Simulation modeling of forest plantation condition

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Abstract. The article substantiates the necessity of creating a simulation model of changes in the states of forest plantations. Such a model makes it possible to repeatedly conduct experiments on the object of study on changes in different parameters in order to predict the consequences and develop operational management scenarios to reduce the negative impact on its processes and objects. The use of structural analysis, synthesis and classification methods allowed us to identify the key objects of such an ecosystem and the processes that influence their germination, growth and death. The results obtained became the basis for the creation of a system dynamics model reflecting the nature of the behavior of the objects and processes under study. With the help of simulation modeling methods, a system of differential equations was created, which takes into account the quantitative instances of objects and the rate of their changes depending on external parameters. Based on this, a graphical model reflecting all aspects of the realization of such processes has been created.

1 Introduction

Large areas with minimal impact of human economic activity are important for the conservation of wildlife biodiversity [1]. Such territories in the long term ensure the presence of viable populations of the vast majority of living organisms, spatial relationships between landscape components and natural dynamics [2]. With the ever-growing population and increasing demand for renewable natural resources, the development of territories for economic development entails a rapid reduction of natural areas occupied by forest [1, 3].

The forest is a complex ecological system consisting of many links. It is a habitat for a large number of different animals and plants, produces oxygen and cleans the air from harmful chemicals, reduces the level of dust and noise, regulates and improves the water balance of water bodies, protects the soil from harmful geological processes (e.g., mudflows, landslides) [4]. Thus, the economic development of lands occupied by forest plantations should be competently compensated, i.e., to maximize the preservation of areas of relatively wild forests without the formation of a deficit of resources necessary for human life, to develop the territories of specialized forest farms.

The use of program means allows to provide control and management of the state of forest farms. Thus, at the current stage of information systems development, software solutions have been created that provide the organization of environmental activities aimed

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at preserving natural resources [5], maintaining forest registries, carrying out geoinformation modeling, forecasting the state of the environment based on a large array of data obtained from sensors or satellites [6, 7]. Gerasimova's work states that for forest ecosystems, mainly processes related to analytical assessment of taxation (attributive) data and analysis of spatial data in the form of forest thematic two-dimensional maps are distinguished [6].

Based on the above, it can be concluded that there are no well-defined information models that allow the prediction of changes in the state of forest plantations depending on changes in environmental parameters and human economic activity. Therefore, the purpose of the study is to obtain a parametric model of the ecological system characterizing changes in forest states. For this purpose, it is necessary to fulfill the tasks: 1) to identify the key objects affecting the quantitative state of forest plantations; 2) to establish the factors determining the nature of processes that change the number of such plantations; 3) to establish functional dependencies between the obtained processes and objects; 4) to create a formal model describing the changes in the states of the system over time.

Theoretical significance of the study is that forest plantations are considered as a unified system that allows to systematize objects and processes occurring in it. Based on the results obtained, it is possible to create models and software products that allow to carry out objective monitoring of the state of the forest system, to manage forestry operations, to create accurate forecasts of the development of forest and economic areas with minimal damage to the ecosystem of the region. In addition, the use of models allows obtaining data necessary for the development of federal or regional programs that ensure sustainable environmental development. All this features the practical significance of the research being conducted.

2 Materials and Methods

To fulfill the formulated tasks, general scientific methods were used.

To obtain a description of the objects of the problem area, the methods of collecting and processing information from regulatory legal documents (defining the activities of forestry farms), structural analysis, synthesis and classification were applied in a comprehensive manner. The result of using the stated methods was a list of key objects and a verbal description of their characteristics and changes in states. All this was used to create a formal model describing changes in the states of the territory where the forest is located.

The model was developed based on the use of simulation modeling methods, involving the creation of a mathematical model and a system dynamics model. The mathematical model is a system of differential equations characterizing the rate of change of the objects' velocity during a certain time. On its basis, a graphical model of system dynamics (or Forrester's model) was created. It is used to show the scheme of information links between the rates of change and the levels of difference between the values of incoming and outgoing flows that form the number of instances of objects of the problem domain.

3 Results

The use of the stated research methods allowed to establish all the objects of the problem domain, the processes changing them, and the parameters affecting the speed of the corresponding processes. Based on this, a graphical representation of the system dynamics model was created (Fig. 1).

