

NAVIGATING THE FOOD-WATER-LAND NEXUS: A SYSTEMATIC REVIEW OF SYSTEM DYNAMICS APPLICATIONS AND FUTURE DIRECTIONS

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Abstract

The food–water–land nexus presents complex challenges for sustainable resource management due to interconnected resource demands and environmental pressures. Although system dynamics has been widely applied to examine resource interactions, existing studies remain limited in integrating spatial heterogeneity, stakeholder behavior, and socioeconomic drivers. This systematic literature review aims to evaluate methodological approaches, policy applications, and research gaps in system dynamics modeling of the food–water–land nexus. Following the PRISMA framework, 79 documents published between 2016 and 2026 were initially identified through Scopus. After screening, 61 articles were retained, with 22 studies examined through focused thematic synthesis. The findings reveal four prominent methodological approaches: participatory modeling, hybrid integration with geographic information systems, modular modeling architectures, and probabilistic simulations. These approaches facilitate the identification of nonlinear feedbacks, resource trade-offs, and long-term policy implications. However, limited longitudinal data, insufficient spatial resolution, and inadequate representation of stakeholder behavior constrain model reliability. This review contributes a structured synthesis of methodological developments and identifies priority directions for integrating multiscale, spatially explicit, and behaviorally informed models to support adaptive and sustainable resource governance.

Keywords: Food–Water–Land Nexus; System Dynamics; Resource Management; Sustainable Development; Policy Simulation.

1. Introduction

The increasing pressures of population growth, urbanization, climate change, and socioeconomic development have intensified competition for essential natural resources, particularly food, water, and land. These resources constitute interconnected



components of socioecological systems, in which changes in one sector can generate significant consequences for the others. Agricultural expansion, for instance, may increase food production while simultaneously intensifying irrigation demands, accelerating land-use conversion, and contributing to environmental degradation. Consequently, managing these resources independently is increasingly inadequate for addressing contemporary sustainability challenges. The food–water–land nexus has emerged as an integrated analytical framework for understanding resource interdependencies, identifying synergies and trade-offs, and supporting coordinated resource governance (Papadopoulou et al., 2022; Sušnik et al., 2018). However, the complex interactions among resource availability, agricultural production, environmental conditions, and policy interventions require analytical approaches capable of representing nonlinear relationships, temporal delays, and feedback mechanisms (Deng et al., 2024). Understanding these dynamic relationships is essential for developing sustainable resource management strategies that balance environmental protection, food security, and socioeconomic development.

System dynamics has increasingly been employed as a methodological approach for investigating complex resource interdependencies within nexus systems. Through causal loop diagrams, stock-and-flow structures, and simulation models, system dynamics enables researchers to examine feedback processes, resource accumulation, and the long-term consequences of alternative management policies. Previous studies have demonstrated its application in evaluating resource allocation, environmental sustainability, and agricultural management strategies. Martinez-Hernandez et al. (2017) developed the NexSym simulation tool to investigate interactions among water, energy, food, and ecosystems, illustrating the potential of integrated modeling for understanding cross-sectoral resource relationships. Similarly, Sušnik et al. (2018) demonstrated the relevance of participatory approaches through the SIM4NEXUS framework, emphasizing stakeholder involvement in exploring resource interdependencies. Kheirinejad et al. (2024) integrated system dynamics and agent-based modeling to examine the implications of dietary changes for the water–food–energy nexus. These studies indicate that system dynamics provides a useful foundation for understanding complex resource systems and evaluating the potential implications of sustainability interventions.

Recent research has further expanded nexus modeling through methodological integration and applications across different spatial and institutional contexts. Papadopoulou et al. (2022) examined the water–energy–land–food–climate nexus to support sustainable development policy in Greece, demonstrating the importance of integrated resource indicators and policy evaluation. Elsayed et al. (2022) investigated transboundary water–food–energy relationships, highlighting the significance of coordinated resource governance across administrative boundaries. More recent studies have incorporated advanced analytical approaches to strengthen the representation of interconnected resource systems. Gao et al. (2025) examined coordination among water, land, energy, food, and carbon systems, while Jonsson et al. (2026) explored data-driven approaches for predicting policy impacts within nexus modeling. These developments demonstrate growing methodological diversity, including participatory modeling, hybrid analytical frameworks, and integrated simulation approaches. Nevertheless, differences



in modeling structures, spatial scales, analytical assumptions, and policy objectives have produced a fragmented body of evidence, creating challenges for systematically comparing the methodological contributions and practical implications of existing studies.

