIS: Geographic information system.

Therefore, achieving this objective requires integrated approaches that connect climate adaptation, sustainable water management, supportive agricultural policies, and inclusive socioeconomic strategies with soil-centered governance frameworks.[65]

Figure 5 highlights the complementary roles of climate adaptation, water resource management, agricultural policies, and socioeconomic development in strengthening sustainable food systems. These enabling conditions create the supportive environment required to improve resilience, resource efficiency, and food security under increasing environmental and societal pressures.

6.1. Climate adaptation

Climate change represents one of the most significant challenges threatening global food security by altering temperature regimes, precipitation patterns, water availability, and the frequency of extreme climatic events. Rising temperatures, prolonged droughts, heat waves, and changing rainfall distributions directly influence crop productivity by affecting plant physiological processes, soil moisture dynamics, nutrient cycling, and ecosystem stability.[66] These impacts are particularly severe in arid and semi-arid regions where agricultural systems already operate under environmental constraints and limited adaptive capacity.[67]

Climate adaptation in agriculture requires a shift from reactive responses toward proactive strategies that enhance system resilience. Soil-centered adaptation approaches, including increasing soil organic matter, improving soil structure, enhancing water retention capacity, and maintaining biological activity, contribute to buffering agricultural systems against climatic stress.[68] Healthy soils function as critical components of climate adaptation, regulating water availability, supporting vegetation recovery, and increasing resistance to drought and extreme weather.[69]

Adaptation strategies increasingly rely on integrated climate information, predictive modeling, and monitoring systems to support timely decision-making. The combination of climate projections, Earth observation data, and agricultural models enables the identification of vulnerable areas, evaluation of future risks, and development of location-specific adaptation strategies. Such approaches are particularly important for regions where climate change interacts with land degradation, water scarcity, and increasing food demand.[70]

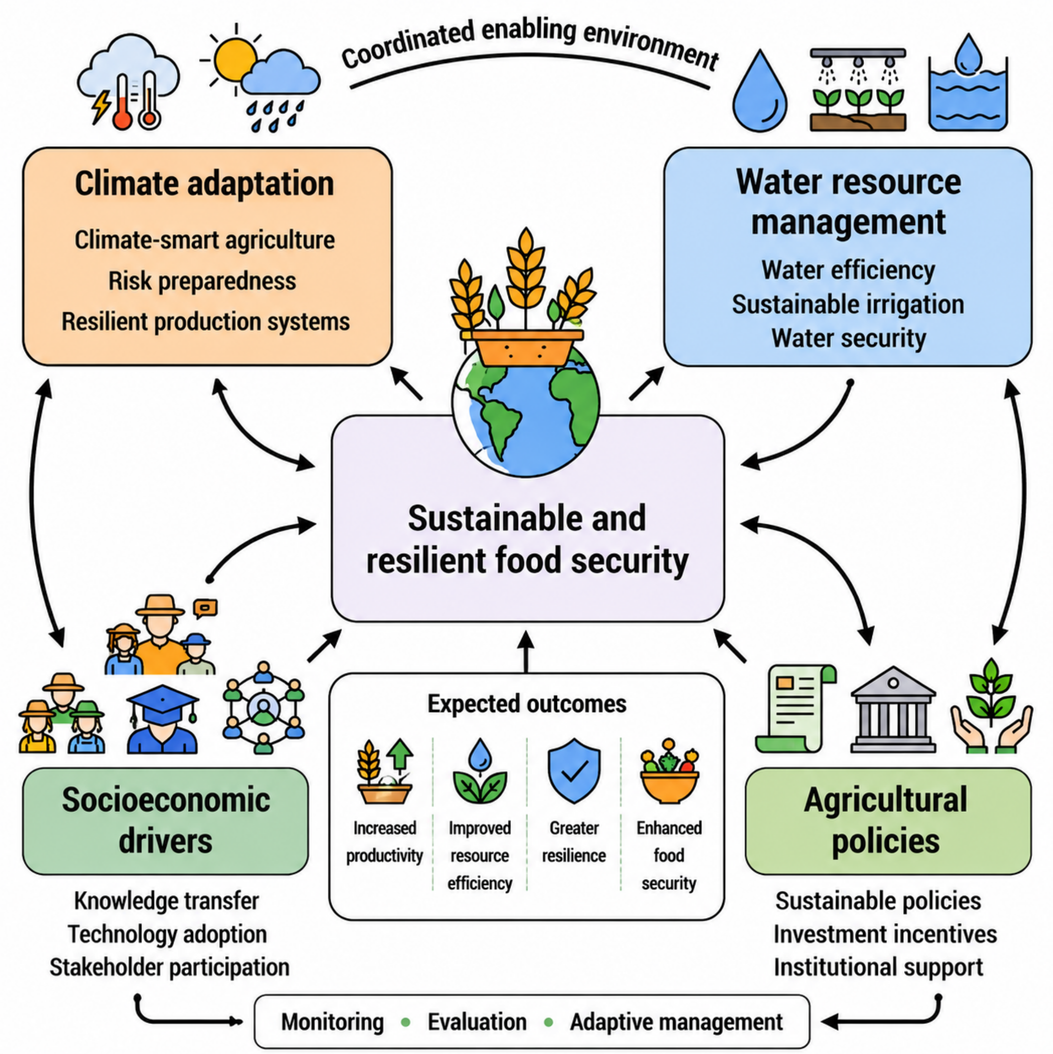

Figure 5. Enabling drivers supporting progress toward sustainable food systems. Image refined with Google Gemini (version 1.5 Pro). Conceptual framework proposed by the author based on the synthesis of the reviewed literature. Directional arrows indicate proposed conceptual linkages and should not be interpreted as experimentally demonstrated causal relationships.

Nature-based solutions and regenerative agricultural practices are also gaining attention as climate adaptation pathways. Practices such as conservation agriculture, agroforestry, crop diversification, and improved soil carbon management can simultaneously enhance resilience, reduce greenhouse gas emissions, and maintain agricultural productivity.[71] However, their successful implementation requires supportive policies, technical capacity, and alignment with local environmental and socioeconomic conditions.

Climate adaptation provides a fundamental pathway for maintaining agricultural productivity under increasing environmental uncertainty. However, adaptation strategies are strongly dependent on sustainable management of limited water resources, particularly in regions where water availability represents the primary constraint on food production. Therefore, effective water resource management constitutes the next critical driver toward achieving resilient and sustainable food systems.

