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Theoretical Aspects of Agent-Based Modeling in the Development of the Forest Complex*

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Abstract. One of the ways to ensure sustainable economic growth in modern Russia is to enhance the efficiency of utilization of forest resources. The forest complex is a comprehensive open system with close relationships between different aspects such as ecological, social, economic, cultural, educational, and public administration. It is difficult to find a comprehensive solution to the issues of development of the forest complex if there is no evidence-based system for management decision-making. One of the promising areas of scientific research in this direction could be the application of agent-based models simulating the processes of using, protecting, and reproducing forests, forest products and forest management. The aim of the paper is to study scientific approaches to the construction of agent-based models applied to the forest sector in order to define common approaches to the formation of a set of agents and create an

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environment for their functioning. We provide an overview of the experience of simulation modeling of individual processes in the forest complex with the use of the agent-based approach. We give a general characteristic of the problems associated with the management of the forest complex in Russia (at the federal and regional levels). We provide an overall assessment of a high complexity of the forest complex as an object of study. The article presents a brief overview of relevant Russian and foreign research devoted to the general methodological issues of simulating the forest complex and specific models implemented with the use of an agent-based approach: the model for the Swiss timber market; the model for protection of forests in British Columbia (Canada) from insect infestation; the models for predicting and controlling forest fires, an enlarged architecture of an agent-based model for the regional forest complex. We define requirements for the regional forest complex model and consider individual aspects in the implementation of its elements. When developing the architecture of the model, we use comprehensive, system, ecosystem and institutional approaches, which allows us to create a model closest to the real forest complex. In conclusion, the article provides a general assessment of the efficiency of application of agent-based modeling in the forest sector.

Key words: agent-based modeling, forest complex, systems for support to decision-making.

Introduction

The forest complex of the Russian Federation occupies an important place in the economy of the country. Forests of Russia are among the most important renewable natural resources. They constitute more than a quarter of world reserves of wood biomass and perform important ecological and environmental functions.

Forestry is a complex system with many different interacting agents, which include public authorities, timber and woodworking enterprises, people that use forest resources for their own needs, etc.

The forest complex is characterized by geographical fragmentation and remoteness of enterprises (forest users), fragmentation and different degree of accessibility to forest resources and markets. Timber processing and logging are seasonal. Climatic fluctuations have strong influence in this regard.

It is obvious that finding a comprehensive solution to the tasks of development of the regional forest complex is difficult without creating an evidence-based system to support management decision-making. One of the promising research areas in this direction could be the development, testing and application of simulation models for the processes of using, protecting, reproducing forests, forest products and forest management.

General approaches to simulating the forest complex as a comprehensive dynamic system

Today, there exist many approaches to structural formalization of the functioning of the forest complex. Russian scholars such as T.N. Ivanova, N.E. Antonova, A.S., Sheingauz, and A.A. Kiseleva consider the subject in detail.

In the work by T.N. Ivanova [7], the timber industry complex is defined as a system of enterprises of the forest industry and related parts of the state apparatus, science and enterprises of other industries, ensuring its functioning. In accordance with the definition the following elements are highlighted:

1) individual enterprises or their associations that manufacture timber products, connected via information, material and energy flows;

2) enterprises that provide goods and services vital for the functioning of the timber industry complex (equipment, energy, transportation services, etc.);

3) governing bodies that regulate the development of the timber industry complex, forming its investment and business climate.

Thus, economic interests for governing bodies include the receipt of tax revenues; for the business community, forest, timber and wood processing sectors – raising investment in the timber industry complex, promotion of expanded reproduction and gaining profit from timber sales.

Researcher N.E. Antonova in her work [1] proposes a verbal model of the regional forest complex as a natural and economic system based on A.S. Sheingauz's functional model of forest management and classification of forest functions into classes such as social, resource, economic-ecological, and landscape-stabilizing.

The basic subsystem of the proposed model is the forest, which is represented as a set of forest environment and forest resources. The main principle of formation of the system architecture is its division into three blocks according to the functional principle associated with the use of the forest. Three ways in which the forest can be used are as follows: social, environmental, and resource. Social use and environmental use fall within the scope of public consumption, and resource use belong to the sphere of private consumption. Private consumption forms the timber industry complex, comprising of three successive stages of timber processing: timber harvesting, physical transformation of timber and chemical (thermo-chemical) treatment of timber. The actors of use are defined for each block. According to the author, such actors include the state, represented by federal and regional authorities, local self-government, forest business, residents, and non-governmental organizations. The actors related to forest business are defines separately. They are represented as economic agents – forest users.

