On the Use of Agent-Based Modeling for Smart Farming

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***Abstract*—In this paper, we investigate the possibility of using Agent-Based Models (ABMs) for describing a crop growing system. Even though ABMs have received increasing attention for modeling ecological systems, their use in modern farming is still limited. To develop such a model, a proper definition of the plants as agents can be provided following a standard protocol named ODD (overview, design concepts, and details). This description allows to define complex interaction between environment (e.g., soil, climatic conditions, and limited resources) and plants, and between plants. To validate this preliminary development, a comparative study is achieved with a classical crop-modeling environment, i.e., AquaCrop, using potato plants as sample crop.**

***Index Terms*—Mathematical modeling, ODD protocol, agricultural systems, Netlogo.**

I. INTRODUCTION

Agriculture and food production are global concerns. From local farmers to governments and global organizations there is a consensus about the need to ensure adequate food for everyone around the world through sustainable agriculture [1]. However, agriculture faces different challenges depending on the country, e.g., weather and resource availability. Traditionally, when the concept of control is used in agriculture, it is related to management strategies and activity planning, to support decision-making, increase production, and maximize economic benefit. All the above mentioned actions are made off-line, based on historical data, in order to analyze and assess production scenarios. As all models use data to calculate or predict an output, it is essential to have as much information as possible at hand. However, data are not always readily available, and research has been dedicated to the development of models based on minimal information while maintaining coherence between reality and modeling assumptions [2] ,[3], [4], [5]. An approach to tackle the scarcity of data is to use learning strategies (e.g., Bayesian networks [6]). Another one is to collect information from existing models [5]. On the other hand, new sources of data are offered by the exploitation of aerial images. However, these images do not provide all the necessary information and require signal processing.

To develop dynamic models an appealing approach is the use of Agent-Based Modeling (ABM), which is particularly adequate to model large and complex systems involving independent, non-homogeneous, and non-connected actors [7].

Over the last two decades, agent-based models have been applied to agricultural processes mostly in cases where the main objective is economical [8] or when stakeholders interact with the environment [9]. A novel approach is to interpret plants as agents, and a first step was made by [10]. The objective of this study is to assess the potential use of ABM to represent a crop growing system, and its potential application to farming system optimization and control.

This paper is organized as follows. Section II introduces crop growing systems and the variables/parameters characterizing such systems, as well as a classical modeling environment, i.e., Aquacrop, which will be used as a reference for comparison purposes. In particular, it is expected that AquaCrop predicts the average behavior of a multi-agent system with uniform properties. In section III, the properties of agents are defined and an ABM model is built using the software Netlogo [11] following the ODD protocol [12]. In section IV, a comparative study is achieved, while section V draws some conclusions and perspectives.

II. CROP GROWING SYSTEMS

Agricultural models have traditionally been developed to understand how inputs, management schemes and climatic variations affect production. However, to define production and understand how it can be controlled, it is necessary to understand how it is created. Therefore, a bottom up description is required. This description will be made avoiding entering into details of the biological and microbiological processes that are beyond the scope of this work.

Basically, the crop is generated from raw materials such as seeds, soil, and water, and depend on environmental conditions. Each of these components is characterized by multiple variables (that can sometimes be measured). For instance, the soil has characteristics such as consistency, water retention capacity, level of nutrients and temperature (which are especially important in the germination stage). The environment conditions include temperature, humidity, and the amount of active radiation for photosynthesis. If the crop is small and is cultivated in a controlled environment, e.g., in a greenhouse, most of these variables can be manipulated to control the growth and development of plants. However, when the process

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takes place in an open field and on a large area of land, it does not make sense to control each of these variables separately.