6.2. Water resource management

Water availability represents one of the most critical constraints affecting global food production, particularly in arid and semi-arid regions where agricultural systems depend heavily on limited freshwater resources. Increasing water demand, declining groundwater availability, competition among sectors, and climate-induced changes in precipitation patterns are intensifying pressure on agricultural water supplies. Consequently, achieving a zero food gap requires transitioning from conventional water-use approaches to integrated water resource management strategies that enhance productivity while preserving long-term ecosystem functions.[72]

Agriculture remains the largest global user of freshwater resources, making water-use efficiency a central component of sustainable food system transformation. Improving irrigation efficiency, reducing conveyance losses, optimizing irrigation scheduling, and adopting precision irrigation technologies can substantially increase crop productivity per unit of water consumed. However, technological improvements alone are insufficient unless combined with appropriate water governance frameworks, institutional coordination, and effective allocation mechanisms that balance agricultural demands with environmental requirements.[73]

The relationship between soil and water management is fundamental to agricultural resilience. Soil properties, including organic matter content, structure, porosity, and infiltration capacity, strongly influence water storage and availability for crops. Sustainable soil management practices that enhance soil water retention, reduce evaporation losses, and improve root-zone conditions contribute to increased water productivity and reduced vulnerability to drought stress. Therefore, soil conservation and water management should be considered interconnected components of integrated resource management rather than independent strategies.[74]

Water scarcity is also closely linked to land degradation processes, particularly salinization in irrigated agricultural systems. Poor irrigation practices, inadequate drainage, and the use of saline water sources can accelerate salt accumulation in soils, reducing crop productivity and threatening agricultural sustainability. Addressing these challenges requires integrated approaches combining improved irrigation management, salinity monitoring, soil restoration practices, and spatial decision-support tools for identifying vulnerable areas and prioritizing interventions.[75]

Recent advances in digital technologies provide new opportunities for improving agricultural water management. Remote sensing, AI, and Internet-of-Things–based monitoring systems enable repeated and spatially extensive monitoring of soil moisture conditions, crop water requirements, and irrigation performance. When integrated with climate information and decision-support platforms, these technologies support adaptive water management by providing timely recommendations and improving resource-use efficiency at farm and regional scales.[76]

Sustainable water management also requires consideration of the broader water–energy–food nexus. Agricultural water decisions influence energy consumption, ecosystem services, and socioeconomic development, highlighting the need for integrated governance approaches that evaluate multiple objectives simultaneously. Such approaches are essential for designing resilient food systems capable of maintaining productivity under increasing environmental pressures while minimizing competition over scarce resources.[77]

Efficient water resource management is therefore a fundamental driver toward achieving the zero food gap by ensuring that limited water resources are used productively, equitably, and sustainably. However, technological solutions and resource management strategies must operate within supportive institutional and policy environments. Section 6.3 examines the role of agricultural policies in creating enabling conditions for sustainable food production and soil-centered governance.

6.3. Agricultural policies

Agricultural policies play a central role in shaping the sustainability, productivity, and resilience of food systems by influencing land-use decisions, production practices, resource allocation, and farmers' adoption of sustainable technologies. While technological innovations and improved resource management provide essential tools for increasing agricultural efficiency, their long-term effectiveness depends strongly on policy environments that create incentives for sustainable practices and reduce barriers to implementation. Therefore, achieving a zero food gap requires agricultural policies that simultaneously support productivity enhancement, environmental protection, and equitable access to resources.[78]

Historically, agricultural policies have often prioritized increasing production through intensification, input subsidies, and expansion of cultivated areas. Although these approaches contributed to substantial increases in global food production, they have also contributed to soil degradation, biodiversity loss, excessive water consumption, and greenhouse gas emissions in many regions. Recent policy approaches increasingly emphasize sustainable intensification, resource-use efficiency, climate-smart agriculture, and regenerative practices as pathways for maintaining productivity while reducing environmental impacts.[79]

Policy integration is particularly important because agricultural sustainability is influenced by multiple interconnected sectors, including soil protection, water management, climate adaptation, biodiversity conservation, and rural development. Coherent agricultural policies should therefore align with broader environmental strategies and international sustainability frameworks, including the Sustainable Development Goals, land degradation neutrality targets, and climate mitigation commitments. Such integration enables agricultural production systems to contribute simultaneously to food security and ecosystem protection.[80]

Financial mechanisms and incentive structures represent key components of effective agricultural policies. Payments for ecosystem services, support for conservation agriculture, carbon farming initiatives, and investments in sustainable technologies can encourage farmers to adopt practices that improve soil health, conserve water, and enhance climate resilience. However, policy instruments must be carefully designed to consider local socioeconomic conditions and avoid creating inequalities among farmers with different levels of access to resources and technologies.[81]

Agricultural policies must also address knowledge transfer, capacity building, and institutional support. The adoption of sustainable practices depends not only on economic incentives but also on farmers' access to extension services, scientific knowledge, digital tools, and technical assistance. Integrating research institutions, policymakers, and farming communities within collaborative innovation systems can accelerate the transition toward more resilient and sustainable agricultural systems.[82]

Emerging policy frameworks increasingly recognize the importance of data-driven agriculture and digital transformation. The integration of remote sensing, digital soil information, and decision support systems into agricultural policies can improve monitoring, targeted interventions, and the evaluation of sustainability outcomes. Such approaches enable policymakers to move from generalized programs toward spatially targeted strategies that address specific environmental and socioeconomic challenges.[83]

Agricultural policies provide the institutional mechanism through which scientific knowledge, technological innovations, and sustainability objectives are translated into practical actions. However, policy effectiveness ultimately depends on social acceptance, economic feasibility, and the capacity of rural communities to participate in sustainable transitions. These socioeconomic dimensions represent the final enabling driver toward achieving resilient food systems and closing the zero food gap.