Researcher A.A. Kiseleva in her works [8, 9] considers that in the structure of the existing regional timber industry complexes there are the following groups of organizations:

1) enterprises engaged in various stages of the technological chain of production and processing of forest resources, which includes silvicultural, forest-harvesting, wood-sawing, woodworking, pulp and paper, and wood chemical production;

2) organizations engaged in the production, social, institutional and market infrastructure, ensuring the functioning and development of major technological forest industry enterprises;

3) enterprises engaged in logistical support of the regional timber industry complex;

4) research structures and educational institutions engaged in the training of human resources for the regional timber industry complex;

5) organizations engaged in the supply of major forest industry enterprises with the means of production (forest-harvesting, wood-sawing, woodworking, chemical, fire protection and other equipment).

The subjects of the timber industry complex are grouped in three major blocks, based on their participation in direct management and use of forest resources.

A large number of works study the cluster approach to the development of the regional forest complex. The cluster architectures they present can also be used as examples of the overall architecture of the forest complex. For instance, A.A. Kiseleva suggests an option of cluster architecture in which the core of the model of the timber industry cluster of the region are the enterprises engaged in the harvesting of timber, production of lumber and wooden containers, manufacture of cellulose, wood pulp, paper and paperboard, manufacture of plywood and wood boards, production of wooden building parts, manufacture of paper containers and paperboard containers and other articles made of paper and paperboard, and wood chemical production. The sales and procurement structures of the business operate under orders and contracts with the enterprises, organizations and business structures within the core of the cluster. Service structures are directly associated with the production functions and sales of the cluster.

Despite significant differences in the approaches described above, it is possible to identify several common points when describing the general scheme of functioning of the regional forest complex [5]:

1. The forest sector is a complex and open dynamic system, in which there are close relationships between its elements from different domains: ecological, social, economic, cultural, educational, public administration, etc. The complexity and openness of the system defines the possibility of multiple architectures of such systems.

2. Such systems, when described, are usually represented as a set of interrelated systems.

3. Existing models of structural formalization of the subject area of the regional forest complex are focused on describing the structure of systems governing the forest complex and, therefore, they cannot be directly used as the basis for creating an architecture for the model aimed to search for common ways of improvement of state management of the forest complex that are associated with the selection of control actions.

4. Many works study the cluster approach to the development of the regional forest complex. The cluster architectures presented in them can also be used as examples of the overall architecture of the forest sector.

5. Sustainable forest management paradigm should become the main goal of using the model.

6. Managing the forest complex should be understood as the targeted impact of the bodies managing the timber industrial complex, which are the subject of management, on the object of management – the timber industrial complex; this impact helps achieve strategic objectives of the timber industrial complex, taking into consideration specific prerequisites and conditions in the regions.

7. When building a model of the regional forest complex, it is necessary to consider many interacting components that are related by their nature to various systems. All these

components should possess a set of properties that ultimately in combination determine the current performance of the forest complex.

Classic methods of analytical modeling have been traditionally used in modeling individual elements in the work of woodworking and timber harvesting companies. But, due to a high complexity of the real system of relations in forestry, the application of these methods faces a number of challenges, the main of which is the necessity of finding a balance between simplification and complexity of the system. As a result, in the development of the models, we have to discard the factors that have no effect (little effect) on the studied characteristics of the system. The choice of factors in this case is highly subjective, since it depends largely on the skill and intuition of the researcher. In addition, in the modeling of complex systems using analytical and simulation methods it is difficult to introduce changes, sometimes even minor, in the structure of the model. In this regard, in order to solve the problems of complex systems modeling, the agent-based modeling paradigm emerged; it uses intelligent agents as a high-level abstraction for formalizing and structuring the subject area and as a powerful tool for the development and implementation of complex models.

