BIO Web of Conferences **93**, 02015 (2024) https://doi.org/10.1051/bioconf/20249302015
Forestry Forum 2023

Simulation model of crop yields

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Abstract. The article identifies the factors that affect the yield of crops grown in the open ground. Most factors are random in nature, which depending on a variety of conditions can positively or negatively affect crop growth processes. To predict the strategy for growing plants to maximize possible yield requires the development of simulation models that allow repeated virtual experiments, taking into account changes in a variety of parameters. This justifies the need for the study to be conducted. The use of structural analysis methods allowed to establish key objects and processes affecting all stages of plant development, to determine the links between them and the rules of interaction. Based on this, a model of system dynamics was developed, reflecting the processes of plant transition from one state to another, and the parameters affecting the speed of such transition. The developed model can be used as the basis for an expert system that manages agricultural processes.

1 Introduction

For planning and decision-making in agricultural production, process modeling is important in order to reliably predict crop yields [1, 2]. Agriculture is an industry characterized by difficult predictability of results, as it depends on many factors, among which natural-climatic conditions and anthropogenic factors should be emphasized. Meteorological conditions affect soil processes, change the dynamics of plant nutrient uptake, provoke the active spread of pests, etc. Weather conditions have a point-and-impermanent character, which has a significant impact on the crop at all stages of its formation [3].

In addition, the quality of technological works related to seed preparation for sowing (e.g., dressing, encrusting), sowing, periodic maintenance works (e.g., rolling, harrowing, protective procedures, fertilization, watering) influences the formation of the plant. These activities depend on the climatic conditions of the area where the crop is grown, seasonality, current weather conditions and quality of planting material [2]. Comprehensive yield assessment and forecasting requires processing of a large amount of historical data (to account for meteorological factors), current indicators from the place of cultivation (e.g., current weather conditions, soil conditions), which is possible using specialized software [4].

When developing such software tools to work with heterogeneous data, universal rules and relationships characterizing the problem domain are required [1, 5]. For this purpose, models are created that simulate objects and processes of the corresponding domain,

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capable of predicting changes in their states with a certain probability [2, 6, 7]. The obtained tools are characterized by the effectiveness of their application, adaptability and efficiency [1].

Thus, the purpose of the study is to develop a model that performs prediction of crop yields. This requires performing the tasks of identifying key objects and processes affecting crop yield, establishing their qualitative characteristics and rules of interaction, and formalizing the obtained results.

The theoretical significance of the study lies in the systematization of heterogeneous data and their formalization for use in research and development related to the digital transformation of agriculture. The practical significance of the study lies in the creation of a tool, the use of which makes it possible to develop control actions that correct the processes of plant cultivation.

2 Materials and Methods

The analysis of studies on similar topics has shown that to perform the formulated tasks requires the step-by-step use of general scientific methods related to simulation modeling. As Kulibaba [8], Boote [2] and Craufurd [6] point out in their works, the creation of an accurate model of the subject area requires obtaining a description of its key aspects affecting the change in the system states. For this purpose, the study makes comprehensive use of structural analysis, stepwise refinement, synthesis and grouping methods. With their help, the objects and their qualitative characteristics affecting germination, growth, formation and maturation of agricultural crops were established.

The obtained results became the basis for a simulation model, which is created by using the method of system dynamics. In the works of researchers it is noted that objects for such models should be described using a system of differential equations or using the language of simulation modeling, which is based on approaches based on the graphical technique of structuring the modeled dynamic processes [1, 3]. In the ongoing study, the methodology of graphical modeling is used, with the help of which the objects and structures of cause-effect relationships of the functioning of a complex dynamic system are shown using the graphical notation applicable to flow diagrams. The concept of Forrester's model was used as the basis for the rules of flow diagram construction, which allows to show the system dynamics in the form of its structure consisting of interacting flows and feedback loops.

3 Results

The use of the stated research methods allowed us to establish all the necessary objects for the creation of the system dynamics model. The main object, whose states are of key importance, is an agricultural crop. Such a crop is in the following states in order to obtain a harvest:

1. Seed state. The interval of time that is characterized from the moment of readiness for planting (after storage, treatment before planting and getting into the ground).
2. Growth state. The longest interval of time that begins from the time the seed enters the soil, forms into a plant, matures and is ready for harvesting.
3. Harvest condition. The moment of harvest time, which comes depending on the peculiarities of maturation of a particular plant, climatic and technological features of harvesting.