6.4. Socioeconomic drivers

The transition toward sustainable and resilient food systems is influenced not only by environmental and technological factors but also by socioeconomic conditions that determine the capacity of communities to adopt and sustain improved agricultural practices. Although advances in soil management, digital technologies, and policy frameworks offer significant opportunities to increase agricultural resilience, their effectiveness depends on farmers' access to financial resources, knowledge, infrastructure, and institutional support. Therefore, socioeconomic development represents a critical enabling dimension for achieving a zero food gap while ensuring equitable participation in sustainable food transitions.[84]

Smallholder farmers constitute a major component of global food production systems, particularly in developing regions where agricultural livelihoods are highly vulnerable to climate variability, resource limitations, and market instability. Limited access to credit, extension services, improved technologies, and reliable markets often restrict the adoption of sustainable practices, even when these practices provide long-term environmental and economic benefits. Addressing these barriers requires inclusive agricultural development strategies that combine technical innovation with socioeconomic empowerment.[85]

Knowledge exchange and capacity building are essential for translating scientific advances into practical agricultural improvements. The adoption of sustainable soil management, precision agriculture, and climate adaptation practices requires farmers to understand new technologies and adapt them to local conditions. Strengthening agricultural extension systems, farmer organizations, and participatory innovation platforms can improve knowledge transfer and increase the effectiveness of sustainability interventions.[86]

Digital transformation provides new opportunities to reduce socioeconomic barriers by improving access to agricultural information, advisory services, and decision-support tools. Mobile technologies, digital platforms, and remote sensing-based services can support farmers through improved weather information, market access, and resource management recommendations. However, unequal access to digital infrastructure, limited digital literacy, and economic constraints may create new forms of inequality if digital transformation is not implemented through inclusive approaches.[87]

Gender equality and social inclusion are also fundamental components of sustainable food system transformation. Women and marginalized groups play important roles in agricultural production and resource management, yet they often face constraints related to land ownership, access to financial services, training opportunities, and participation in decision-making processes. Policies that promote inclusive access to resources and strengthen community participation can improve both agricultural productivity and social resilience.[88]

Economic incentives and market mechanisms further influence the adoption of sustainable practices. Farmers are more likely to invest in soil restoration, water conservation, and climate-smart practices when these actions provide economic benefits or are supported through appropriate incentive systems. Linking sustainable production with value chains, certification schemes, ecosystem service payments, and emerging carbon markets can create additional pathways for aligning environmental objectives with farmers' livelihoods.[89]

Socioeconomic conditions ultimately determine whether sustainable agricultural transformations can move from scientific concepts and policy frameworks into widespread practice. Ensuring access to knowledge, finance, technology, and inclusive institutions is therefore essential for converting soil-centered governance and resource management strategies into measurable improvements in food security. Together, climate adaptation, water management, agricultural policies, and socioeconomic development form the interconnected foundation required to advance toward a zero food gap.

Achieving a zero food gap requires an integrated transformation of food systems that combines climate adaptation, efficient water management, supportive agricultural policies, and socioeconomic inclusion. These interconnected drivers enhance agricultural resilience, improve resource-use efficiency, and facilitate the adoption of sustainable practices.

However, increasing food production alone is insufficient; long-term food security depends on strengthening the capacity of agricultural systems and communities to adapt to environmental and socioeconomic pressures. Integrating sustainable soil management, digital technologies, effective policies, and inclusive development approaches provides the foundation for the integrated framework presented in Section 7.

7. Integrated framework toward zero food gap

The proposed framework advances beyond existing soil-health, digital-agriculture, food security, and governance frameworks by integrating these dimensions through a soil-centered governance perspective. Rather than treating soil management, digital technologies, governance, and food security as separate components, the framework proposes their interaction through four interconnected domains: (i) sustainable soil management, (ii) digital soil intelligence, (iii) sustainable soil governance, and (iv) enabling societal drivers. This configuration conceptualizes soil governance as an integrative interface through which scientific knowledge and digital information can be connected with management, policy, and socioeconomic action, while recognizing that its influence operates alongside other environmental, economic, institutional, and food-system drivers.

The framework does not assign quantitative priorities or relative weights to these domains. Because the framework was derived from thematic synthesis rather than quantitative attribution or comparative modeling, the relative contributions of soil governance, climate, water, economic, and institutional factors cannot be empirically ranked in this review.

Addressing the global challenge of zero food gap requires a transition from fragmented agricultural interventions toward an integrated framework that connects soil sustainability, digital intelligence, governance mechanisms, and enabling socioeconomic conditions. Previous sections have demonstrated that soil degradation, climate change, water scarcity, and institutional limitations are interconnected challenges that cannot be effectively addressed through isolated solutions. Therefore, achieving sustainable food security requires a systems-based approach capable of linking environmental processes, technological innovations, and decision-making structures. In addition, sustainable soil governance should not be interpreted as a direct or sufficient mechanism for closing the food gap. Food security outcomes are influenced by broader food system and socioeconomic conditions, including food distribution, affordability, trade, dietary patterns, food loss and waste, conflict and political instability, infrastructure, and market access. Accordingly, soil governance represents one coordinating pathway that can contribute to productive capacity, resource resilience, and sustainable food system development, while its effectiveness depends on interactions with these wider determinants.

Despite advances in digital technologies and governance approaches, several challenges continue to limit the transition toward resilient food systems. These challenges include fragmented soil information, limited monitoring capacity, insufficient integration of digital tools into decision-making processes, and socioeconomic barriers affecting technology adoption. Addressing these limitations requires an integrated approach that connects scientific knowledge, technological innovation, governance mechanisms, and stakeholder participation. The major challenges, research gaps, and corresponding opportunities addressed by the proposed framework are summarized in Table 4.

The proposed framework is based on four interconnected pillars: (i) sustainable soil management, (ii) digital soil intelligence, (iii) sustainable soil governance, and (iv) enabling drivers for food system transformation (Figure 6). These pillars operate through continuous feedback mechanisms, allowing monitoring, assessment, decision-making, and adaptive management across multiple spatial and temporal scales.

The first pillar, sustainable soil management, represents the ecological foundation of the framework. It emphasizes maintaining and restoring soil functions through practices that enhance soil health, increase organic carbon storage, improve nutrient cycling, conserve water, and strengthen resilience against climate stresses. Soil restoration, regenerative agriculture, and conservation practices provide the biological and physical basis for sustaining agricultural productivity while reducing environmental degradation.

The second pillar, digital soil intelligence, transforms soil and environmental information into actionable knowledge. The integration of Earth observation, AI, and geospatial analytics enables repeated spatial monitoring of soil conditions, land degradation risks, water availability, and crop performance. These capabilities support spatially explicit decision-making and allow targeted interventions based on real-time environmental conditions.

The third pillar, sustainable soil governance, provides the institutional framework required to translate scientific knowledge into effective management actions. It integrates policy coordination, regulatory mechanisms, stakeholder participation, and monitoring systems to ensure that soil resources are managed as strategic assets for long-term food security. Governance approaches connect local management practices with national sustainability strategies and international commitments related to land degradation neutrality and climate adaptation.