Agent-based modeling is a kind of simulation modeling. Its distinctive feature consists in the use of agents with individual behavior as basic elements. The agents have such properties as activity, initiative, ability to learn and communicate, intelligence, etc. Moreover, each agent possesses not only a given set of personal characteristics, but also an objective function, on the basis of which responses to changes in the external environment and the behavior of other agents are simulated.

One of the main advantages of agent-based approach includes the ability to simulate the system as close to reality as possible. Limitations in the degree of detail in such models depend only on computational performance of the computers used [12]. Another important advantage of models of this type is "bottom-up" modeling that provides an opportunity to build adequate models in the absence of knowledge about global dependencies in a given subject area.

Review of foreign agent-based models in the forest industry

Currently, despite the fact that the method of agent-based modeling is relatively new, the range of scientific works devoted to its application in various branches of forestry is wide enough. This applies mainly to foreign studies. A large number of materials are dedicated to various aspects of modeling timber markets. Klaus G. Troitzsch [30] attempts to apply agent-based models of the urban housing market in Brazil and the German pharmaceutical market to build the model of the wood market in Switzerland. Noting significant differences between the forest industry compared to other industries, Klaus G. Troitzsch comes to the conclusion that in order to understand the actual wood market the agent-based models are more appropriate than the classical models of markets, because they can take into account all the characteristic features of forestry.

Ernst Gebetsroither, Alexander Kaufmann, Ute Gigler, Andreas Resetarits [21] present a comprehensive agent-based model of self-organization processes in adaptive forest management. The proposed model consists of two interrelated but, in all other aspects, independent subsystems that are implemented with the use of agents. The first – socio-economic – subsystem is represented by agents that perform the roles in the harvesting, processing and sale of timber. The second – environmental – subsystem simulates the processes of forest development. The agents are trees competing for living space.

Of interest can be a model described in the works of F. Kostadinova and others [24, 25], which presents the timber market of Switzerland, constructed with the use of agent-based models. The simulation was conducted on the basis of the Swiss canton of Aargau due to the following factors:

– relative availability of necessary input data for modeling;

– geographical position and conditions for wood production among Swiss cantons;

– availability of the necessary number of agents sufficient from the point of view of modeling, allowing to provide a large number of interactions among themselves, while ensuring reasonable timing of calculations.

When the model was designed, it took into account only the production and consumption of forest wood, including wood fuel produced from industrial production waste, excluding other sources, such as secondary wood processing.

The following data were used for model calibration:

– the number, size and location of wood-fueled heating systems in Switzerland;

– the number of loggers and the number of forests according to the results of the third Swiss National Forest Inventory (2010);

– the dynamics of forecast prices of oil over the past period for the purpose of determining, among other factors, the attractiveness of installing wood-fueled heating systems to consumers;

– classification and typology of forest management and wood processing enterprises, private forest owners, users of wood fuel, expert assessments.

The model identifies the following classes of agents:

– Forestries – specialized organizations for forest management on behalf of third parties (municipal and state forests).

– Private forest owners – the owners of woodlots. The average size of woodlots in private ownership is much less in comparison with the forests managed by forestries. In the baseline model scenario, 50% of private forest owners have little interest in timber production and remain inactive throughout the simulation.

– Timber merchants – the intermediaries in the sale of round wood and wood fuel in both markets. They do not produce or consume either round wood or wood fuel.

– Sawmills – the only class in the model that consumes round wood. At the same time they act as suppliers of wood fuel.

– Small private consumers of wood fuel – detached houses with wood-fueled heating systems. Consume a relatively small amount of wood.

– Commercial consumers of wood fuel – private organizations that service commercial buildings that use wood-fueled heating systems.

– Public consumers of wood fuel – municipalities or similar organizations that service buildings under public ownership (schools, fire-fighting, etc.). Enjoy certain benefits in the market of wood fuel.

