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Essay

Crop simulation models as a tool for agroecosystem analysis

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Abstract

Systems theory aims to contextualize and understand the environment of the human being, with the agroecosystem being a concept that tries to understand the productive processes of goods and services derived from the synergistic relationship between nature and society. The concept has been deconstructed in at least three generations of systems thinking, achieving a more objective and practical vision to be used as a unit of study in the design, management, and assessment of agroecosystems, so it is necessary to have tools that consider the complexity involved in the use of the concept. In this sense, crop models are a viable option to analyze the biophysical aspect of agroecosystems, considering the importance and necessary complementarity of the experiential introspective paradigm to understand the social environment that the cybernetics of production systems entails. This research aimed to theoretically describe the application of crop simulation models in the management and assessment of agroecosystems to contribute to their efficient development.

Keywords:

agricultural systems, modeling, systems thinking.

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Agriculture transformed the life of humanity by moving from nomadic to sedentary forms, and its productive surpluses led to the social division of labor and the increase in the complexity of societies (Harari, 2015). The agroecosystem (AES) approach considers the physical-biological aspects of ecology and the social content of agriculture. The difference between an ecosystem and the agroecosystem lies in the intervention of man as a transformer of the natural ecosystem to obtain products (Gliessman, 2002).

Therefore, this system considers the physical-biological aspects related to ecology and the social, economic, cultural, and political aspects that influence the production of food, goods, and services. This current of thought is based on holism and Von Bertalanffy (1976) general systems theory (GST), whose episteme considers agricultural sciences as an entity interrelated by disciplinary knowledge and adopts a way of thinking based on the totality and its components in order to understand the reality of the productive sector.

In systems, their parts act with a common orientation and purpose, requiring the correct functioning of their elements for their effective performance (Chiavenato, 1997). In analogy, agricultural development is a process of change that impacts the national economic, social, political, and physical structures, as well as the value system and the way of life of the people (Weitz, 1971).

Agroecosystems are complex and when modifying them, their elements and interactions must be considered. Mechanistic crop models (MCMs) are useful in addressing such complexity. These models are a detailed mathematical representation of the physical, biological, and chemical processes in a given crop to understand and simulate their behavior. MCMs are highly detailed and accurate, but they require a large volume of data and a high degree of complexity for their construction and use (Jones *et al*., 2017a).

Most MCMs include a crop management module (Williams *et al*., 1989; Brisson *et al*., 2003; Jones *et al*., 2003), which allows the user to alter the system at will in addition to performing multiple simulations under different management scenarios, extending the prediction capacity with a reduced cost in time and resources. Considering the importance of the AES approach to modify agricultural productivity and the application of MCMs for this purpose, this paper theoretically describes the performance of crop simulation models in the management and assessment of agroecosystems for their efficient development. To this end, the paper includes a description of the evolution of the concept of AES and the theoretical perspective of the functioning and use of MCMs in the management and evaluation of agroecosystems.

The concept of agroecosystem: first and second generation of systems thinking

The approaches of the first generation of systems thinking, such as cybernetics and the theories of operations and information research, were insufficient to address the agricultural reality as they considered the functioning of closed systems. During the second generation of systems thinking, Von Bertalanffy (1976) GST founded agroecology and the agroecosystem as its unit of study.

Agroecology was consolidated through hierarchy to define the object of study through the identification of subsystems, systems and suprasystems proposed by the GST, facilitating the methodological design of the research (Casanova *et al*., 2016). The difference between the two generations lies in the recognition of the complexity of AES, including social, political, economic, and ecological aspects, in addition to its consideration as a conceptual model.

When defining the agroecosystem, historically, the concepts of the authors present similarities and differences according to their current of thought. Hernández (1977) describes it as an ecosystem with gradual modifications to exploit natural resources. Montaldo (1982) emphasizes human responsibility in creating these systems and their sustainability. Hart (1985) considers it a system with species-specific interactions and energy flows. For Marten and Rambo (1988), they are ecosystems modified by man for agricultural and livestock production. Platas-Rosado *et al*. (2017) describe it as an area of study with its own characteristics.

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Regarding the role of man in the agroecosystem, Altieri (1995) highlights their capacity to control and define production. As analyzed by Palacios and Dávila (2023), from an epistemic-scientific approach based on systems theory, systems of equations and under a system of agroecological concepts, in contrast to the doxa of rumorology (electrical, mechanical, and biological systems), agroecosystems need a cybernetic controller (peasant or farmer). These authors pointed to human participation and agricultural production as the essence of the agroecosystem. Where the participation of man, through their decisions, influences its management and assessment, considering the interactions between the ecosystem and agriculture in its processes of change and development, limited by the controller's own or social interests.