Table 4. Research gaps, challenges, and opportunities for sustainable soil governance toward zero food gap

Challenge/Research gap	Current limitations	Potential opportunities	Contribution of the proposed framework
Fragmented soil information and limited monitoring capacity	Conventional soil surveys are spatially limited and often unable to capture temporal changes in soil conditions	Integration of Earth observation, digital soil mapping, and field observations	Enables continuous and spatially explicit soil assessment
Declining soil functions due to degradation	Soil degradation processes reduce productivity, carbon storage, and ecosystem resilience	Soil restoration, regenerative agriculture, and conservation practices	Places soil health as the foundation of sustainable food systems
Limited integration of digital technologies	Remote sensing and AI applications are often developed separately from management decisions	Multi-source data integration and AI-based decision support systems	Transforms environmental data into actionable management information
Weak connection between science and governance	Scientific knowledge is not always effectively incorporated into policies and land management strategies	Evidence-based governance and policy integration	Links digital soil intelligence with sustainable governance decisions
Data accessibility and interoperability challenges	Differences among datasets, scales, and formats restrict integrated analysis	Open-access databases, standardized protocols, and interoperable platforms	Supports harmonized and scalable soil information systems
Socioeconomic barriers to sustainable practice adoption	Limited financial resources, knowledge gaps, and unequal technology access restrict implementation	Capacity building, extension services, incentives, and inclusive digital solutions	Ensures that sustainable approaches are socially feasible and widely adopted
Lack of integrated food system perspective	Soil management, climate adaptation, water management, and agricultural policies are often addressed separately	Cross-sectoral approaches linking environment, technology, and society	Provides a pathway toward zero food gap through system integration

Abbreviation: AI: Artificial intelligence.

The fourth pillar, enabling drivers for food system transformation, includes climate adaptation, water resource management, agricultural policies, and socioeconomic empowerment. It also recognizes wider food system conditions, including market access, food affordability and distribution, trade, infrastructure, dietary patterns, food loss and waste, and social and political stability. These interacting drivers determine the feasibility, equity, and scalability of sustainable solutions by addressing external pressures and supporting farmers and food-system actors through appropriate incentives, knowledge transfer, digital accessibility, and institutional capacity building. Progress toward the broader vision of zero food gap therefore depends on coordinated interactions among soil management, digital technologies, governance mechanisms, and these wider enabling food-system conditions. Rather than addressing these components independently, the proposed framework suggests that their integration can strengthen the resilience and sustainability of food systems by connecting soil health improvement, data-driven decision-making, policy support, and inclusive participation. The key pathways linking sustainable soil management with resilient food systems are illustrated in Table 5.

A key feature of this framework is the transition from reactive management toward anticipatory and adaptive governance. Instead of responding only after soil degradation or productivity losses occur, integrated monitoring and predictive modeling enable early identification of risks and proactive implementation of sustainable interventions. This shift improves resource efficiency, reduces vulnerability, and enhances the resilience of agricultural systems under future climate and socioeconomic uncertainties.

The proposed framework conceptualizes zero food gap as a multidimensional sustainability challenge rather than a simple production target. Closing the food gap requires maintaining productive soils, optimizing resource use, strengthening governance capacity, and ensuring inclusive participation of agricultural communities. By integrating ecological knowledge with digital technologies and policy

Table 5. Integrated pathways linking sustainable soil management to zero food gap

Framework component	Main actions	Key enabling technologies/mechanisms	Expected outcomes
Sustainable soil management	Soil conservation, organic matter enhancement, regenerative practices, erosion control, nutrient management	Soil health indicators, field monitoring, restoration strategies	Improved soil functions, increased productivity, enhanced ecosystem resilience
Digital soil intelligence	Soil condition monitoring, degradation risk prediction, management decision support	Earth observation, digital soil mapping, AI, GIS, decision-support systems	Timely information, targeted interventions, improved resource-use efficiency
Sustainable soil governance	Policy integration, regulatory frameworks, stakeholder coordination, monitoring programs	Data-driven governance, sustainability indicators, institutional collaboration	Effective implementation of soil protection strategies and long-term resource security
Climate adaptation	Risk assessment, resilient cropping systems, adaptive management practices	Climate models, early warning systems, vulnerability assessment tools	Reduced climate impacts and improved agricultural resilience
Water resource management	Efficient irrigation, water conservation, improved water productivity	Remote sensing, smart irrigation, hydrological modeling	Enhanced water security and sustainable agricultural production
Agricultural policies	Incentives for sustainable practices, support for innovation, market-based mechanisms	Policy instruments, extension services, sustainability standards	Increased adoption of sustainable agricultural practices
Socioeconomic empowerment	Capacity building, equitable access to technology, farmer participation	Digital extension, training programs, inclusive institutions	Improved adoption, social resilience, and sustainable livelihoods
Zero food gap outcome	Integrated management of resources and production systems	Soil–water–climate–society nexus approach	Resilient, sustainable, and food-secure systems

Abbreviations: AI: Artificial intelligence; GIS: Geographic information system.