Since the internal variables of agricultural systems can hardly be manipulated (e.g., the amount of nitrogen uptake by plants or the amount of radiation used in photosynthesis), the most convenient way to change the growing performance of a crop is to manipulate the independent inputs (e.g., irrigation, fertilization and herbicide among others). These limitations, in addition to the need of measurements of soil variables and internal plant processes variables, constrain the control strategies. However, there are highly developed and documented strategies for independent input variables [13]. On the other hand, if the internal variables are not available one possibility is to consider each plant as an entity with properties and behaviors,i.e., as an agent.

Common models of agricultural systems are associated to a software package. These packages come with specific functionalities and allow the user to define a complete simulation scenario for crop management, decision-making process, or investment budget [3]. A popular software is AquaCrop, which is a crop growth model developed by FAO to evaluate the environmental impact of water use on crop production. AquaCrop simulates the biomass and yield response of crops to water [14]. This model performs four computational steps: i) green canopy cover, ii) crop transpiration; iii) above-ground, biomass, iv) crop yield.

In this work, AquaCrop is used as a reference model for two reasons. First, it assumes the homogeneity of the plants in the crop and this characteristic allows increasing the size of the field. Second, as a mechanistic open model, it is easy to change crop performance.

III. Agent-Based Model

An agent is an entity with properties and characteristics that allow it to interact in an environment with other agents. These characteristics are assigned individually and depend entirely on local information known by the agent. This allows agents to make decisions or actions to reach their objectives. On the other hand, the properties are assigned as rules of interaction with other agents, which allows to create a collective behavior based on independent behaviors. In general, agents are defined by:

- agents are identifiable, i.e., they are part of a discrete set;
- agents are heterogeneous;
- agents are space-aware in an environment;
- agents are able to make autonomous and independent decisions;
- agents interact with the environment in which they are immersed.

A model composed of a combination of agents in an environment, under a set of rules of interaction and behavior is considered an agent-based model.

In order to assess an agent-based crop model, an implementation is achieved using Netlogo. Among the advantages of using this platform to implement an agent-based model are the low model development effort plus the computational strength and scalability [15]. In this model, every plant is an agent and every portion of soil where is located a plant is a patch.

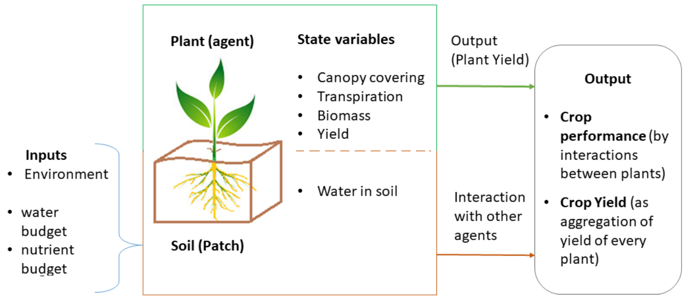

Fig. 1. General diagram of the proposed model following the description suggested by ODD protocol.

As the aim of this work is to assess the potential use of ABMs, a broader description is provided and an overview of the model is given in Fig. 1.

In [12], the authors propose a standard protocol named ODD (i.e., *Overview, Design concepts, and Details*) for individual and agent-based models. Below is the description of the model following the ODD protocol.

A. Overview

1) Purpose: The main goal of this crop growing model is to develop a structure based on agents suited for dynamical systems that allow an application of a control technique to improve its performance (e.g., increase the crop yield, control the nutrients level, optimize the consume of water or make a prediction over the crop performance subject to climatic changes).

2) State variables and scales: In the ODD protocol, the definition of the state variables is related to the lowest level of variables that are needed to fully define an agent. These variables are related to parameters that can be measured or quantified directly. However, if only those variables are considered (i.e., humidity, temperature, amount of water in the soil, amount of active radiation, etc.) it is not possible to define the growth of a plant. If, on the other hand, variables such as the amount of water available in the soil, the development of green foliage, the transpiration of the plants, the amount of biomass and the crop yield are selected, it is possible to define the growth and development of a plant every day. For this reason, in the model the state variables are i) the amount of water available in the soil W; ii) the green canopy covering CC; iii) the transpiration of each plant Tr; iv) the amount of biomass per plant B; and v) the individual yield per plant Y. All the state variables have a numerical value during the phenology stages (i.e., sowing, germination, anthesis, maturity and harvest), and every phenology stage has a duration in days in a known interval.