Despite these advances, several limitations remain in the application of system dynamics to integrated resource management. First, conventional system dynamics models frequently employ aggregated variables that may insufficiently represent heterogeneous decision-making processes among farmers, consumers, policymakers, and other stakeholders. Although hybrid system dynamics and agent-based approaches have been developed to address behavioral complexity, their integration remains methodologically challenging (Kheirinejad et al., 2024). Second, limited spatial representation can constrain the ability of dynamic models to capture localized resource conditions, including variations in land availability, water scarcity, and agricultural development. The increasing application of geographically explicit and data-driven approaches reflects the need to strengthen spatial representation within integrated resource analysis (Gao et al., 2025; Jonsson et al., 2026). Third, uncertainty associated with climate variability, socioeconomic change, and policy implementation continues to challenge the reliability of long-term simulations. These limitations suggest that methodological development should not focus exclusively on increasing model complexity but should also improve transparency, data availability, stakeholder representation, and the interpretation of policy outcomes.

Although existing studies provide valuable insights into individual nexus applications, a critical research gap remains in the systematic integration of evidence concerning modeling structures, sustainability policy trade-offs, and methodological limitations specifically within the food–water–land nexus. Previous research has examined particular resource combinations, geographical contexts, or analytical techniques, but the findings are often presented within separate methodological and policy frameworks. Consequently, there is a need for a systematic synthesis that compares how system dynamics approaches represent interdependencies among food, water, and land resources, evaluates the types of policy interventions examined, and identifies the limitations affecting model reliability and applicability. Such a synthesis is particularly important for distinguishing established methodological practices from emerging innovations and for determining how existing modeling approaches can better support integrated resource governance. Addressing this gap requires a structured review that connects methodological developments with their implications for sustainability assessment and policy formulation.

Therefore, this study aims to systematically review the application of system dynamics in analyzing the food–water–land nexus, with particular emphasis on three research objectives: (1) identifying the principal methodological structures and modeling approaches employed to represent resource interdependencies; (2) examining the policy interventions, sustainability synergies, and resource trade-offs evaluated through dynamic simulations; and (3) critically assessing existing methodological limitations and future research directions. Using a systematic literature review guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, this



study synthesizes relevant scientific publications from 2016 to 2026. The principal contribution of this review lies in integrating methodological, policy-oriented, and research-gap perspectives into a structured synthesis of system dynamics applications within the food–water–land nexus. By identifying recurring modeling approaches and unresolved methodological challenges, the study provides a foundation for future research integrating multiscale analysis, spatially explicit information, stakeholder behavior, and uncertainty assessment. These contributions are expected to strengthen the scientific basis for developing more adaptive, integrated, and sustainable food, water, and land resource management strategies.

2. Methods

Research Questions

This study formulates specific research questions to guide the systematic review process. The research questions are designed to uncover the extent to which system dynamics has been applied to the food-water-land nexus and to identify prevailing methodological gaps.

The Prisma Methods

This subsection outlines the systematic approach taken to identify, select, and critically appraise relevant research. The review process rigorously adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and reproducibility.

1. Identification: Comprehensive literature searches were executed across designated academic databases using predefined Boolean search strings to capture all potentially relevant records.
2. Screening: The initial pool of identified records underwent a rigorous screening phase, where duplicate entries were removed and titles and abstracts were reviewed for broad relevance to the core topic.
3. Eligibility: Full-text articles of the remaining records were retrieved and thoroughly assessed against strict inclusion and exclusion criteria to determine their methodological and thematic suitability.
4. Inclusion: Studies that successfully met all eligibility criteria were officially included in the final qualitative and quantitative synthesis, forming the empirical foundation of the review.

