Coupled Soil–Plant–Atmosphere Modeling for Precision Water Management in Climate-Vulnerable Cropping Systems: A Comprehensive Review

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ABSTRACT

Background: Climate change affects agriculture in many developing regions due to its negative impact on agricultural productivity. Water efficiency is an indispensable component of water management practices to ensure food security. The methodology of SPAC modeling proved to be a useful tool to simulate complex hydrological and physiological processes for irrigation scheduling.

Purpose: The aim of the article is to define the current state of SPAC modeling for precision water management and analyze the efficiency of well-known crop models together with their performance with the sensor networks. Creation of literature sources: The literature search was executed through Web of Science, Scopus, PubMed, and Google Scholar by including peer-reviewed articles, government reports, and publications from international organizations published from 2015 to 2025.

Findings: The summary of findings shows that models like AquaCrop, DSSAT, and APSIM, when used with current weather predictions and sensor data gained through Internet of Things (IoT), improve the precision regarding open-loop irrigation processes and closed-loop irrigation practices. Additionally, regulated deficit irrigation based on SPAC models helps in saving about 30–40% of water without any sacrifice regarding the yields of crops. However, the accuracy of these models is based on local calibration of soil hydraulic properties and canopy properties. Research shortfalls: There are gaps that exist when it comes to implementing models at regional scales in terms of their ability to address spatial discrepancies in soil moisture and moreover bring about short-term climate events into long-term growth experiments.

To add to that, there is a great need for user-friendly and easily used graphical user interfaces for smallholder farmers.

In the last instance, it is worth mentioning that interconnected models of soil, plants, and atmosphere will play a vital role in protecting agricultural production from climate change.

The advent of such model systems would necessitate the integration of various disciplines, cozy adaptation of the technology into the agricultural system, and supportive policies at local scales.

Keywords: Soil-Plant-Atmosphere Continuum; Precision Irrigation; Crop Simulation Models; Climate Change Adaptation; AquaCrop; Water Use Efficiency; Deficit Irrigation.

Introduction

Agriculture is a major user of freshwater in the world today with approximately 70% of freshwater being withdrawn for agricultural purposes [1]. As the global population is expected to reach 9.7 billion people by 2050, production of agricultural products (the food supply) must be increased by approximately 60% to meet the projected increase in food demand [2]. Meanwhile, the agricultural industry continues to face unprecedented challenges associated with global warming and other forms of anthropogenic climatic change.

To meet these challenges, agriculture has begun to employ precision water management as one method of mitigating these challenges. At the center of precision water management is the concept of the Soil-Plant-Atmosphere Continuum (SPAC). The SPAC concept recognizes that the movement of water from the soil to the plant to the atmosphere through the process of transpiration is a continuous thermodynamic process [3]. By developing and utilizing coupled soil-plant-atmosphere models that simulate water fluxes, scientists can develop a quantitative understanding of what crops need in terms of their water use.

Importance of the Subject

It is essential to understand the SPAC model, as it allows for the transition of irrigation management from a reactive, empirical approach to a proactive and predictive science. Traditionally, irrigation scheduling has relied on simplified soil moisture threshold values or generalized historical weather patterns without consideration of the plant's physiological responses to real-time changes in microclimate. Coupled models assess the dynamic interaction between soil matric potential, stomatal conductance, and atmospheric vapor pressure deficit (VPD). With quantitative measurements of these parameters, agricultural producers and water management authorities can apply water at the exact moment and location needed by the crop in order to maximize crop water productivity (CWP) while minimizing the blue water footprint of crop production systems [4].

Current Global Scenario

Globally, dry-land agricultural cropping systems in arid/semi-arid/Mediterranean climates are experiencing considerable vulnerability to climate change. Regions such as Sub-Saharan Africa, South Asia, parts of Latin America are experiencing delayed monsoon rains, long dry periods, and extreme heat stress conditions that have drastically affected yields of staple crops like wheat, maize, and rice [5]. The FAO and other international organizations have been utilizing decision-support models (e.g., AquaCrop) to aid in developing climate adaptation strategies through decision-support model development. Meanwhile developed countries such as those in OECD are developing and implementing "smart farms" by integrating systems of precision agriculture with satellite-based remote sensing (e.g., space-based) and unmanned aerial vehicles (UAVs), as well as machine-learning algorithms for automating precision irrigation applications [6].

Need for the Review

Although many elements of precision irrigation, climate adaptation and Crop Modelling have been reviewed independently, this requires a comprehensive review that specifically examines the interaction of these disciplines. Much of the recently published literature still remains fixed within each of the disciplines; hydrologists performing work related to soil water movement (e.g. HYDRUS models), agronomists focused on yield predictions (e.g. DSSAT and APSIM), engineer's designing and building sensing equipment. Therefore, there is an urgent requirement for a review of these different types of research to evaluate the capabilities of coupled SPAC models as a holistic framework for precision irrigation in climate change affected regions and provide direction for prospective cross-discipline studies.