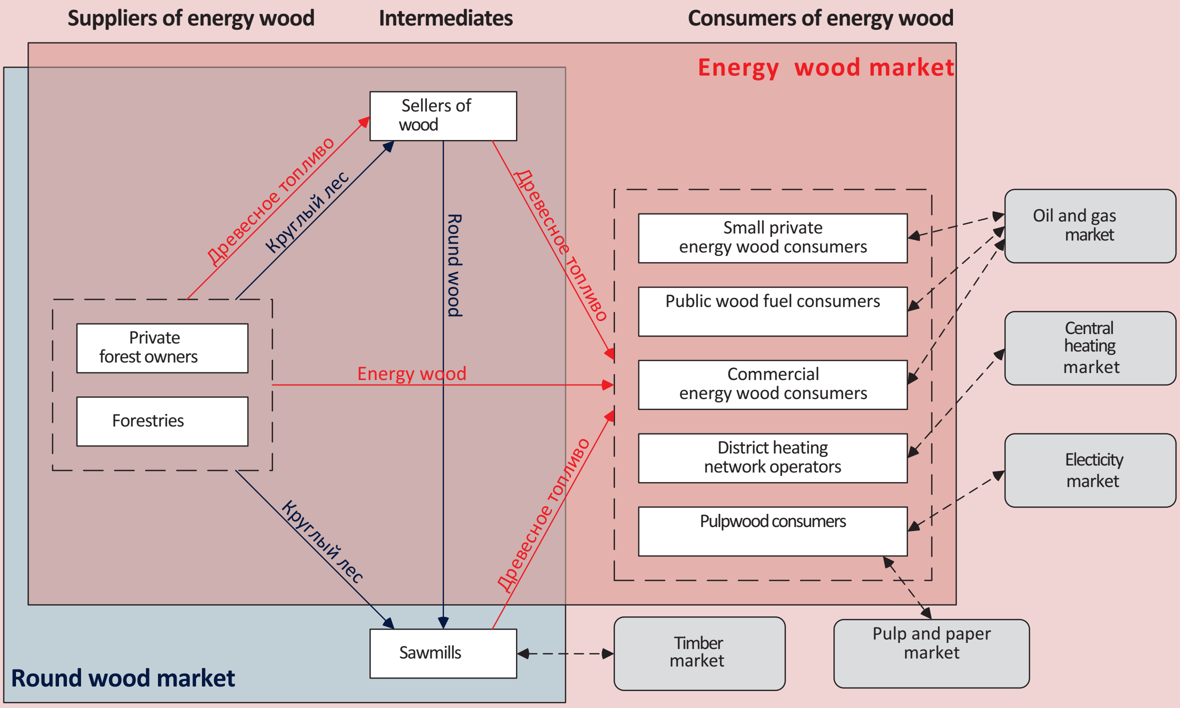
– Operators of district heating networks – commercial producers of heat. They service buildings connected to the central heating system.

– Consumers of pulpwood – chemical and paper industry. They compete for timber with other consumers of wood fuel.

The general scheme of interaction of agents on the market and with the external environment is shown in *Fig. 1*.

All agents have a fixed geographical location, possess a set of parameters and resources that include forests (for wood manufacturers), the supply of round wood and wood fuel (for wood consumers), and money. Agents act as suppliers, consumers or intermediaries in the market of round wood or wood fuel, depending on their role. For each class of agents there are algorithms of actions and decision-making; in addition to the criteria of profit maximization, the model takes into account the criteria of the "value of friendship" (transactions of purchase and sale with agents

Figure 1. Scheme of interaction of agents on the market and with the external environment



Source: Kostadinov F., Steubing B. *An agent-based model of an energy wood market in a Swiss region*. Available at: http://www.issw.ch/fe/waldressourcen/produktionssysteme/publikationen/ESSA2011_FabianKostadinov_v2.pdf who are friends), the criteria of "providing support to local markets" (the choice of the counterparty may be influenced by the desire to support local producers).

However, it is necessary to note some limitations of the model. We can see in Figure 1 that some markets such as the markets of oil and gas, central heating, electricity, timber and pulp and paper industry are outside the scope of the model and are considered as external environment. Even though some agents are quite strongly dependent on these highly aggregated markets, their interaction, as in the case of markets for round wood and wood fuel, does not take place.

In the proposed model, the pattern of natural changes in the forest fund is simplified considerably. Forest resources are simulated as homogeneous renewable resources of a certain size with natural upper threshold. The growth of the trees is distributed with the passage of time. The model does not include seasonal effects, changes in weather conditions, natural disasters, etc.