3) Process overview and scheduling: To perform the schedule of the model, a general algorithm is presented in Algorithm 1. It is important to mention that despite all variables are updated daily, the agents must perform this algorithm in strict order because the highly dependence on the agent-environmental relationship that governs the interaction between agents.

Algorithm 1

Initialization of global variables
Setup soil enviroment
Setup plant variables
for $0 < t \leq$ crop-maturity-time **do**
  Calculate stress factors
  if $W <$ water field capacity **then**
    $W \leftarrow$ water balance
    $Ks \leftarrow$ water stress factor
    $Kpp \leftarrow$ interaction-factor
  else if $W \geq$ water field capacity **then**
    crop is flooded
    Stop and report to user
  end if
  Plant procedures
  Calculate green crop canopy
  if $t < senescense - time$ **then**
    $CC \leftarrow$ green crop canopy
  else if $t \geq senescense - time$ **then**
    $CC \leftarrow$ natural crop decrement
  end if
  Crop transpiration
  $Tr \leftarrow (Ks * Kpp * CC * ET_0)$
  $B \leftarrow$ biomass
  $Y \leftarrow$ plant yield
end for
Calculate crop yield

B. Design concepts

1) Emergence: The behavior of each plant is determined by deterministic rules that consecutively link the state variables. However, given that each agent can have different parameters, the behavior of the crop emerges from the combination of individual co-behaviors.

2) Fitness: The fitness of each individual is guided by the crop yield. This yield is the most relevant characteristic of individuals, as well as their contribution to the whole crop performance.

3) Sensing: Individuals know the values of the parameters and variables that allow them to calculate the state variables.

4) Interaction: Individuals interact with their neighbors within the radius of influence (i.e., if the distance is less than 50cm for the test model). The interaction is related by the parameter Kpp. This interaction directly affects the budget of water and nutrients available to each plant during its development. Therefore, its impact is greater in the stages of growth and maturity.

5) Observation: For the model test, each one of the state variables is verified every day to observe the behaviors between plants and the general crop behavior. Only the crop yield subject to the water budget is observed to assess the model.

C. Details

1) Initialization: A limited set of individuals is created in a specific location inside the field. All plants are supposed to be at the same distance from each other. Then, all global parameter are defined based on the particular crop selected. In addition, for general purposes, environmental conditions are assumed the same for all agents. The differentiating values for agents are the budgets (i.e., water and nutrients). Due to the water budget is the first state variable, every agent will start with the calculation of this value. The next step is set the other four state variables to zero. The initial time ($t = 0$) is the time in days after seeding or after transplanting.

2) Input: Irrigation and rainfall are the main inputs. Irrigation is assigned according to the schedule established a priori. However, the agent-based model seeks to determine the best possible irrigation scheme, taking into account the scarcity of water resources. On the other hand, rain is considered as a stochastic input. Although for validation cases, the historical values of rainfall are considered in the region where the test crop is located.

3) Submodels: The water balance W available for each plant is given by

$$W = W_0 - Wc + Irr + Rain \tag{1}$$

where W_0 is the amount of water after sowing or transplanting each plant. W_c is the amount of water consumed by the plant or drained from the soil each day. It is affected directly by the interaction factor Kpp. Irr is the amount of daily irrigation and $Rain$ is the value of daily rainfall.