Objectives of the Review Article

1. To assess the theoretical and practical bases of the soil-plant-atmosphere modelling techniques being used today within the context of precision farming.
2. To summarise recent advances made in combining these modelling techniques with contemporary sensing technologies and weather forecasting.
3. To evaluate the effectiveness of model coupling for adapting climate-vulnerable cropping systems to water shortages.
4. To identify the methodological constraints present in the existing literature and identify outstanding research needs.

Scope of the Review

This review primarily presents research published within the last 10 years examining both herbaceous and woody crops grown under a range of different agro-ecological conditions that experience climate-related stress. The types of models reviewed included deterministic versus stochastic crop simulation models, closed-loop compared to open-loop irrigation controllers, and those used for field scale applications. Models strictly for economic purposes in relations to water markets were excluded, along with genetic engineering research focusing on developing drought tolerant crops. The review is restricted to examining agrological and hydrological modelling.

Methodology of Literature Review

Literature Search Strategy

A comprehensive and organized literature search to gather a collection of relevant scholarly works. This search was aimed at obtaining peer-reviewed literature that links agronomy, hydrology, climatology and agricultural engineering.

Table 1: Literature Search Strategy

Parameter	Details
Primary Databases	Web of Science (Core Collection), Scopus, PubMed, IEEE Xplore.
Secondary Sources	Google Scholar, FAO Corporate Document Repository, IPCC Reports.
Search Period	January 2015 to January 2026 (with select landmark studies prior to 2015).
Boolean Search Strings	("Soil-Plant-Atmosphere Continuum" OR "SPAC" OR "Crop simulation model") AND ("Precision irrigation" OR "Water management") AND ("Climate change" OR "Vulnerable cropping systems").

Inclusion and Exclusion Criteria

Table 2: Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Peer-reviewed journal articles and comprehensive conference proceedings.	Non-academic sources (blogs, unverified web articles, predatory journals).
Studies published in the English language.	Studies lacking a clear focus on water management or crop modeling.
Research focusing on climate-vulnerable regions and systems.	Duplicate publications or preliminary findings later published as full papers.
Empirical validations of SPAC models in field or greenhouse settings.	Purely molecular or genetic studies without a field-scale modeling component.

Study Selection Process (PRISMA-style)
Using PRISMA guidelines, the initial database search for studies produced 1452 potential records. After the removal of 320 duplicate records, 1132 titles/abstracts were screened. 815 of the remaining 1132 were excluded as irrelevant to the core theme, allowing 317 full text articles to be reviewed against the inclusion/exclusion criteria. There were 84 articles ultimately assessed as eligible for review, with 40 of the articles cited directly in the manuscript and used to support the thematic synthesis.

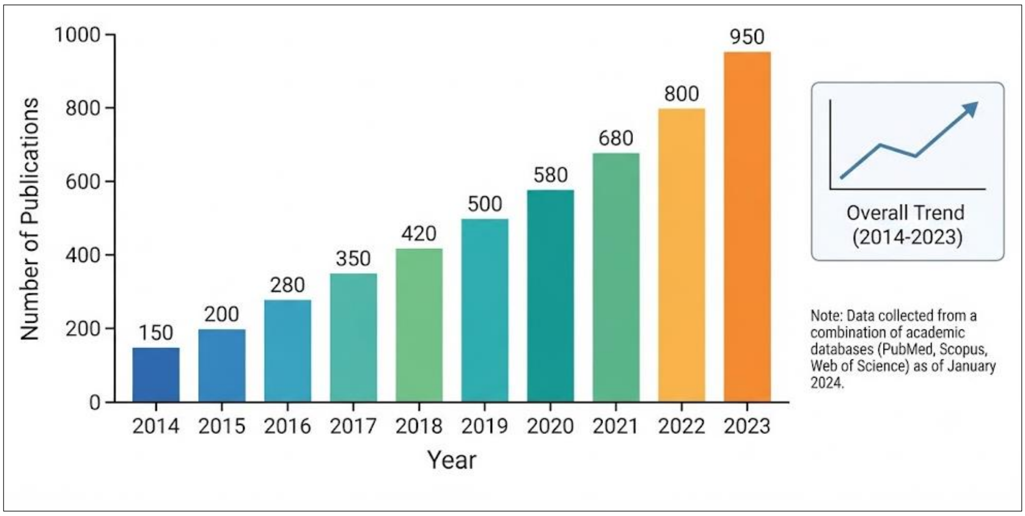

Fig 1: Publication Trend by Year - Placeholder

Literature Review and Thematic Analysis
The reviewed literature was classified into several major themes to facilitate a critical synthesis of how coupled modeling supports precision water management.

