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Integrated Decision-Support Perspectives for Soil, Water, and Plant Health Management in Semi-Arid Agriculture

M'barka El Mouedden[1], Driss AZDEM [1], Jamal Mabrouki[1], Souad El Hajjaji[1]*

[1]Laboratory of Spectroscopy, Molecular Modeling, Materials, Nanomaterial's, Water and Environment, CERNE2D, Mohammed V University in Rabat, Faculty of Science, AV Ibn Battouta, BP1014, Agdal, Rabat, Morocco

Abstract. In semi-arid areas of the world agriculture is often challenged by numerous interconnected issues that are related to water availability, soil deterioration, climate fluctuations and increased susceptibility of crops to environmental and biological stress factors. As many of these factors seldom exist alone, the relationships between irrigation practices, the status of the soil and the health of plants develop and evolve over time through multiple interactions at different spatial and temporal levels. Yet, many current decision support tools are limited to single agronomic criteria; therefore, they do not adequately address the complexities of managing agricultural production under realistic field conditions. In response to the need for integrated crop management, this research addresses the dynamic interdependencies of soil, water and plant health in semi-arid agricultural systems. Therefore, the emphasis of this proposed methodology will be on coordinated interpretation versus separate prediction capabilities which will result in decision making that is both consistent with agronomic best practices and more reliable. Through analysis of soil moisture variability, irrigation sensitivities and disease pressures from an integrated point of view, the objectives of this research are to demonstrate that multi-dimensional decision-making processes may lead to improved crop resilience and decreased risk associated with management decisions. Ultimately, the objective of this research is to emphasize the need for comprehensive decision support tools that support sustainable and adaptable agricultural production in data-limited, semi-arid environments.

1 Introduction

Semi-arid regions are subject to many complex structural and environmental factors that limit crop production and yields because of several interrelated limiting factors including climate, soils and water supply[1]. Compared to other types of climates (humid, temperate) semi-arid agricultural systems operate in environments with high levels of water deficit; with high degrees of variability of precipitation; with significant seasonal variation of environmental conditions and therefore require very responsive and flexible forms of management for dealing with short term variations and long term degradations[2].

Water deficits are one of the most limiting factor in this type of environment. Water deficits directly affect plant growth; yield stability and resilience. In semi-arid areas there exists a large degree of spatiotemporal variability in soil moisture due to heterogeneity in soil texture; differences in infiltration capacity and spatially variable evaporation from the surface. The variability in soil moisture makes it very difficult to make generalization about irrigation across an entire field because similar amounts of irrigation water can result in very different soil and water relations at any given point in time, depending upon the particular local conditions. Irrigation errors (either over or under irrigating) can have rapid impacts on the health of crops[3].

Soil degradation risk is enhanced by poor irrigation techniques which lead to increased risk of salinization and nutrient imbalances. Salt accumulates in the root zone through salt buildup due to limited leaching and high evaporation in arid climates. Therefore, soil and water management are closely linked (interdependent) and therefore irrigation cannot be considered in isolation of the physical chemical and biological soil characteristics[4].

Crop performance will be largely influenced by how well a crop grows under semi-arid conditions; the soil-plant-water continuum determines this. Root growth and nutrient availability depend upon soil structure and moisture, while plant physiology influences water uptake and transpiration. Compaction, salinity, and water stress can all disrupt this continuum causing increased sensitivity to biotic stress. Semi-arid crops have an increased likelihood of being affected by plant pathogens due to weakened immune systems caused by stress and their rapid progress to disease.

Climate extremes including severe heatwaves and long duration droughts significantly amplify these vulnerabilities. Heatwaves increase evapotranspiration and drying of the soil, and alter microclimates that support disease outbreaks. Therefore, agricultural risk in semi-arid regions arise from compound effects rather than individual factors, thereby limiting traditional decision making approaches that are based on optimizing one variable at a time.

In terms of information, the data collected by the farmer in this context typically are fragmented and heterogeneous and stem from different sources including soil analysis, irrigation records, weather station readings, and field level measurements of crop growth. In addition to improving our understanding of individual processes through the use of new sensor technologies, remote sensing technologies and data driven models such as machine learning based multimodal soil moisture prediction, the data that are currently being used to support agronomic decisions remain largely disassociated with one another in practice. Therefore, the fragmentation of the current data sets limit the capacity of both the farmer and decision makers to understand the interconnectedness of system-wide processes between soil, water and plant health domains[5].