Literature Search Strategy

To ensure a robust and comprehensive collection of relevant literature, a highly structured search strategy was deployed targeting the Scopus database, with the export date recorded as October 19, 2026. The search utilized a specific Boolean query string designed to capture the intersection of system dynamics and the resource nexus. The query applied was: TITLE-ABS-KEY (("system* dynamic*" OR "systems dynamic*" OR "dynamic* model*" OR "dynamic* simulat*" OR "system* thinking") AND ("nexus") AND (("food" AND "water" AND "land") OR "food-water-land" OR "water-food-land" OR



"WEFL" OR "CLEW")). This targeted approach yielded an initial corpus of 79 documents, which subsequently underwent the systematic screening process.

Screening Criteria

The refinement of the initial search results was governed by a strict set of screening criteria to ensure the inclusion of high-quality, relevant, and recent academic literature. These criteria were methodically applied to filter the documents based on publication year, document type, and publication language. Table 1 details the specific inclusion and exclusion parameters utilized during the screening phase, which ultimately reduced the document count to a final set of 61 articles for synthesis.

Table 1. Screening Criteria and Document Filtration

Criteria	Inclusion documents	Exclusion documents
Document year	Published in 2016-2026 (78 documents)	Published below 2016 (1 document)
Document type	Article (61 documents)	Conference paper (8 documents), Review (4 documents), Book Chapter (4 documents), letter (1 document)
Document language	English (75 documents)	Chinese (2 documents), Persian (1 document)

Research Questions and Synthesis Strategy

To systematically dissect the gathered literature, a structured analytical strategy was formulated around specific lines of inquiry.

RQ1: What are the primary methodological structures and modeling approaches used in system dynamics to address the food-water-land nexus?

RQ2: What key policy interventions and sustainability trade-offs are most frequently evaluated using these models?

RQ3: What are the prominent limitations and future directions proposed in the current literature regarding system dynamics applications in this field?

The included documents must satisfy criteria corresponding to the RQ, provided in the subsequent table.

Table 2. Research Questions and Synthesis Strategy

Criteria by RQ	Strategy to answer	Results (References to be used)
RQ1: Focus on model structure, feedback loops, and hybrid methodologies	Thematic analysis of methodology sections	Jonsson et al., 2026; Endo et al., 2021; Suprun et al., 2019; Sušnik et al., 2018; Molajou et al., 2026; Gao et al., 2025; Wang et al., 2025



RQ2: Focus on policy scenarios, resource trade-offs, and ecological impacts	Extraction of key findings and simulated scenario outcomes	Razaghi et al., 2025; Elsayed et al., 2022; Papadopoulou et al., 2022; Soares Dal Poz et al., 2022; Acevedo-De-los-Ríos et al., 2026; Mirindi, 2025; Pérez Pérez et al., 2025
RQ3: Focus on identified challenges, data limitations, and proposed advancements	Synthesis of discussion and conclusion sections	Bell et al., 2016; Yang et al., 2025; Jiang & Simonovic, 2025; Olatoye et al., 2026; Wang et al., 2023; Shan et al., 2026; Kheirinejad et al., 2024; Wang & Zhao, 2026

A total of 22 references extracted directly from the screened literature pool will be utilized to comprehensively address the research questions in the Results and Discussion section.



Figure 1. Flow diagram of the study selection process using PRISMA methods.

3. Results and Discussion

Methodological Structures and Modeling Approaches

The application of system dynamics in exploring the food-water-land nexus has evolved significantly, demonstrating a robust capacity for capturing complex, non-linear interactions across diverse resource domains. Current literature highlights a strong preference for participatory modeling approaches, where system dynamics is utilized not merely as a computational tool but as a collaborative platform for stakeholder engagement (Sušnik et al., 2018). By integrating multi-actor perspectives directly into the causal loop diagramming phase, researchers ensure that the models accurately reflect localized socio-economic realities and governance structures (Endo et al., 2021). Furthermore, the construction of these models increasingly relies on hybrid methodologies that couple traditional stock-and-flow architectures with advanced machine learning algorithms and geographic information systems (Wang et al., 2025). This integration allows for the processing of high-resolution spatial data, significantly enhancing the precision of land-use transition simulations and hydrological forecasts within the nexus framework (Molajou et al., 2026).