Fig. 1 shows the developed model of system dynamics of crop change, according to the specified states and parameters affecting the rate of each change.

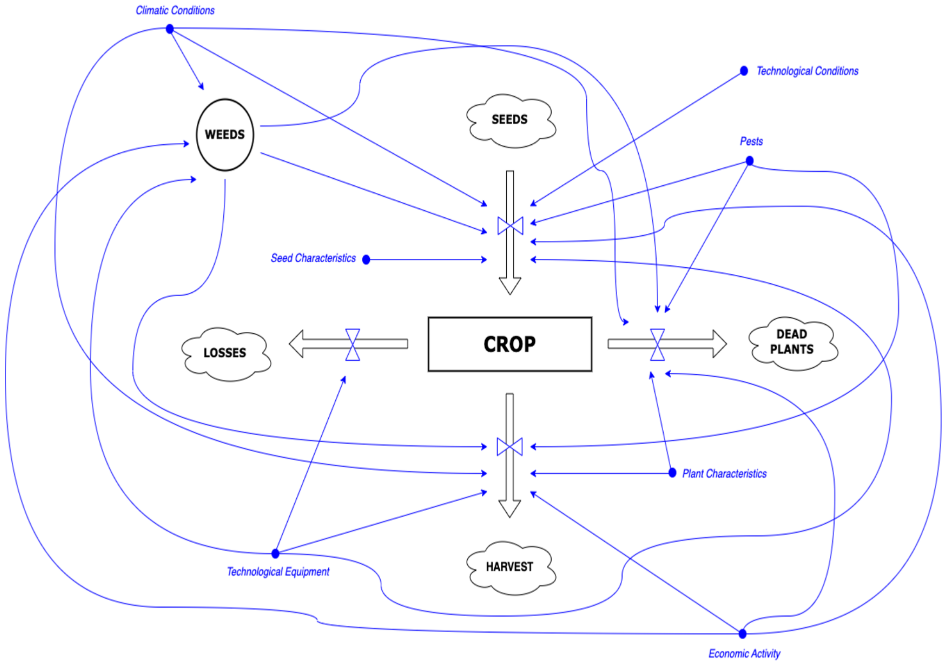

Fig. 1. System dynamics model of an open-pollinated agricultural crop

Let us present a brief description of the features of each of the state transitions:

1. Transition from seed to plant. Starts at the moment of entering the soil and ends at the moment the plant completes maturation. The slowing down of this process is influenced by climate-related parameters. Accordingly, coefficients related to:

- with growing conditions: geographical (soil composition, seasonality, air humidity, duration of illumination, etc.) and current weather conditions (windiness, soil humidity, temperature regime, etc.);
- with technological equipment of the farm, which determines the coefficients of seed spoilage at planting, marriage and spoilage of emerging plants when treating them against pests or weeds.
- with economic activity related to coefficients of negative impact on plant quality from human activity (presence of nearby sources of emissions, soil, air or water pollutants, excessive fertilizer application).
- with the number of pests, i.e., the presence of microorganisms, insects and animals that can harm both seeds and the unformed plant (e.g., consumption, parasitism, etc.).
- with the number of weeds that retard the formation of the plant due to competition for resources needed for its growth (nutrients, light, area) and the extent of their reproduction.
- with the plant variety, determining the coefficients of germination, longevity, resistance to diseases.
- with technological peculiarities of seed preparation for planting (e.g., presence of impurities in the planting material, degree of dressing).

2. Transition from mature plant to harvested crop. Includes the harvest period and the time of implementation of the relevant technological processes (until transportation to the place of sorting or storage). Such processes depend on the following parameters:

- plant characteristics (yield, resistance and susceptibility to diseases);
- economic activity (time and methods of harvesting, degree of influence of anthropogenic factors affecting crop quality);

- technological equipment (degree of use of specialized means in the harvesting process);

- climatic conditions related to the terrain (e.g., length and frequency of seasons) and current weather conditions affecting the frequency and duration of harvest (e.g., probability of precipitation, strong winds that increase the amount of lost yield);

- The presence of weeds that reduce the usable area of crops and lead to soil decline;

- the presence of pests or animals that consume the crop.