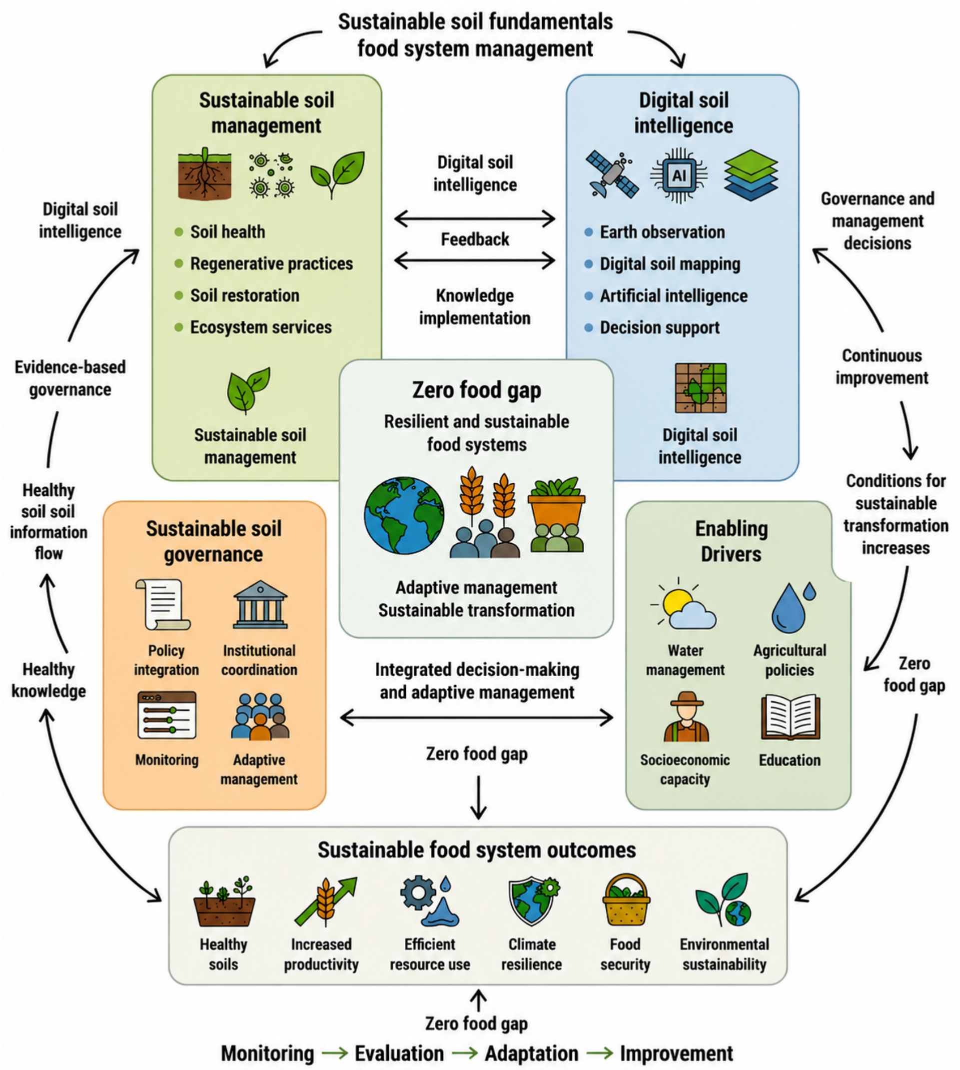

Figure 6. Sustainable Soil Governance Pathway Toward Zero Food Gap. Progress toward zero food gap is influenced by multiple interacting food-system, environmental, economic, institutional, and socioeconomic conditions. Image refined with Google Gemini (version 1.5 Pro). Conceptual framework proposed by the author based on thematic synthesis of the reviewed literature. The relationships shown are proposed conceptual linkages rather than experimentally demonstrated causal relationships.

mechanisms, the framework provides a pathway toward resilient, sustainable, and future-ready food systems.

Because the framework was developed through thematic synthesis of heterogeneous literature, it does not establish quantitative causal relationships or provide a single measurable endpoint for zero food gap. Its primary contribution is therefore conceptual and integrative: it identifies the major interacting domains and enabling conditions that the reviewed evidence suggests are important for progressing toward more resilient and sustainable food systems. Future empirical research can operationalize these domains through context-specific indicators and evaluate their relationships using quantitative assessment and longitudinal evidence.

8. Conclusion

Achieving a zero food gap requires a fundamental transformation in how soil resources, agricultural systems, and food production pathways are managed. This review indicates that sustainable food security requires more than increased agricultural production. Maintaining soil ecological functions is essential for long-term productivity and resilience. Healthy soils represent the foundation of sustainable food systems by regulating nutrient cycling, water availability, carbon storage, and ecosystem stability. However, accelerating soil degradation, climate change, and increasing pressure on water resources threaten these essential functions. Therefore, sustainable soil management and restoration practices emerge from the reviewed literature as critical components of future food security strategies.

The integration of Earth observation, AI, digital soil mapping, and decision-support technologies offers significant opportunities for monitoring soil conditions, identifying risks, and optimizing management interventions. Digital soil intelligence can support a transition from conventional, reactive approaches toward predictive and adaptive management systems capable of supporting evidence-based decisions.

Nevertheless, technological advances alone cannot ensure sustainable transformation. The synthesis indicates that effective soil governance, supportive agricultural policies, and socioeconomic inclusion are essential for translating scientific knowledge into practical actions. Enhancing farmers' access to knowledge, financial resources, digital tools, and institutional support can accelerate the adoption of sustainable practices.

Based on the thematic synthesis of the reviewed literature, the proposed integrated framework suggests that progress toward zero food gap depends on coordinated interactions among sustainable soil management, digital innovation, governance structures, climate adaptation, water management, and socioeconomic development. The framework therefore proposes sustainable soil governance as a central coordinating pathway for connecting these dimensions and supporting resilient food systems, rather than demonstrating a quantitatively validated causal relationship among them.

Future progress will potentially depend on strengthening interdisciplinary collaboration, improving digital infrastructure, enhancing policy coherence, and developing locally adapted solutions that balance productivity with environmental sustainability. The review further indicates that integrating ecological principles with technological innovation and inclusive governance may strengthen the capacity of sustainable soil management to contribute to resilient food systems under increasing global change.

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References

1. Falcon WP, Naylor RL, Shankar ND. Rethinking global food demand for 2050. *Popul Dev Rev*. 2022;48(4):921-957.

   doi: 10.1111/padr.12508

2. van Dijk M, Morley T, Rau ML, Saghai Y. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nat Food*. 2021;2(7):494-501.

   doi: 10.1038/s43016-021-00322-9

3. Amundson R, Berhe AA, Hopmans JW, Olson C, Sztein AE, Sparks DL. Soil and human security in the 21st century. *Science*. 2015;348(6235):1261071.

   doi: 10.1126/science.1261071

4. le Maire G, Marsden C, Nouvellon Y, *et al.* MODIS NDVI time-series allow the monitoring of Eucalyptus plantation biomass. *Remote Sens Environ*. 2011;115(10):2613-2625.

   doi: 10.1016/j.rse.2011.05.017

5. Odebiri O, Mutanga O, Odindi J. Deep learning-based national scale soil organic carbon mapping with Sentinel-3 data. *Geoderma*. 2022;411:115695.

   doi: 10.1016/j.geoderma.2022.115695

6. Hou D, Bolan NS, Tsang DCW, Kirkham MB, O'Connor D. Sustainable soil use and management: an interdisciplinary and systematic approach. *Sci Total Environ*. 2020;729:138961.