Therefore, the current limitations on decision making by the farmer, due to the current lack of integration of soil and water related information with respect to crop health, emphasize the importance of developing integrated and coordinated approaches to understanding the complex relationships between soil, water and plant health and developing decision-support tools that will be able to integrate soil, water and plant health information into a single decision-making framework. These types of frameworks will be important in increasing the productivity of semi-arid agricultural systems while reducing the risk associated with environmental degradation and enhancing the overall sustainability of semi-arid agricultural systems[6].

The purpose of this research is to identify the limitations of non-integrated decision-making in semi-arid agriculture and develop a conceptual framework for integrating soil, water and plant reasoning to support semi-arid agricultural decision-making.

2 Limits of Isolated Decision-Making in Agriculture

2.1 Soil only approaches

The main limitation of soil-only based assessments is their reliance on static assessment of physico-chemical properties of soils (pH, Salinity, Texture, Nutrient Availability). Therefore, the recommendations generated by such an approach are static, based solely on laboratory results for specific points within a given field area; or static and based on empirical values developed from existing agronomic standards. Soil-only assessments do not take into account changes in soil properties resulting from changing climate patterns, irrigation, crop growth, and soil/plant/soil interaction effects on crop production[7]. The limitations of soil-only assessments become even more pronounced when assessing sanitary risks related to diseases, which develop in response to dynamic factors in soil moisture levels, increasing salinity levels, or structural changes in soils in semi-arid agriculture. Therefore, while soil-only assessments provide useful initial baseline diagnostics, they are insufficient to enable adaptive and operational agronomic decisions regarding crop management in water limited agricultural settings[8].

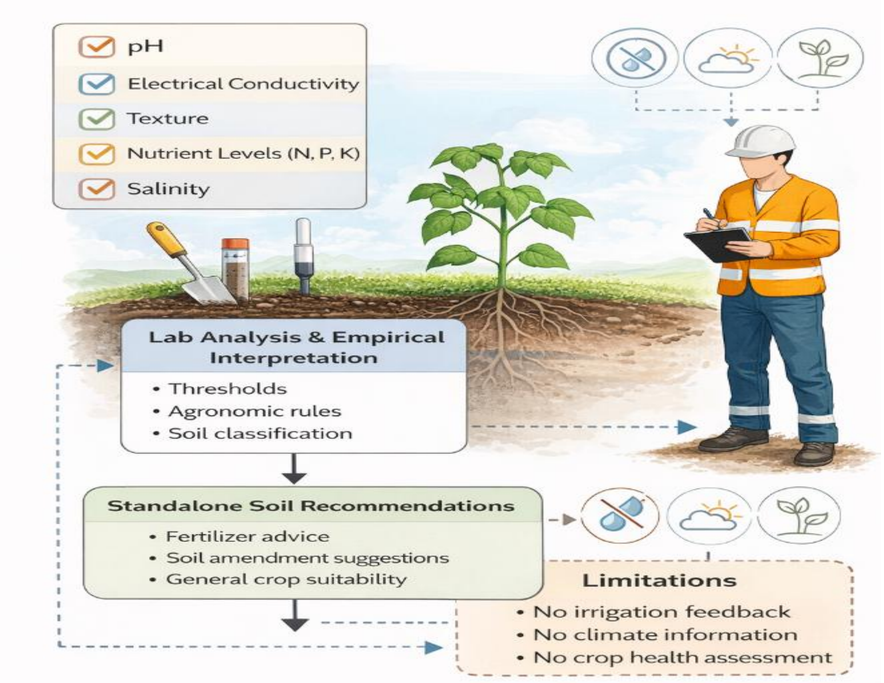

Fig. 1. Conceptual representation of Soil only approaches

2.2 Irrigation only approaches

The use of only irrigation strategies is based upon the optimization of water applications to crops through improved water-use efficiency due to lack of availability of water[9]. The most commonly used approaches for these strategies are based on soil moisture thresholds, irrigation calendars, evapotranspiration (ET) models, and sensor-based irrigation scheduling methods for determining when to irrigate and how much water to apply. The effectiveness of irrigation-only strategies has been demonstrated in semi-arid areas by significantly reducing water loss and preventing excessive irrigation[10].