The remain four state variables are calculated taking as reference the AquaCrop development equations as follows: To compute green canopy cover, a set of initial parameters must be given to the setup and then the software build a salt and water budgets.The green canopy cover development CC is computed combining an exponential growth when $CC \leq CC_x/2$ and an exponential decay using when $CC > CC_x/2$.

$$CC = CC_0\, e^{tCGC} \tag{2a}$$

$$CC = CC_x - 0.25 \frac{{CC_x}^2}{CC_0} e^{-tCGC} \tag{2b}$$

where t is the time in days since the transplant. CGC is the canopy growth coefficient which is up to the salt and water budgets. CC_x is the maximum green canopy cover and CC_0 is the canopy cover at 90%.

After obtaining canopy growth and collecting climatic information, crop transpiration is calculated as

$$Tr = Ks\, Ks_{Tr}\, CC^*\, ET_o \tag{3}$$

where ETo is the atmospheric evaporation capacity, Ks_{Tr} represents the stress by temperature and Ks is the stress coefficient related to the amount of water available in the soil. This coefficient changes its value in the interval $[0\ 1]$. It takes a unitary value when there is no stress that is, above the water field capacity and goes to zero under complete stress, which means close to the permanent wilting point. Equation (3) allows us to interpret how the water balance in the plant changes from the changes in climatic conditions and the water demand when the crop begins top grow.

Given Tr the next step is to calculate dry biomass (above-ground) each day. This is given by

$$B = WP^* \sum \frac{Tr}{ET_o} \quad (4)$$

where $WP*$ is the crop biomass water productivity normalized for ETo and the air CO_2 concentration. And a cumulative transpiration factor weighted by the atmospheric evaporation power ETo.

Finally, the last step is the calculation of crop yield as follows

$$Y = f_{HI} HI_0 B \quad (5)$$

where B is dry above-ground biomass, HIo is the reference Harvest Index and f_{HI} is an adjustment factor for other stress effects.

Taking into account that (2 to 5) are given for the crop and not for each plant, it is necessary to disaggregate them and scale some of the parameters used. However, (4) and (5) are applied directly and both the biomass and the yield of the entire crop are calculated by accumulating the individual value of each of the plants.

Kpp interaction factor: it is computed based on spatial and input conditions (i.e., distance between plants, distance between rows of plants, slope of crop, fertilization and irrigation scheme). It has a direct impact in the water budget of every plant under water stress cases. Moreover, if plants density is high (i.e., more than 4 plants per square meter) and terrain slope is high (e.g., more than 20 degrees) the effect of this parameter is strong in the development of CC.

IV. VALIDATION

To evaluate the model performance, a potato crop is selected for all practical purposes. It is selected because potato crop is highly sensitive to the amount of water in the soil [16].

The test scenario to perform the validation is a one-hectare field. This land does not have slope and the type of soil is silty mud. For the agent-based model, a density of four plants per square meter is considered, meaning that each plant is separated 0.5m from its neighbors. All the simulation parameters used for the agent-based model are presented in Table I, as are suggested in [14] and [16]. For this test, irrigation schemes or climatic variations are not considered.

Since each plant represents an agent and each agent has its own parameters. This is mainly reflected in the effect that different stress constants have on the consumption of water and nutrients. However, for this first version of the agent model, all agents are considered homogeneous.

TABLE I
REFERENCE SIMULATION PARAMETERS

Parameter	value	Unit
GCC	0.26994	–
CC_0	0.0015	$m^2\ m^{-2}$
CC_x	0.87	$m^2\ m^{-2}$
CDC	0.02781	d^{-1}
CO_2	369.41	ppm
T_{avg}	20	$^\circ C$
ET_0	5	$mm\ d^{-1}$
WP	18	$g/m\ m^2$
HI_0	75	%

For the evaluation of the proposed model, each one of the state variables is analyzed individually. The first state variable is the amount of water available in the soil W. This variable is directly related to the environment and is the only one that is calculated as a patch procedure. In Fig. 2 the comparison between the behavior of the water balance is shown for reference model in continuous line and on dotted line for the agent-based model. Both behaviors exhibit a different dynamic, but their tendency towards water depletion is similar. This is because the reference model takes into account other soil parameters (e.g., consistency, density, and distribution of salts among others). In addition, it is possible to identify how each of the phenology stages evolves every time that there is a change in the dynamics of water balance. On the other hand, the agent-based model only has a rule of mass conservation, which makes it little sensitive to phenology stages.