   doi: 10.1016/j.scitotenv.2020.138961

7. Tzoulas K, Korpela K, Venn S, *et al.* Promoting ecosystem and human health in urban areas using green infrastructure: a literature review. *Landsc Urban Plan*. 2007;81(3):167-178.

   doi: 10.1016/j.landurbplan.2007.02.001

8. Page MJ, McKenzie JE, Bossuyt PM, *et al.* The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. 2021;372:n71.

doi: 10.1136/bmj.n71

9. Hou D. Soil health and ecosystem services. *Soil Use Manag*. 2023;39(4):1259-1266.

   doi: 10.1111/sum.12945

10. Bünemann EK, Bongiorno G, Bai Z, *et al.* Soil quality—a critical review. *Soil Biol Biochem*. 2018;120:105-125.

    doi: 10.1016/j.soilbio.2018.01.030

11. Cadel M, Cousin I, Therond O. Relationships between soil ecosystem services in temperate annual field crops: a systematic review. *Sci Total Environ*. 2023;902:165930.

    doi: 10.1016/j.scitotenv.2023.165930

12. Banerjee S, van der Heijden MGA. Soil microbiomes and one health. *Nat Rev Microbiol*. 2023;21(1):6-20.

    doi: 10.1038/s41579-022-00779-w

13. Schjønning P, van den Akker JJH, Keller T, *et al.* Driver-pressure-state-impact-response (DPSIR) analysis and risk assessment for soil compaction: a European perspective. *Adv Agron*. 2015;133:183-237.

    doi: 10.1016/bs.agron.2015.06.001

14. Panagos P, Vieira D, Eekhout JPC, *et al.* How the EU Soil Observatory contributes to a stronger soil erosion community. *Environ Res*. 2024;248:118319.

    doi: 10.1016/j.envres.2024.118319

15. Hassani A, Azapagic A, Shokri N. Global predictions of primary soil salinization under changing climate in the 21st century. *Nat Commun*. 2021;12(1):6663.

    doi: 10.1038/s41467-021-26907-3

16. Guerra CA, Bardgett RD, Caon L, *et al.* Tracking, targeting, and conserving soil biodiversity. *Science*. 2021;371(6526):239-241.

    doi: 10.1126/science.abd7926

17. Lal R. Regenerative agriculture for food and climate. *J Soil Water Conserv*. 2020;75(5):123A-124A.

    doi: 10.2489/jswc.2020.0620A

18. Newton P, Civita N, Frankel-Goldwater L, Bartel K, Johns C. What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. *Front Sustain Food Syst*. 2020;4:577723.

    doi: 10.3389/fsufs.2020.577723

19. Schreefel L, Schulte RPO, de Boer IJM, Schrijver AP, van Zanten HHE. Regenerative agriculture - the soil is the base. *Glob Food Secur*. 2020;26:100404.

    doi: 10.1016/j.gfs.2020.100404

20. Khangura R, Ferris D, Wagg C, Bowyer J. Regenerative agriculture—a literature review on the practices and mechanisms used to improve soil health. *Sustainability*. 2023;15(3):2338.

    doi: 10.3390/su15032338

21. Rehberger E, West PC, Spillane C, McKeown PC. What climate and environmental benefits of regenerative agriculture practices? An evidence review. *Environ Res Commun*. 2023;5(5):052001.

    doi: 10.1088/2515-7620/acd6dc

22. Wiesmeier M, Urbanski L, Hobley E, *et al.* Soil organic carbon storage as a key function of soils—a review of drivers and indicators at various scales. *Geoderma*. 2019;333(5):149-162.

    doi: 10.1016/j.geoderma.2018.07.026

23. Joseph S, Cowie AL, Van Zwieten L, *et al.* How biochar works, and when it does not: a review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy*. 2021;13(11):1731-1764.

    doi: 10.1111/gcbb.12885

24. Vanlauwe B, Bationo A, Chianu J, *et al.* Integrated soil fertility management: operational definition and consequences for implementation and dissemination. *Outlook Agric*. 2010;39(1):17-24.

    doi: 10.5367/000000010791169998

25. Chazdon RL, Brancalion PHS, Lamb D, Laestadius L, Calmon M, Kumar C. A policy-driven knowledge agenda for global forest and landscape restoration. *Conserv Lett*. 2017;10(1):125-132.

    doi: 10.1111/conl.12220

26. Syromiatnykov Y, Mamatov F, Sholoiko A, *et al.* Geometry-optimized strip tillage for improving soil physical quality and hydraulic function in semi-arid vineyards. *Agriculture*. 2026;16(7):751.

    doi: 10.3390/agriculture16070751

27. Syromyatnikov Y, Troyanovskaya I, Zagidullin R, Tikhonov E, Orekhovskaya A, Voinash S. Soil density in traditional mouldboard tillage. *Acta Technol Agric*. 2023;26(3):159-165.

    doi: 10.2478/ata-2023-0021

28. Pashchenko VF, Syromyatnikov YUN, Hramov NS, Vojnash SA. The influence of local loosening of the soil on soybean productivity. *Tractors Agric Mach*. 2019;86(5):79-86.

    doi: 10.31992/0321-4443-2019-5-79-86

29. Syromiatnykov Y. Sustainable soybean cultivation using nitrogen-fixing bacteria and humic products derived from agricultural waste: a review. *Asian J Water Environ Pollut*. 2025;22(6):1-20.

    doi: 10.36922/AJWEP025230190

30. Syromiatnykov Y, Mamatov F, Fayzullaev K, *et al.* Optimization of Leveler-Compactor parameters in combined strip tillage for soil preparation under plastic film for melon crops. *Agronomy*. 2026;16(8):809.

doi: 10.3390/agronomy16080809

31. Wadoux AMJC, Minasny B, McBratney AB. Machine learning for digital soil mapping: applications, challenges and suggested solutions. *Earth Sci Rev*. 2020;210:103359.

    doi: 10.1016/j.earscirev.2020.103359

32. Padarian J, Minasny B, McBratney AB. Using deep learning for digital soil mapping. *SOIL*. 2019;5(1):79-89.

    doi: 10.5194/soil-5-79-2019

33. Peng J, Albergel C, Balenzano A, *et al.* A roadmap for high-resolution satellite soil moisture applications: confronting product characteristics with user requirements. *Remote Sens Environ*. 2021;252:112162.

    doi: 10.1016/j.rse.2020.112162

34. Arrouays D, Poggio L, Mulder VL, Salazar O. Digital soil mapping and GlobalSoilMap—scientific advances and the operational use of digital soil mapping to address global environmental challenges. *Geoderma Reg*. 2021;26:e00414.