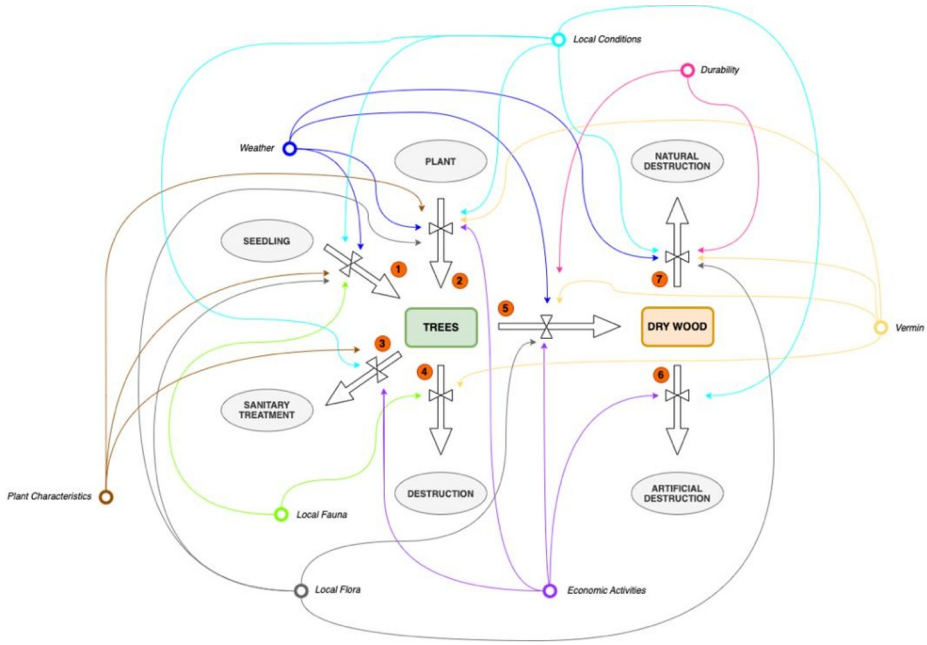

Fig. 1. Forest System Dynamics Model

In Fig. 1, the numbers denote the processes, during the realization of which the corresponding objects pass from one state to another. In this case, the number of these objects necessarily changes:

- if the arrow is directed towards an object, the number of its instances increases;
- if the arrow starts at the object, the number of its instances decreases.

It should be noted that the number of decreasing instances of one object may not coincide with the number of arriving instances to the linked object. The change in the number of instances depends on the coefficients whose colored arrows indicate the process of transition from one state to another. Let us present the characteristics of each of the processes of the model:

1. *Seeds → Trees*. Seeds fall into the soil naturally (if the plant is propagated in this way). In addition, seeds can be spread by animals or birds. Seed germination depends on current weather conditions (temperature regimes, humidity, windiness), local conditions (soil composition, density of plants placed on the plot, light, seasonality), plant characteristics (germination, viability, purity of material), local fauna (as a means of transport from plot to plot) and local flora (plants affecting germination, e.g., weeds). These parameters can both accelerate seed germination (e.g., favorable weather conditions, suitable soil, high seed resistance) and slow it down or stop it (e.g. seeds may serve as a food source for birds or animals, weeds reduce sources needed for growth, lack of adequate moisture levels).
2. *Seedlings → Plant*. In this model, seedlings are a generalized concept that includes young plants that have entered the soil with human help, shoots from trees. The number of young plants is influenced by the level of human economic activity (frequency of ecological and sanitary actions aimed at increasing the area of green spaces). The reduction in the number of such green spaces depends on the level of pests (including diseases). Characterization of all other parameters that affect the process of seedling growth corresponds to seed sprouting.
3. *Plant → Sanitization*. The process which reduces the number of plants, regardless of their age. It depends on human economic activity and is aimed at increasing the level of

preservation of green spaces from pests, diseases or fire safety of nearby territories and objects. Actions realized within the process depend on the level of forest overgrowth, seasonality and random factors (e.g., the presence of drought affecting the rate of fire).

4. *Trees → Destruction*. The process of eradication involves the complete disappearance of a tree, mostly at a young age. This is due to the fact that it has become a source of food for animals or has been affected by pests.

5. *Trees → Drywood*. Under certain conditions, trees may die while remaining in place or become unstable. For example, mortality can be due to pests (including parasitic plants), human economic activity (e.g., man-made emergencies), and weather conditions (e.g., floods, droughts, hurricanes). All of the above characteristics increase the rate at which a tree can become deadwood.

6. *Drywood → Sanitization*. In order to increase the number of green spaces, periodic collection and removal of deadwood for disposal is required. At the same time, such works may be carried out unscheduled in connection with the occurrence of natural or man-made emergencies.

7. *Drywood → Natural Destruction*. In the absence of timely sanitation of drywood utilization, weather conditions, wood type, or the activities of living organisms, drywood can become part of the forest biosystem.