The second state variable is the development of green canopy cover CC as seen in Fig. 3. The solid line indicates the behavior of the variable in the reference model and the line punctuated the behavior of the agent-based model. The calculation of this variable requires few parameters and is relatively easy to obtain. This is why the two graphs present

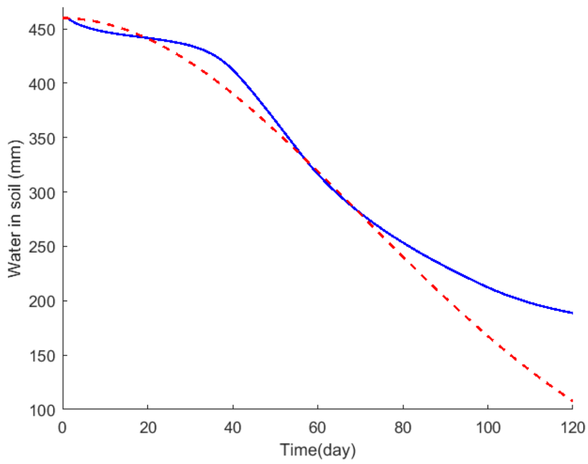

Fig. 2. Water available in soil related to the deep of root zone. Both models start from the same field capacity and shown a decreasing tendency. Solid line represents the reference model and dotted line shows the results for the proposed model.

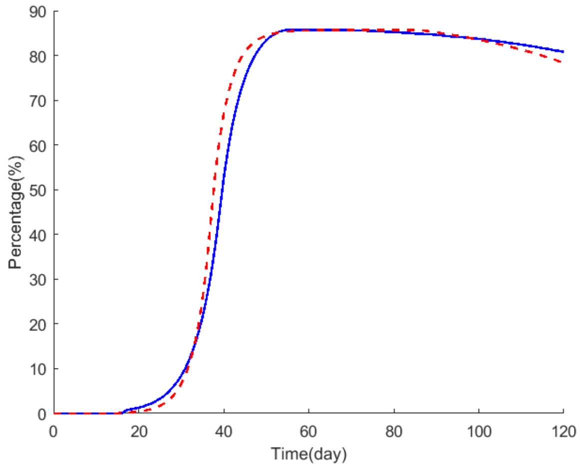

Fig. 3. Green canopy coverage CC. Solid line represents the reference model and dotted line shows the results for the agent-based model.

a similar dynamic. The differences occur mainly because the stress caused by crop transpiration is not taken into account in the agent-based model. Figure 4 shows the behavior of crop transpiration Tr. The behavior is similar but once again, the difference between both is that the reference model takes into account all the environmental and stress parameters of the plant, and the simplified agent-based model does not. This has a direct effect on the other two state variables. Finally, Fig. 5 shows both the biomass and crop yield of the reference model in solid lines and the model proposed in dotted lines. At this point, it is clear that the accumulated differences of the previous state variables make the dynamics different, even when the trends are similar, these do not reach exactly the same final values. The main reason is that the production of biomass stagnates because the plants stop transpiration.

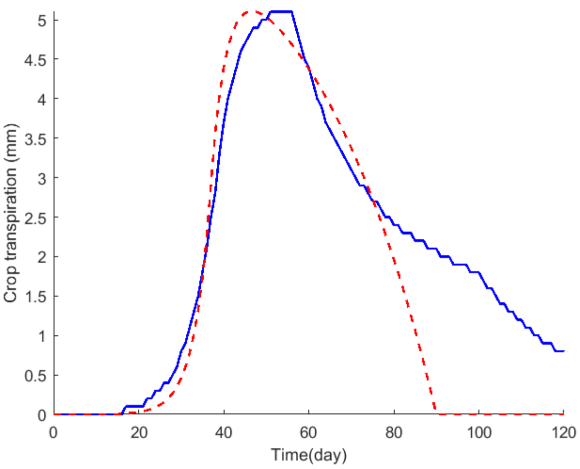

Fig. 4. Crop transpiration. The continuous line represents the reference model and dotted line shows the results for the proposed model.