    doi: 10.1016/j.geodrs.2021.e00414

35. Poggio L, de Sousa LM, Batjes NH, *et al.* SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty. *SOIL*. 2021;7(1):217-240.

    doi: 10.5194/soil-7-217-2021

36. Lamichhane S, Kumar L, Wilson B. Digital soil mapping algorithms and covariates for soil organic carbon mapping and their implications: a review. *Geoderma*. 2019;352:395-413.

    doi: 10.1016/j.geoderma.2019.05.031

37. Chen S, Arrouays D, Mulder VL, *et al.* Digital mapping of GlobalSoilMap soil properties at a broad scale: a review. *Geoderma*. 2022;409:115567.

    doi: 10.1016/j.geoderma.2021.115567

38. van der Westhuizen S, Heuvelink GBM, Hofmeyr DP. Multivariate random forest for digital soil mapping. *Geoderma*. 2023;431:116365.

    doi: 10.1016/j.geoderma.2023.116365

39. Li Q, Zhang C, Shangguan W, Li L, Dai Y. A novel local-global dependency deep learning model for soil mapping. *Geoderma*. 2023;438:116649.

    doi: 10.1016/j.geoderma.2023.116649

40. Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R. Google Earth Engine: planetary-scale geospatial analysis for everyone. *Remote Sens Environ*. 2017;202:18-27.

    doi: 10.1016/j.rse.2017.06.031

41. Tamiminia H, Salehi B, Mahdianpari M, Quackenbush L, Adeli S, Brisco B. Google Earth Engine for geo-big data applications: A meta-analysis and systematic review. *ISPRS J Photogramm Remote Sens*. 2020;164:152-170.

    doi: 10.1016/j.isprsjprs.2020.04.001

42. Piikki K, Wetterlind J, Söderström M, Stenberg B. Perspectives on validation in digital soil mapping of continuous attributes—a review. *Soil Use Manag*. 2021;37(1):7-21.

    doi: 10.1111/sum.12694

43. Walling E, Vaneeckhaute C. Developing successful environmental decision support systems: challenges and best practices. *J Environ Manag*. 2020;264:110513.

    doi: 10.1016/j.jenvman.2020.110513

44. Zhai Z, Martínez JF, Beltran V, Martínez NL. Decision support systems for agriculture 4.0: survey and challenges. *Comput Electron Agric*. 2020;170:105256.

    doi: 10.1016/j.compag.2020.105256

45. Arrouays D, McBratney A, Bouma J, *et al.* Impressions of digital soil maps: the good, the not so good, and making them ever better. *Geoderma Reg*. 2020;20:e00255.

    doi: 10.1016/j.geodrs.2020.e00255

46. Colapinto C, Jayaraman R, Ben Abdelaziz F, La Torre D. Environmental sustainability and multifaceted development: multi-criteria decision models with applications. *Ann Oper Res*. 2020;293(2):405-432.

    doi: 10.1007/s10479-019-03403-y

47. Rivera-Marin D, Dash J, Ogutu B. The use of remote sensing for desertification studies: a review. *J Arid Environ*. 2022;206(2):104829.

    doi: 10.1016/j.jaridenv.2022.104829

48. Liu J, Li M, Jafari Shalamzari M, *et al.* A remote sensing-based early warning system for desertification: monitoring spatiotemporal dynamics and identifying risk zones. *Land Degrad Dev*. 2026;37(11):6496-6515.

    doi: 10.1002/ldr.70529

49. Peake LR, Robb C. Saving the ground beneath our feet: establishing priorities and criteria for governing soil use and protection. *R Soc Open Sci*. 2021;8(11):201994.

    doi: 10.1098/rsos.201994

50. Bodle R. International soil governance. *Soil Secur*. 2022;6:100037.

    doi: 10.1016/j.soisec.2022.100037

51. Ginzky H, Ruppel OC. Soil protection law in Africa: insights and recommendations based on country studies from Cameroon, Kenya and Zambia. *Soil Secur*. 2022;6:100032.

    doi: 10.1016/j.soisec.2021.100032

52. Eugenio NR, Ginzky H, Heuser IL, Hannam I, Ruppel OC, Sambo PT. Foreword of the second special issue on "Soil Governance." *Soil Secur*. 2024;16:100138.

    doi: 10.1016/j.soisec.2024.100138

53. Bouma J, Montanarella L. Facing policy challenges with inter- and transdisciplinary soil research focused on the United Nations Sustainable Development Goals. *SOIL*. 2016;2(2):135-145.

doi: 10.5194/soil-2-135-2016

54. Peake LR, Robb C. The global standard bearers of soil governance. *Soil Secur*. 2022;6:100055.

doi: 10.1016/j.soisec.2022.100055

55. Sanchez-Garcia C, Button E, Wynne-Jones S, Porter H, Rugg I, Hannam JA. Finding common ground: co-producing national soil policy in Wales through academic and government collaboration. *Soil Secur*. 2023;11:100095.

doi: 10.1016/j.soisec.2023.100095

56. Helming K, Daedlow K, Hansjürgens B, Koellner T. Assessment and governance of sustainable soil management. *Sustainability*. 2018;10(12):4432.

doi: 10.3390/su10124432

57. Ginzky H. Soil governance: the case of implementation and enforcement. *Soil Secur*. 2022;6:100040.

doi: 10.1016/j.soisec.2022.100040

58. Sharififar A, Borrelli P, Evangelista SJ, *et al.* Soil policy principles and a policymaking framework using the soil security concept. *Environ Sci Policy*. 2025;168:104057.

doi: 10.1016/j.envsci.2025.104057

59. Ovienmhada U, Mouftaou F, Wood D. Inclusive design of Earth observation decision support systems for environmental governance: a case study of Lake Nokoué. *Front Clim*. 2021;3:717418.

doi: 10.3389/fclim.2021.717418

60. Gebreegziabher T, Suryabhagavan KV, Raghuvanshi TK. WebGIS-based decision support system for soil erosion assessment in Legedadi watershed, Oromia Region, Ethiopia. *Geol Ecol Landsc*. 2023;7(2):97-114.

doi: 10.1080/24749508.2021.1924441

61. Cinelli M, Kadziński M, Miebs G, Gonzalez M, Słowiński R. Recommending multiple criteria decision analysis methods with a new taxonomy-based decision support system. *Eur J Oper Res*. 2022;302(2):633-651.