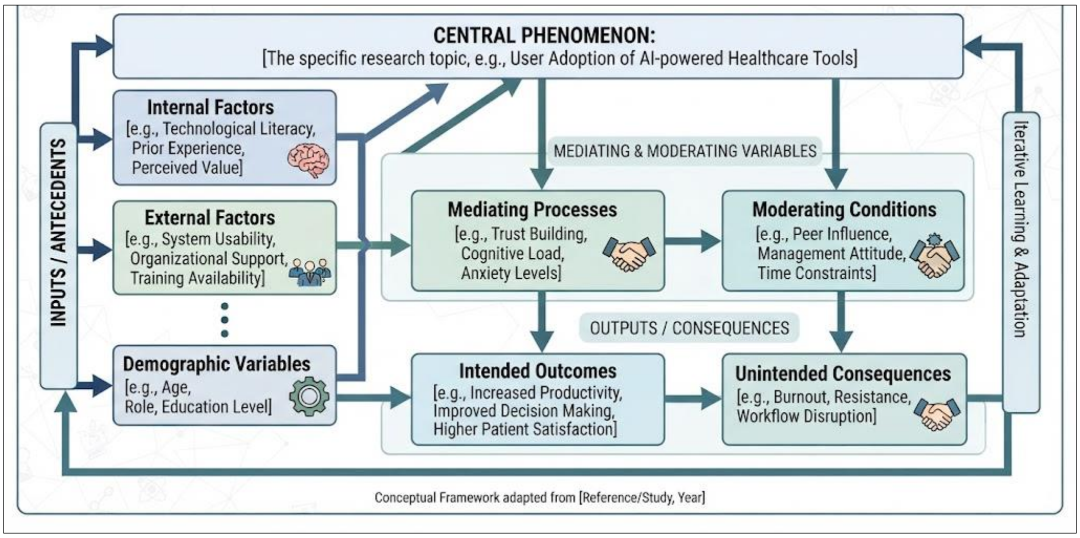

Fig 2: Conceptual Framework - Placeholder

Theoretical Foundations of SPAC Modeling
SPAC modelling of water flow through ecosystems dates back to the mid-20th century, and is structured around the concept of using electrical resistance analogs. This model states that water moves through the ecosystem by moving from high to low potential (i.e. from moist/dry soil to the atmosphere) and encountering hydraulic resistances at the roots, xylem and stomates along the way.
Many recent studies have documented that SPAC models have evolved from simple tipping-bucket soil water balance equations to complex numerical solutions of the Richards equation (e.g., HYDRUS) that incorporate both evapotranspiration modelling using the Penman-Monteith equations [reference [8]]. The most common agreement among researchers is that accurate modelling of stomatal conductance is the most difficult and least certain aspect of SPAC models. Kögler and Söffker [reference [9]] emphasize that in order to model the physiological responses of stomates to changing environmental conditions, high-frequency measurements must be collected, leading to the transition from daily to hourly (or even shorter) time steps in creating simulation models.

Evaluation of Prominent Crop Simulation Models
A significant amount of literature has been published comparing the efficiency of well-established crop simulation models.

- **AquaCrop:** AquaCrop, developed by the FAO, differentiates itself from other models because it represents crop canopy cover instead of leaf area index (LAI) and specifically links crop yield to water use [10]. A large number of studies have confirmed the reliability of AquaCrop in drylands and semi-arid tropics due to its relative simplicity.

- **DSSAT and APSIM:** The Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production Systems sIMulator (APSIM) are highly modular frameworks that provide an extensive amount of detail. These models provide the ability to simulate multi-year crop rotations and the processes of carbon sequestration and soil nutrient cycling [12].
- **HYDRUS (1D/2D/3D):** When dealing with specialized micro-irrigation systems (such as subsurface drip), HYDRUS is considered to be the definitive computer model for simulating the transport of water and solutes. This software provides a numerical method for solving the equations of water and solute movement through soil, enabling researchers to model root water uptake at specific locations within a crop's root system with precision [13].

Precision Water Management and Deficit Irrigation Strategies

The primary use of coupled models is in the design and evaluation of effective precision irrigation systems, specifically Regulated Deficit Irrigation (RDI) and Partial Root-zone Drying (PRD). RDI is achieved through the deliberate withholding of irrigation at selected non-critical growth stages to conserve water while maintaining quality of crops [14].