3. Transition of a plant into a state of loss. The rate of transition from one state to another depends on the use of machinery during harvest. Faulty or outdated machinery may damage the crop during harvest such that it is not suitable for further processing. The parameter affecting the rate of transition should take into account the depreciation characteristics of the machinery used.

4. Transition of the plant to a state of natural death. The death of a plant can occur at any moment of its formation or waiting for harvesting. This is due to unfavorable current climatic conditions, economic activity (lack of proper care of crops, excessive influence of anthropogenic factors). As a consequence, plants become susceptible to diseases, spread of pests and weeds. At the same time, the rate of plant death from the above factors depends on its quality or variety.

Each of the parameters specified in the state transition processes slows down or speeds up the corresponding process. Such parameters have a quantitative value and are determined by tables, for example, containing a description of the characteristics of a particular crop, peculiarities of the area where they are grown.

An additional element of the model is the number of weeds, which influence almost all transitions of crop states. The model does not separate the nature of weed emergence into the crop area (on the hair of a wild animal, with the wind, as an admixture in planting material, wild seedling, etc.). All this does not matter, because the formation of a crop is affected only by the presence of the weed, its reproduction rate, the nature of its growth (e.g., occupied area), resistance to weather conditions and technological means of its destruction. Thus, all the above factors are grouped into groups of parameters that influence the rate of change in the number of weeds, which include climatic conditions, management activities and technological equipment.

4 Discussion

The developed model corresponds in its characteristics to those models obtained as a result of related studies. Such models are characterized by the identification of the key process, its analysis and creation of a digital twin that reproduces all the characteristics of the corresponding object of the real world [7, 8]. At the basis of the created model, the process related to obtaining the yield of agricultural crops when growing in the open ground is realized. For this purpose, all objects and relations between them affecting the rate of change of the process are established. In research related to crop cultivation, the main objective is to set such process parameters at which the maximum yield value is possible [2, 4, 6]. The results obtained in this way are used in the improvement of cultivation technologies, development or modernization of machinery (equipment) involved in the processes of planting, growing and harvesting, pest and weed control technologies, creation of robotic complexes and expert systems capable of monitoring in real time the state of the growing plant and developing solutions for effective care [1, 7]. The developed model can be used as the basis for such an expert system, as it allows simulating scenarios of changes in plant states depending on the qualitative and quantitative characteristics of objects and processes of the subject area. The use of a universal graphical language of simulation modeling allows to carry out digitalization of the created model of system dynamics.

In addition, the created simulation model can be used in the educational process in the training of specialized specialists. In the studies devoted to the development of teaching methods in areas related to dynamic systems (e.g., agriculture, ecology, state and municipal management), it is noted that the formation of professional competencies requires the use of electronic educational resources capable of simulating different scenarios of behavior of complex real-world objects [9, 10]. Thus, it is possible in the conditions of an educational organization to use digital simulators of processes and assess the consequences of decisions made on the use of control actions by students without significant expenditures on consumables [11, 12]. The developed model meets all the requirements that allow it to be used as a basis for the development of a digital educational resource (e.g., variable input parameters, a set of rules of interaction of objects among themselves).

5 Conclusions

In agriculture, the use of simulation models is characteristic for choosing an effective production strategy of a farm, estimating the profit (loss) of a crop depending on climatic conditions, or determining the economic strategy. All this is relevant at any time, but it is especially necessary in periods of adverse weather, allowing to develop a set of measures to minimize damage. This requires the creation of simulation models that are able to show results taking into account changes in a large number of parameters and multiple repetition of experiments. In this case, the parameters have nonlinear, dynamic and random nature.

The development of accurate models that reflect the nature of the problem domain is a fundamental task in the creation of expert systems. The expert system, which will be based on the model of system dynamics of agricultural yields, will allow making decisions and forming recommendations on the organization of the schedule of different types of work related to plant care, timely harvesting, adjust the composition of such work depending on the current weather factors and the current state of plants, soil and the surrounding air.

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