Despite being effective at optimizing water usage from an irrigation perspective, irrigation-only strategies often ignore the soil and crop health context in which they are operating. Soils have numerous characteristics (e.g., fertility levels, salinity levels, structure) that affect crop water absorption and response to irrigation and are ignored in many cases. Therefore, while irrigation strategies may be hydrologically efficient, they will be agronomically ineffective in degraded or chemically impaired soils[11].
Irrigation-only systems also do not take into consideration the overall health of plants or the presence of diseases. Irrigation can affect the susceptibility of plants to disease and the spread of disease; therefore, this omission limits their reliability under conditions where multiple stresses are present, as is the case in semi-arid agriculture. Due to the complexity of field environments and the limitations of irrigation-only strategies in such environments, there is a significant need for decision support systems that integrate water, soil and plant health to provide optimal management decisions.

Table 1. Main characteristics and limitations of irrigation-only decision-support approaches.

Aspect	Description	Refs
Primary objective	Optimization of water supply and irrigation efficiency	[12]
Typical data sources	Soil moisture sensors, ET models, irrigation calendars	[12]
Consideration of soil properties	Limited or absent	[13]
Consideration of soil fertility and salinity	Rarely integrated	[13]
Integration of crop health and diseases	Generally absent	[14]
Response to combined stresses	Weak	[14]
Performance context	Effective in controlled conditions	[15]
Performance context	Lack of holistic soil–plant–environment integration	[15]

2.3 Disease only approaches

The primary focus of Disease Only Approaches is the identification and categorization of Plant Diseases. These can be identified visually or by using Machine Learning Techniques based on Image Analysis[16]. The recent advancements in Computer Vision and Deep Learning have made it possible to recognize diseases with high accuracy by analyzing leaf images, which has made this method attractive for Rapid Diagnosis and Automated Detection. Alongside these methods, there exist other systems that utilize symptom-based Expert Rules or Historical Disease Records to Support Disease Identification.
Although Disease Only Approaches are successful in identifying disease at both the Leaf/Plant Scale, they are generally developed without reference to Soil/Water Management Strategies[17]. These approaches do not take into consideration soil moisture levels, irrigation practices, or nutrient content as these will affect how and when diseases emerge and progress. Therefore, Disease Detection Outputs generated from these methods are typically disconnected from the Agronomic Factors driving Disease Pressure in Semi-Arid Environments[18].
Additionally, Many Disease-Focused Systems Are Developed to Provide Single-Time Point or Single-Image Predictions; thus limiting the ability to Monitor Temporally or Assess

Populations. This limitation also hampers their ability to Support Operational Decision-Making Where Disease Management is Dependent Upon Overall Disease Prevalence, Stress Interactions, and Evolving Field Conditions. Although Disease Only Approaches are Valuable for Early Detection and Diagnostic Support, Their Isolation Limits Their Ability to Support Integrated Preventive Crop Management Strategies in Complex Agricultural Systems[19].

3 Conceptual Framework for Integrated Agronomic Reasoning

3.1 Systemic Nature of Semi-Arid Agroecosystems

Semi-arid agriculture operates in highly interdependent socio-ecological systems where climate strongly controls changes to soil conditions, water availability and the physical response of plants at the same time. In contrast to humid agroecosystems, semi-arid environments have chronic water limitation, high evaporative potential, and high spatial and temporal variability, all of which increase interactions between sub-systems in an agricultural system[20].

As with other systems, most management actions in semi-arid environments do not act on one variable alone; for example, irrigation acts to alter soil moisture levels and salinity, both of which can affect nutrient availability, root growth and disease susceptibility of plants. Conversely, plant stress will alter the rate of water absorption by plants and create negative feedbacks to the spatial distribution of soil moisture. The non-linear nature of these feedback mechanisms implies that decisions related to managing semi-arid agricultural systems should be made at the system level, i.e., as part of a holistic approach, rather than optimizing soil, water and/or plant characteristics separately.

The overall purpose of this framework is to develop a system thinking approach to understanding how crop yield and risk arise from the interdependence of various sub-systems (e.g., soil, water, plant) and not solely due to the operation of individual components. This approach does not replace specific expertise for each sub-system, but provides a way to coordinate their use in a logical analytical structure that mimics actual field behaviors.