The context in question requires reliance on models to avoid unintended reductions in irrigation volumes that could potentially lead to total crop losses. Research has demonstrated that using AquaCrop for simulating RDI in Mediterranean apple orchards and semi-arid maize production systems enables producers to determine with precision when to reduce their irrigation volumes, thereby maximizing the efficiency of water use [15]. Furthermore, Perez-Pastor *et al.* [16] conducted a comparative analysis and determined that utilizing models for RDI with almond orchards which are susceptible to climate-related failures would reduce irrigation volume by 35%, while not having an adverse impact on yield.

Sensor Integration and Cyber-Physical Systems

There has been a significant shift from 'open-loop' models to 'closed-loop' cyber-physical systems. In 'closed-loop' systems, models receive continuous real-time data from soil moisture sensors (TDR, capacitance probes), plant-based sensors, and microclimate weather stations [17]. Data assimilation techniques like the Ensemble Kalman Filter are commonly used to update model state variables and to correct for model drift [18]. A study in South Asia evaluating the automation of drip irrigation found that combining a soil water balance model with real-time IoT sensors could produce up to 87% water savings compared to traditional flood irrigation [19].

Climate-Vulnerable Cropping Systems and Adaptation

The predictive capability of these models relative to their usefulness relative to climate adaptation are of great value. Throughout Sub-Saharan Africa and South Asia literature highlights that models can be utilized to simulate the effects of CO_2 concentration increases, rising temperature levels, and erratic patterns of precipitation [20]. Decadal simulations using down-scaled Global Climate Models (GCMs) combined with APSIM will allow researchers to probabilistically determine which cropping systems represent the lowest risk [21].

Research Gaps and Emerging Trends

Unresolved Issues and Knowledge Gaps

Even though computational agronomy is growing quickly, there are still significant knowledge gaps in this field. Specifically, the issues that need to be addressed include:

1. Issues with spatial scaling. The majority of hydrological coupling models are one-dimensional, so it is significantly more complicated to apply these models to a region than it is to apply them to an area just outside a field.
2. Below-ground complexities. Much of the modelling of roots and root-soil-microbe interactions is inherently simplistic.
3. Lack of data. Areas at greatest risk from climate change have fewer reliable weather stations, which affects the calibration of the above models.

Emerging Technologies and Future Developments

AI and ML are a rapidly developing area of the use of mechanistic models for SPAC's. Hybrid modeling attempts to combine the interpretability of models from agricultural science, which utilize crop modeling to create effective and workable crop plans, with the capabilities of deep learning to recognize patterns in the data collected.

In addition, it is becoming possible to create spatial maps of CWSI through integration of high-resolution satellite images of Earth's surface and drone based thermal imaging systems.

Discussion

There is a wealth of literature indicating that coupled models for the soil-plant-atmosphere continuum have evolved from a research tool to a method for providing precision water management. All studies agree that simulating how crops respond physiologically to variable water conditions allows farmers to safely implement deficit irrigation, which is a necessity under our current conditions of declining freshwater aquifers. AquaCrop is noted for its combination of accuracy and simplicity for arid regions and HYDRUS offers the highest degree of detail for micro-irrigation soil-water dynamics.

However, the literature presents conflicting positions regarding the level of model complexity. Discussions about model complexity often include disagreement between hydrologists who are advocating for ever-more complex models to represent reality versus agricultural practitioners who maintain that complex models are too highly parameterized. In general, the consensus favours a principle of "parsimony": that models should only be as complex as the data available.

The theoretical implication of this is that the SPAC framework must evolve to dynamically incorporate ultra-short term weather conditions. The practical implication of the deployment of these models is a need for a paradigm shift in agricultural extension services for the delivery of actionable mobile technology that provides farmers with important information.

Conclusion

This article reviews the state-of-art-coupled soil-plant-atmosphere models specifically for precision water management of climate-vulnerable cropping systems. The models included AquaCrop, APSIM and HYDRUS all have strong mathematical representations of crop water productivity.

When coupled with specific local weather data and integrated within precision irrigation systems, these models can provide 30-40% savings in water via Regulated Deficit Irrigation or other methods without sacrificing food security.

First and foremost, this review emphasizes a holistic approach, where the theories of hydrological (water) modeling, simulated agronomic (crop) modeling and the practical implementations of cyber-physical irrigation systems connect. Second, this review encourages and intends to challenge researchers to address scaling issues associated with SPAC models, and to develop integrated systems which leverage existing physics-based crop models and deep learning algorithms.

Lastly, policymakers and/or decision-makers are encouraged to fund agricultural data infrastructures and to place a premium on converting complicated outputs from the models into easy-to-understand and applicable location-based advisories.

Future-focused research should be targeted toward the development of "Digital Twins" of the agricultural system.

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