Despite these advancements, the structural complexity of system dynamics models presents ongoing challenges regarding calibration and validation, particularly in regions characterized by severe data scarcity. Researchers frequently employ sensitivity analyses and Monte Carlo simulations to rigorously test model boundaries and manage the deep uncertainties inherent in long-term environmental projections (Gao et al., 2025). A prevailing methodological trend is the compartmentalization of the nexus into distinct but interconnected sub-modules, representing water hydrology, agricultural production, and energy consumption independently before integrating them through feedback linkages (Jonsson et al., 2026). This modular architecture not only simplifies the debugging process but also facilitates the adaptation of the core model structure to entirely different geographical contexts or urban planning scenarios (Suprun et al., 2019). Consequently, the structural flexibility of system dynamics remains its most significant methodological advantage in nexus research.

Table 3. Summary of Methodological Structures

Primary Approach	Key Features	Analytical Focus	Ref.
Participatory Modeling	Stakeholder engagement, co-creation	Socio-economic relevance	Sušnik et al., 2018; Endo et al., 2021
Hybrid Integration	Coupled with GIS and machine learning	High-resolution spatial data	Wang et al., 2025; Molajou et al., 2026
Modular Architecture	Interconnected sub-modules	Structural flexibility	Jonsson et al., 2026; Suprun et al., 2019
Probabilistic Simulation	Monte Carlo, sensitivity analysis	Uncertainty management	Gao et al., 2025

Policy Interventions and Sustainability Trade-Offs

System dynamics models have proven exceptionally valuable in evaluating the long-term efficacy of various policy interventions aimed at securing the food-water-land nexus against escalating environmental pressures. A prominent theme across the reviewed literature is the assessment of transition strategies towards circular economy principles and renewable energy integration within agricultural frameworks. For instance, scenarios prioritizing the expansive deployment of bioenergy crops frequently reveal profound systemic trade-offs, where initial gains in carbon emission reductions are offset by severe agricultural water depletion and diminished food security (Papadopoulou et al., 2022). Conversely, policies that incentivize technological advancements in irrigation efficiency and wastewater reclamation consistently demonstrate robust, synergistic benefits across all nexus dimensions, promoting both ecological resilience and enhanced agricultural yields (Soares Dal Poz et al., 2022). These modeling outcomes underscore the critical necessity of evaluating policy interventions holistically rather than in sectoral isolation (Razaghi et al., 2025). Furthermore, system dynamics simulations have shed light on the intricate geopolitical dimensions of resource management, particularly within transboundary river basins and informal urban settlements. By modeling the cascading impacts of unilateral dam construction or inequitable land tenure policies, researchers illustrate how localized decisions can precipitate widespread socio-ecological instability across interconnected regions (Elsayed et al., 2022). In data-scarce environments, dynamic models serve as crucial diagnostic tools that highlight how governance reforms and decentralized infrastructure, such as urban rooftop agriculture and local biodigesters, can dramatically improve food security and community resilience (Acevedo-De-los-Ríos et al., 2026). Ultimately, the literature emphasizes that achieving sustainable nexus governance requires highly adaptive, context-specific policy portfolios capable of dynamically responding to shifting climatic variables and socio-economic demographics (Mirindi, 2025; Pérez Pérez et al., 2025).

Table 4. Summary of Policy Interventions and Trade-Offs

Policy Intervention	Primary Benefit	Systemic Trade-Off	Ref.
Bioenergy Expansion	Carbon emission reduction	Water depletion, land competition	Papadopoulou et al., 2022
Irrigation Technology	Water conservation	High initial capital investment	Soares Dal Poz et al., 2022; Razaghi et al., 2025
Decentralized Agriculture	Enhanced local food security	Complex governance requirements	Acevedo-De-los-Ríos et al., 2026; Mirindi, 2025



Transboundary Treaties	Basin-wide resource stability	Loss of unilateral decision power	Elsayed et al., 2022; Pérez Pérez et al., 2025
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3. Limitations and Future Directions