The parametric representation of the model shown in Fig. 1 includes a system consisting of differential:

$$\begin{cases} \dfrac{d(TREES)}{dt} = (SEEDLING) + (PLANT) - (DRY\ WOOD) - (DESTRUCTION) - \\ \qquad - (SANITARY\ TREATMENT), \\ \dfrac{d(DRY\ WOOD)}{dt} = (TREES) - (NATURAL\ DESTRUCTION) - \\ \qquad -(ARTIFICIAL\ DESTRUCTION), \end{cases}$$

here t – time interval of process realization.

Each variable expresses a certain number of trees at a certain point in time. This number is influenced by certain coefficients, the values of which are determined from statistical data and sensor readings. Table 1 shows the correspondence between the coefficients and the parameters they affect.

Table 1. Table of correspondence between the coefficients affecting the processes of changing the number of objects in the system

Process	Process designation in a parametric model	Coefficient list
Seeds → Plant	(*SEEDLING*)	• Local Fauna, • Local Flora, • Plant Characteristics, • Weather, • Local Conditions
Seedlings→ Plant	(*PLANT*)	• Weather, • Plant Characteristics, • Local Flora, • Economic Activities, • Local Conditions, • Vermin
Plant → Sanitization	(*SANITARY TREATMENT*)	• Economic Activities, • Local Conditions,

		• Plant Characteristics
Plant → Destruction	(*DESTRUCTION*)	• Local Fauna, • Vermin
Drywood → Natural Destruction	(*NATURAL DESTRUCTION*)	• Vermin, • Durability, • Local Conditions, • Local Flora, • Weather
Drywood → Sanitization	(*ARTIFICIAL DESTRUCTION*)	• Economic Activities, • Local Conditions
Trees → Drywood	(*TREES*)	• Local Flora, • Economic Activities, • Vermin, • Durability, • Weather

Accordingly, obtaining the final form of the parametric model requires each object to be multiplied by all the coefficients associated with it.

4 Discussion

Research, one of the tasks of which is to obtain a formal description of objects and processes of the subject area, uses the method of structural analysis in conjunction with methods that allow to refine the obtained details depending on the level of accuracy (e.g., clustering, observation, synthesis). Thus, the authors of the works obtain, for example, lists of parameters affecting the density of transport macroflows [8], rules of interaction between pedestrian and traffic flows in a limited area [9, 10], the degree of influence of the occurrence of random events on the realization of strictly defined processes [11, 12]. The composition and nature of such results of the above methods correspond to the current result in the ongoing study: a list of key objects involved in the processes of forest growth, development and destruction, as well as a list of parameters affecting the rate of these processes have been established.

Such results are usually used to create simulation models of the processes of behavior of complex systems. In the analyzed studies, the results of structural analysis were used as input parameters for the simulation model of transport systems [8, 13], creation of algorithms for the functioning of specialized information systems [5, 14]. The methodology of working with data in such studies allowed its authors to create a model in which all the dependencies between objects and processes are established, allowing us to actually talk about the digital twin of the studied subject area. In the conducted research, a model of processes is obtained, which allows conducting different experiments to control changes in the values of parameters of processes or objects.

Researchers in their works explain such experiments by the need to develop operational management concepts to reduce the negative consequences of changes in the objects of the problem domain [8, 15], to assess the economic effect of the chosen strategy of process management [16] or to create educational resources for conducting practice-oriented classes in educational organizations during the training of profile specialists [17]. The developed model within the framework of the research allows us to conduct such experiments.

5 Conclusions

The process of modeling has a strictly directed character, using the methodology of analysis to build a generalized model reflecting all factors of the real system taking into account random external influences on individual objects or processes of the system. Although the models obtained in this way do not provide an optimal solution to any problem, they are a convenient auxiliary tool for the system analyst to find solutions to certain problems, the basis for the development of expert systems. With their help, the problems of studying the structures of complex systems and their dynamics, analyzing "bottlenecks", forecasting and planning, resource allocation, etc. are solved.

The use of such models in the field of forestry is a justified step. This is due to the fact that the forest is a complex ecosystem that has an enormous impact on human life and economic activity. Changing at least one element of such a system can lead to irreversible consequences of uncontrolled change or destruction of individual objects of ecosystems or the ecosystem as a whole. With the help of digital twins, it is possible to repeatedly conduct experiments on changing the states of objects and processes in order to accurately predict and develop an acceptable scenario for managing human activity or changing the qualitative or quantitative composition of ecosystem objects.

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