3.2 State-Based Representation of the Agro-System

At a given time t, the agroecosystem is described by three interacting state domains:

- Soil state :

$$S_t = \{\text{pH, electrical conductivity, texture, nutrient availability, moisture}\} \quad (1)$$

- Water and irrigation state :

$$W_t = \{\text{irrigation inputs, timing, frequency, water quality}\} \quad (2)$$

- Plant health state :

$$P_t = \{\textit{growth condition, stress indicators, disease presence}\} \quad (3)$$

These state variables are influenced by exogenous climatic drivers C_t, including temperature extremes, rainfall variability, and evaporative demand. The explicit representation of system states provides a structured basis for integrating heterogeneous agronomic information within a unified decision-support logic.

3.3 Coupled Dynamics and Decision Dependencies

The evolution of the agro-system is governed by interdependent functional relationships:

$$S_{t+1} = f\,(S_t,\ W_t,\ C_t) \quad (4)$$

$$P_{t+1} = g\,(P_t,\ S_t,\ W_t,\ C_t) \quad (5)$$

$$D_t = h\,(S_t, W_t, P_t) \qquad (6)$$

where:

- f (St, Wt, Ct) describes soil dynamics influenced by irrigation practices and climatic conditions.
- g (Pt, St, Wt, Ct) captures plant physiological responses, including stress development and disease susceptibility,
- h (St, Wt, Pt) represents the agronomic decision function generating management recommendations Dt.

This formulation emphasizes that irrigation strategies cannot be evaluated independently of soil constraints, nor can plant health be interpreted without accounting for both soil and water conditions. Disease emergence is thus framed as a systemic outcome rather than an isolated biological event.

3.4 Conceptual Decision Logic

Within this framework, agronomic decision-making is formulated as a multi-criteria reasoning process rather than a single-objective optimization problem.
At each time step, the decision vector D_t is expressed as:

$$D_t = \phi\,(S_t, W_t, P_t, C_t) \qquad (7)$$

Where $\phi\,(S_t, W_t, P_t, C_t)$ integrates domain-specific knowledge (thresholds, empirical rules, or predictive models) while preserving cross-domain consistency.
This approach ensures that:

- irrigation recommendations respect soil chemical and structural constraints,
- disease risk interpretation accounts for water and stress conditions,
- soil correction strategies consider downstream effects on water use and plant health.

3.5 Conceptual Contribution

A broad, independent-of-application and semi-arid agriculture integrative agronomical reasoning framework is offered. The framework does not introduce new algorithms or models but instead will serve as a theoretical structure that can unify a variety of different types of data sources, analytical techniques, and decision-making strategies under one system approach to provide a more generalizable structure than have previously been proposed with respect to semi-arid agriculture.
The proposed framework will address a major limitation of the previous domain-based systems by providing an explicit description of how states interact and evolve temporally, which will include feedback loops, and thus establish a base for future developments in areas such as integrated decision-support, digital agronomy, and sustainable resource management[21].

4 Conclusion

This paper introduced an integrated agronomic decision-making conceptual framework for semi-arid agricultural systems, where plant health, water management, and soil conditions interact and affect one another. The framework utilizes a systems-based perspective that goes beyond analytical approaches used on separate components, and emphasizes interpreting agronomic information within a structured and cohesive whole. This integration is especially important in semi-arid regions, due to increased risk of production caused by joint impacts of soil degradation, climate variability, and water scarcity.

The framework explicitly captures the interactions between the agro-ecosystem through state domains; and incorporates many of the time-related dynamics (e.g., soil health over time) and feedback loops that are frequently ignored in analyses focused on individual component states (disease emergence, irrigation efficacy, etc.). The proposed framework also establishes disease emergence, irrigation efficacy, and soil constraints as coupled processes thereby providing a more realistic basis for agronomic decision support. Additionally, the framework is application independent, and can be applied using different data sources, analytical techniques, and degrees of technology adoption.
On a broader scale, this research contributes to the emerging trend of transitioning from fragmented digital agriculture solutions towards more comprehensive and context aware agronomic decision making. Future research will have the opportunity to use this conceptual model to provide empirical validation, analyze uncertainty, and develop adaptive learning mechanisms that support more resilient and sustainable crop management strategies under water limited conditions.

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