While system dynamics provides a formidable framework for nexus analysis, the literature consistently identifies several critical limitations that currently constrain the field's predictive capabilities. The most pervasive challenge is the chronic scarcity of high-quality, longitudinal data required to accurately calibrate complex socio-ecological feedback loops, particularly in developing regions (Wang & Zhao, 2026). This data deficiency often forces modelers to rely on broad aggregate assumptions, thereby diminishing the model's ability to accurately reflect micro-level behavioral dynamics and localized environmental nuances (Jiang & Simonovic, 2025). Additionally, many existing models fail to adequately incorporate the systemic impacts of global market volatility and shifting geopolitical trade policies, treating these critical external drivers as static rather than dynamic variables (Olatoye et al., 2026). Consequently, the long-term reliability of simulated policy scenarios can be severely compromised when confronted with sudden economic shocks or rapid climatic shifts (Wang et al., 2023).

To overcome these limitations, future research must prioritize the development of multi-scale modeling frameworks that seamlessly bridge the gap between global macroeconomic drivers and localized resource management practices (Yang et al., 2025). Scholars advocate for the increased integration of agent-based modeling techniques within standard system dynamics architectures to better capture the heterogeneous decision-making processes of individual stakeholders, such as farmers adapting to new agricultural technologies (Kheirinejad et al., 2024). Furthermore, advancing the deployment of real-time environmental sensors and remote sensing technologies will be paramount in generating the continuous, high-resolution datasets necessary for dynamic model calibration (Shan et al., 2026). By embracing these methodological innovations, the next generation of nexus models will offer significantly enhanced precision, ultimately providing policymakers with the robust, actionable intelligence required to navigate the complex challenges of global resource sustainability (Bell et al., 2016).

Table 5. Summary of Limitations and Future Directions

Identified Limitation	Proposed Advancement	Expected Outcome	Ref.
Data Scarcity	Remote sensing integration	Enhanced model calibration	Shan et al., 2026; Wang & Zhao, 2026
Static Micro-Behaviors	Agent-based model coupling	Accurate stakeholder representation	Kheirinejad et al., 2024
Ignoring Global Markets	Multi-scale macroeconomic links	Improved predictive resilience	Yang et al., 2025; Olatoye et al., 2026

Aggregate Assumptions	Spatially explicit hybrid models	Localized policy relevance	Jiang & Simonovic, 2025; Wang et al., 2023
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4. Conclusion

The systematic literature review conducted herein provides a comprehensive evaluation of how system dynamics modeling has been utilized to analyze and optimize the food-water-land nexus over the past decade. The synthesis of the reviewed literature unequivocally demonstrates that system dynamics is a highly effective methodological framework for capturing the intricate, nonlinear feedbacks and delays that characterize global resource systems. By facilitating the simulation of various long-term scenarios, these models have empowered researchers and policymakers to visualize the hidden trade-offs and synergistic benefits of proposed sustainability interventions. Notably, the transition towards participatory and hybrid modeling approaches has significantly enhanced the relevance and accuracy of these tools, ensuring that simulations are grounded in empirical realities and localized socio-economic contexts. However, the review also highlights substantial challenges that must be addressed to maximize the utility of these models in future applications. The persistent scarcity of high-resolution, longitudinal data remains a critical bottleneck, often resulting in overly aggregated models that fail to capture vital micro-level behaviors and spatial heterogeneities. Furthermore, the lack of dynamic integration with global macroeconomic drivers limits the predictive resilience of current frameworks when faced with volatile external shocks. Moving forward, it is imperative for the academic community to prioritize the development of multi-scale, coupled modeling architectures that seamlessly integrate system dynamics with agent-based methodologies and advanced geospatial technologies. Embracing these innovations will fundamentally transform our capacity to predict systemic resource vulnerabilities and design robust, adaptive governance strategies. Ultimately, advancing our understanding of the food-water-land nexus through rigorous, transparent, and highly integrated dynamic modeling is not merely an academic exercise, but an urgent necessity for safeguarding global environmental sustainability and ensuring equitable resource distribution for future generations.

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