The agroecosystem as an autopoietic unit of study: third generation of systems thinking

To fill the knowledge gaps, the contributions of the third generation of systems thinking included Luhmann (2006) theory of autopoietic social systems, whose conceptual and theoretical architecture knows no political-administrative boundaries. It studies, with greater abstraction, the role of economics, politics, and science in the evolution of contemporary agriculture. This construction uses structural tools to understand the complex relationships between society and nature, from the global and the local and from the spatial and the temporal (Casanova-Pérez *et al*., 2015; Cruz-Bautista *et al*., 2017).

As an antecedent to this theory, Loveluck (1985) postulated the Gaia theory by establishing that living systems, such as the Earth, are self-regulating and involve processes of synergism, mutualism, and intrinsic endogenous processes with systemic relationships. Subsequently, Maturana and Varela (2004) introduced the term 'autopoiesis', describing the capacity of living systems to generate and reproduce their own components, maintaining their organization and stability. Therefore, autopoietic systems are those complex systems capable of maintaining and reproducing themselves through a feedback process

For his part, Luhmann (2006), in his theory of autopoietic social systems, extended this concept to those social systems that persist and reproduce autonomously through the continuous production and reproduction of their components, made up of the norms, values, and rules that regulate their functioning. For Vilaboa *et al*. (2006), the agroecosystem is an ecological system modified by man, as a social and communicative entity, whose role determines the use of natural resources in production and analyzes the environment made up of the productive factors.

According to Vilaboa *et al*. (2009), the approach and concept of agroecosystem is an abstract and research model to interpret the agricultural reality. For their part, Bustillos *et al*. (2009) consider the AES as an autopoietic unit, where there is a structural link between man and the environment. Sandoval and Villanueva (2009) consider the AES as a unit of study of agricultural production systems, where humans control natural resources to produce the food and raw materials demanded by society.

Therefore, in agroecosystems, the translocation of energy and energy sources that man modifies in the unit of study occurs under a deliberate process according to the transformation processes of the cybernetic controller. With the evolution of systems thinking in its third generation, the concept of AES, from a Galilean epistemological line (Cruz-Bautista *et al*., 2017), is consolidated as a multidisciplinary approach that integrates cybernetic, theoretical, and methodological aspects to understand and analyze human-nature interaction.

The AES was understood as an autopoietic system, a unit of study and a model that reflects the complexity and interconnection of its own ecological, social, and economic processes. As Altieri and Toledo (2011) point out, the complexity of an AES as a biological-physical-social entity requires transdisciplinary approaches to understand in depth the interactions and processes that influence its functioning.

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From an agroecological approach, it is intended to reconcile the natural and social sciences to understand the relationship between the environmental, economic, and social processes that affect the structure and function of the agroecosystem. In this sense, Altieri and Toledo (2011) propose that agronomists understand the sociocultural and economic elements of agroecosystems and, in turn, social scientists receive feedback from this. In the context of contemporary agriculture, the agroecosystem must be studied as a whole, recognizing the human being and their social context as an agent of change in decision-making.

For this study and considering the different systemic approaches, the following concept is constructed: the agroecosystem is a model of reality that studies ecosystems modified by man to produce food, fibers, and other agricultural products. Its study, analysis, and complex management requires a transdisciplinary approach to understand the relationship between the physical, biological, and social processes that affect its structure and function.

It is dynamic, depending on environmental changes and human actions. It is characterized by its autopoietic property, which involves the exchange of matter and energy with the outside. The analysis of its physical-biological and technical aspects is carried out using mechanistic crop simulation models that consider different environments or scenarios.

Mechanistic crop simulation models: design, management, and assessment of agroecosystems

Reality has been approached from various philosophical perspectives throughout history. Plato held a dualistic vision where the intelligible world of ideas and forms represents true reality, contrasting with Aristotle's theory that empirically observes the sensible world (Aguirre, 2015). In the Middle Ages, Thomas Aquinas defended that reality is created by God and is known through reason and divine revelation (Thomas, 2020).

During the Enlightenment, philosophers such as Descartes proposed a theory based on methodical doubt and reason, arguing that true reality is known through empirical evidence (Descartes, 2012). Kant, on the other hand, proposed a Platonist theory where reality is constructed by the human mind through a priori categories and concepts (Kant, 2020). In the twentieth century, existentialists such as Heidegger and Sartre argued that reality is subjective and experiential for the subject (Sartre, 2006). From the perspective of the GST, it is recognized that reality is complex and is composed of multiple levels and types of interconnected systems in constant evolution (Von Bertalanffy, 1976).

One strategy to address the complexity of reality is model building. According to Galagovsky and Aduriz-Bravo (2001), a model is an abstraction that seeks to represent reality by predicting phenomena through a system of analysis. Boccara (2004) defines a model as a simplified mathematical representation capable of capturing key elements of the system.

AESs, being part of human reality, are complex and involve interrelated physical, biological, and social processes along with objective and subjective issues. To understand and modify AESs effectively, it is necessary to approach them holistically, identifying their interconnections, subordinations, and process feedback, as well as the subjectivities of the handler such as culture, scale of values, priorities, or desires.