doi: 10.1016/j.ejor.2022.01.011

62. Kandakoglu A, Frini A, Ben Amor S. Multicriteria decision making for sustainable development: a systematic review. *J Multi-Crit Decis Anal*. 2019;26(5-6):202-251.

doi: 10.1002/mcda.1682

63. Purcell W, Neubauer T. Digital twins in agriculture: a state-of-the-art review. *Smart Agric Technol*. 2023;3:100094.

doi: 10.1016/j.atech.2022.100094

64. Ortiz-Bobea A, Ault TR, Carrillo CM, Chambers RG, Lobell DB. Anthropogenic climate change has slowed global agricultural productivity growth. *Nat Clim Chang*. 2021;11(4):306-312.

doi: 10.1038/s41558-021-01000-1

65. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press; 2023.

doi: 10.1017/9781009325844

66. Wheeler T, von Braun J. Climate change impacts on global food security. *Science*. 2013;341(6145):508-513.

doi: 10.1126/science.1239402

67. Lobell DB, Gourdji SM. The influence of climate change on global crop productivity. *Plant Physiol*. 2012;160(4):1686-1697.

doi: 10.1104/pp.112.208298

68. Oldfield EE, Bradford MA, Wood SA. Global meta-analysis of the relationship between soil organic matter and crop yields. *SOIL*. 2019;5(1):15-32.

doi: 10.5194/soil-5-15-2019

69. Emde D, Hannam KD, Most I, Nelson LM, Jones MD. Soil organic carbon in irrigated agricultural systems: a meta-analysis. *Glob Change Biol*. 2021;27(16):3898-3910.

doi: 10.1111/gcb.15680

70. Seddon N. Harnessing the potential of nature-based solutions for mitigating and adapting to climate change. *Science*. 2022;376(6600):1410-1416.

doi: 10.1126/science.abn9668

71. Turner B, Devisscher T, Chabaneix N, Woroniecki S, Messier C, Seddon N. The role of nature-based solutions in supporting social-ecological resilience for climate change adaptation. *Annu Rev Environ Resour*. 2022;47:123-148.

doi: 10.1146/annurev-environ-012220-010017

72. Mekonnen MM, Hoekstra AY. Four billion people facing severe water scarcity. *Sci Adv*. 2016;2(2).

doi: 10.1126/sciadv.1500323

73. Rosa L, Chiarelli DD, Rulli MC, Dell'Angelo J, D'Odorico P. Global agricultural economic water scarcity. *Sci Adv*. 2020;6(18).

doi: 10.1126/sciadv.aaz6031

74. Jägermeyr J, Pastor A, Biemans H, Gerten D. Reconciling irrigated food production with environmental flows for sustainable development goals implementation. *Nat Commun*. 2017;8(1):15900.

doi: 10.1038/ncomms15900

75. Corona-López E, Román-Gutiérrez AD, Otazo-Sánchez

EM, Guzmán-Ortiz FA, Acevedo-Sandoval QA. Water-food nexus assessment in agriculture: a systematic review. *Int J Environ Res Public Health*. 2021;18(9):4983.

doi: 10.3390/ijerph18094983

76. Talaviya T, Shah D, Patel N, Yagnik H, Shah M. Implementation of artificial intelligence in agriculture for optimisation of irrigation and application of pesticides and herbicides. *Artif Intell Agric*. 2020;4:58-73.

doi: 10.1016/j.aiia.2020.04.002

77. Gorguner M, Kavvas ML. Modeling impacts of future climate change on reservoir storages and irrigation water demands in a Mediterranean basin. *Sci Total Environ*. 2020;748:141246.

doi: 10.1016/j.scitotenv.2020.141246

78. Wahbeh S, Anastasiadis F, Sundarakani B, Manikas I. Exploration of food security challenges towards more sustainable food production: a systematic literature review of the major drivers and policies. *Foods*. 2022;11(23):3804.

doi: 10.3390/foods11233804

79. Pretty J, Benton TG, Bharucha ZP, *et al.* Global assessment of agricultural system redesign for sustainable intensification. *Nat Sustain*. 2018;1(8):441-446.

doi: 10.1038/s41893-018-0114-0

80. Webb P, Benton TG, Beddington J, Flynn D, Kelly NM, Thomas SM. The urgency of food system transformation is now irrefutable. *Nat Food*. 2020;1(10):584-585.

doi: 10.1038/s43016-020-00161-0

81. Giller KE, Delaune T, Silva JV, *et al.* The future of farming: who will produce our food? *Food Secur*. 2021;13(5):1073-1099.

doi: 10.1007/s12571-021-01184-6

82. Birner R, Daum T, Pray C. Who drives the digital revolution in agriculture? A review of supply-side trends, players and challenges. *Appl Econ Perspect Policy*. 2021;43(4):1260-1285.

doi: 10.1002/aepp.13145

83. Zougmoré RB, Läderach P, Campbell BM. Transforming food systems in Africa under climate change pressure: role of climate-smart agriculture. *Sustainability*. 2021;13(8):4305.

doi: 10.3390/su13084305

84. Melesse MB, van den Berg M, Béné C, de Brauw A, Brouwer ID. Metrics to analyze and improve diets through food systems in low and middle income countries. *Food Secur*. 2020;12(5):1085-1105.

doi: 10.1007/s12571-020-01091-2

85. Barbosa Junior M, Pinheiro E, Sokulski CC, Ramos Huarachi DA, de Francisco AC. How to identify barriers to the adoption of sustainable agriculture? A study based on a multi-criteria model. *Sustainability*. 2022;14(20):13277.

doi: 10.3390/su142013277

86. Klerkx L, Rose D. Dealing with the game-changing technologies of Agriculture 4.0: how do we manage diversity and responsibility in food system transition pathways? *Glob Food Secur*. 2020;24:100347.

doi: 10.1016/j.gfs.2019.100347

87. Fabregas R, Kremer M, Schilbach F. Realizing the potential of digital development: the case of agricultural advice. *Science*. 2019;366(6471).

doi: 10.1126/science.aay3038

88. Doss C. Women and agricultural productivity: reframing the issues. *Dev Policy Rev*. 2018;36(1):35-50.

doi: 10.1111/dpr.12243

89. Piñeiro V, Arias J, Dürr J, *et al.* A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. *Nat Sustain*. 2020;3(10):809-820.

doi: 10.1038/s41893-020-00617-y