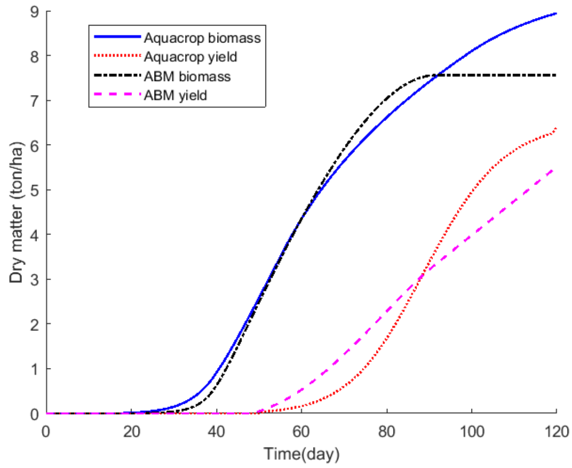

Fig. 5. Biomass and crop yield.

Consequently, both the biomass and crop yield in the proposed model are lower.

The AquaCrop model is aimed at interpreting the development of a crop subject to changes in the global water and nutrient budget in the soil. It is based on more than 140 equations that describe the different processes and reactions necessary to develop organic matter. On the other hand, the agent-based model seeks to interpret crop yield from the individual development of each plant. This implies that each plant can have a different budget of water and nutrients. Additionally, the development of each plant is heterogeneous because it is conditioned by its spatial location. Finally, the overall yield of the crop based on agents is the weighted average of the individual development of each plant.

In the growth of each plant, the relationship between it and the environment is involved. This means that although the water budget (i.e., the contribution of irrigation, rain, drained water, runoff and evaporated water) and nutrients are related to the soil and its calculation is done outside of each agent, its effect is direct. Additionally, these budgets are affected by the density of plants sown per square meter among other spatial parameters. Therefore, it is necessary to include this parameter of relationship between neighboring plants. In the agent-based model, the parameter is Kpp. The Kpp factor allows to establish the dynamics between the plants and the environment. This relationship is always convex between neighboring plants within the radius of influence of each plant.

V. CONCLUSIONS AND FUTURE WORK

ABM is proving to be a good approach to a crop system from control systems perspective due to its structure traits and flexibility. Even with a limited set of crop model parameters, it is clear the similarity with the results of the full AquaCrop model in standard conditions (i.e., no seasonal, soil characteristics and climatic changes are included).This shows that the model is suited to increase the crop yield by optimizing water usage. Nevertheless, to provide a proper fertilization scheme, an extended version of the software model must be developed. To enhance the application of this model, it will be necessary to include additional stress parameters mainly related to soil and consider diverse weather scenarios. The proposed model provide a framework to identify and interpret crop properties that cannot be defined a priori with a limited set of data (e.g., soil water depletion) but require a larger set of scenarios combining different levels of agents behaviors to enhance its performance.

On the other hand, one of the promising trends with ABMs is the flexibility to allow heterogeneous agents, which could be seen as a combination of two or more species of plants for instance to reduce some plagues or diseases effects or, to consider differences in the soil across a large field. This heterogeneity is an advantage over AquaCrop and it remains unexplored, despite the economic and technical implications.

As future work, several improvements in the agent definition should be made as well as changes in the way that environmental processes are defined to allow the inclusion of climatic variables. Although, a diverse series of tests must be run with different initial parameters to identify which rules or properties in agents can be updated. This will allow a robust model definition and suited for specific applications.

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