Agricultural simulation models, used in the productive sector to support decisions, calculate, forecast, and assess environmental and resource management aspects, considering the spatial variability of the soil and meteorological conditions (Sargent, 2013). According to Leiva (2008), these models are tools to understand scenarios of physiological, environmental, and human interactions in agricultural AES cycles, allowing the planning of tasks to achieve expected yields and evaluate environmental impacts.

Agricultural simulation models also facilitate the assessment and improvement of management practices, the prediction of impacts, and support in decision-making processes. Some integrate multiple submodels to simulate multiple crops or improve yield assessment, while others incorporate Geographic Information Systems (GISs) for accurate zoning of productive potential (Carvalho-Lopes and Steidle-Neto, 2011).

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Simulation models for crop growth are fundamental tools for assessing productivity in relation to various factors based on changes in climate (maximum daily temperature, minimum daily temperature, daily precipitation, solar radiation, relative humidity, etc.), edaphic issues (texture, pH, cation exchange capacity, albedo, USLE K, organic matter content, electrical conductivity, hydraulic conductivity, depth, number of horizons, etc.), physiological parameters (canopy height, leaf area index, efficiency in the use of radiation, sunlight reflection factor, stomatal gas exchange, ideal maximum and minimum temperature, harvest index, etc.) and management (planting date, dates and type of cultural operations, fertilization dose dates, harvest date). Examples are the following crop models: Epic (Williams *et al*., 1989), Swat (Arnold, 1998) and Dssat (Jones *et al*., 1998).

Although current models do not address all the complexity of an AES, they do manage to predict the behavior of crops under different scenarios. These models represent the system's key variables in a simplified way, using symbols, diagrams and equations to mimic how they work and obtain predictive results.

Creating a crop model involves defining the system, establishing boundaries between the inside and the outside, as well as drawing up a flowchart with inputs, interconnected processes and outputs. Through the model, the development of the AES is simulated from initial conditions and input variables, evaluating the effect of various measures with low costs in time and resources.

Simulation models, compared to descriptive models, offer significant advantages by allowing us to understand the relationships between components and predict manipulation effects. These models can be statistical, based on historical data, limited to specific geographic areas and temporalities, or based on physiological processes to mimic environmental influence on crop growth and yield (Lobell and Asseng, 2017; Jones *et al*., 2017b).

Process-based crop models represent mathematical equations that describe the plant's internal processes and interactions with its environment (Kephe *et al*., 2021) or are tools that use mathematical equations to describe crop growth, development, and yield, influenced by environmental conditions and management practices (Chenu *et al*., 2017).

The development of process-based crop models dates back to the 1960s, ranging from simple equations for estimating yield to complex integrative platforms, such as Dssat (Jones *et al*., 2003) or Stics (Brisson *et al*., 2003), and even three-dimensional models such as Hi-sAFe (Dupraz *et al*., 2019) to simulate complex agricultural systems. This evolution has been driven by advances in computational capacity and cost reduction.

According to Basso *et al*. (2013), process-based crop simulation models can be mechanistic or functional. Mechanistic models rigorously represent the physiological processes of crops, using detailed data, such as light interception and canopy gas exchange (Farquhar *et al*., 1980), whereas functional models, such as the radiation use efficiency index (Asseng *et al*., 2019), are more simplified and require more general data.

According to Jones *et al*. (2017b), the development of process-based crop models is motivated by both scientific understanding and support for policy decisions. Mechanistic models focus on scientific understanding, whereas functional models are more useful for the design, management and evaluation of agroecosystems due to their less complex approach and requirement of fewer specific variables.

Based on what Candelaria *et al*. (2011) mentioned, crop models do not directly represent the AES in its entirety, but are a simplified representation of the crop subsystem. AES encompasses biophysical, social, economic, and cultural phenomena that cannot be fully included in a crop model, affecting decisions about what to simulate and how to interpret the resulting information.

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Conclusions

The concept of agroecosystem is a historical abstraction influenced by the understanding of natural and social systems. Since the emergence of the GST, there has been an attempt to understand the processes involved in the relationships between society, nature, and the production processes of goods and services. As it is an abstraction, the origin of the concept has transcended through hypotheses and the currents of thought of various authors who have justified the use of the concept according to its episteme. The concept evolved by the feedback of ideas from each author according to their temporality.

In the first and second generations of systems thinking, the relationship between human beings and ecosystems was considered, and then society and its environment were included. With the theories of autopoietic social systems of the third generation, the agroecosystem was understood in a more feasible and objective manner, usable as a unit of study and less fallible; achieving a more objective conceptualization and an interpretation close to the reality of the agronomic and social environment.

The design, management, and evaluation of AES require tools that involve and encompass the complexity involved in the use of the concept. From the perspective of the inductive empirical approach of the Galilean line, crop models are a feasible option for the analysis of agroecosystems in the biological-physical field, without forgetting the tools of the experiential introspective line immersed in the social environment that the cybernetics of production systems entails.

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