Nevertheless, at this stage, the authors themselves pursued the goal of proving the possibility and prospects of agent-based modeling to design the models of complex systems such as the timber markets.

A characteristic feature for the majority of models under consideration is the fact that certain associations of people such as private households, municipalities, commercial organizations, etc. are chosen as main agents. In the works of Stefan Holm et al. [23], Jessica E. Leahy et al. [26], Diana D. Valeriano et al. [31], the forest is considered as a resource with an algorithm of development that is simple and does not require complex modeling. Another approach to the application of agent-based modeling methods is used in the works of Liliana Pérez and Suzana Dragicevic [28] on the protection of forests from insect infestation.

The research examines the impact of methods of protection of forests in British Columbia (Canada) from the outbreaks of mountain pine beetle (Dendroctonus ponderosae Hopkins, DENCPO) infestation that has resulted in extensive mortality of trees on an area of several thousand square kilometers. Given the fact that the dynamics of DENCPO infestation occurring between the trees and the insects within them, is part of a complex spatiotemporal process, at the first stage it was proposed to design an agent-based model for the behavior of insect colonies that would effectively reflect the regularities of trees being killed due to outbreaks of infection DENCPO infestation. At the next stage, different scenarios of forest management were added in the model for the purpose of assessing the effectiveness of protection of forests from pests.

Thus, the model consists of three types of agents: Beetle Agent, Pine Agent, and Forest Management Agent.

The Beetle Agent captures the behavior and life cycle of DENCPO based on the number of rules that determine the movement patterns in the forest, and selection of a healthy tree to attack, feed and breed.

When choosing a tree to attack the Beetle Agent takes into account parameters such as the arrangement of trees in the forest with the use of fuzzy sets, the natural range of DENCPO flight, and the prevailing wind pattern in the region. Next, each tree located within the potential area of attack is estimated by the Beetle Agent by four parameters: health state of the trees within the stand, type of trees, average age and diameter at breast height. After the assessment of the hosts, the Beetle Agents decide whether to stay or fly to a different stand.

During its life cycle, the Beetle Agent passes through the following stages: egg, larva, and male or female beetle. Each stage is characterized by its own set of parameters and behaviors. The simulation takes into account the seasonal factor, when during the winter cold 80% of the DENCPO population is killed.

The Pine Agent is implemented to simulate the built-in mechanisms of resistance and self-protection of the trees against insect infestation. This agent is an autonomous entity (a separate tree) characterized by a number of parameters affecting the probability of infestation, such as type, age, height, health state, and diameter at breast height. In order to estimate the beetle population density per tree, Pine Agents are in charge to calculate the total bole surface area and on the basis of these calculations proceed to evaluate the population density of Beetle Agents per 1 m^2. If certain density values are exceeded, Beetle Agents start searching for new trees to attack.

To control the outbreaks of DENCPO infestations the Forest Management Agent is introduced in the model. The tasks of the agent is to assess the degree of infestation of each forest site in order to make decisions about the implementation of certain forest protection measures depending on the model scenario. The model provides for three scenarios upon which the Forest Management Agent acts. Scenario 1 involves no action on the part of Forest Management Agents and gives them only an opportunity for monitoring and evaluation. Scenarios 2 and 3 provide for the possibility of making decisions about carrying out sanitation harvest or salvage harvesting to prevent further infection of healthy trees or entire forest stands.

The series of model experiments have confirmed the high effectiveness of active strategies of forest protection; although from our point of view, this model is interesting due to its selection of the agents, giving a new perspective on forecasting the development of forest ecosystems.

Many studies on the use of agent-based models in the forest industry are devoted to the issue of combating forest fires. Thus, the study carried out by Guangjun Zhang and Yaodong Li [22] implemented an agent-based model of a forest fire, considered as a typical open complex system. Muaz A. Niazi et al. [27] propose a virtual multi-agent forest fire simulation model based on FWI (Fire Weather Index – as estimation of the risk of fire according to weather conditions). These works are more theoretical in nature and are designed to confirm the applicability of simulation methods to complex systems.

We would like to highlight the work of Thomas A. Spies et al. [29], which uses an agent-based model of the interrelated social and natural systems to assess the impact of alternative management scenarios on the indicators of fire and environmental safety in a fire-prone landscape in Oregon, USA.

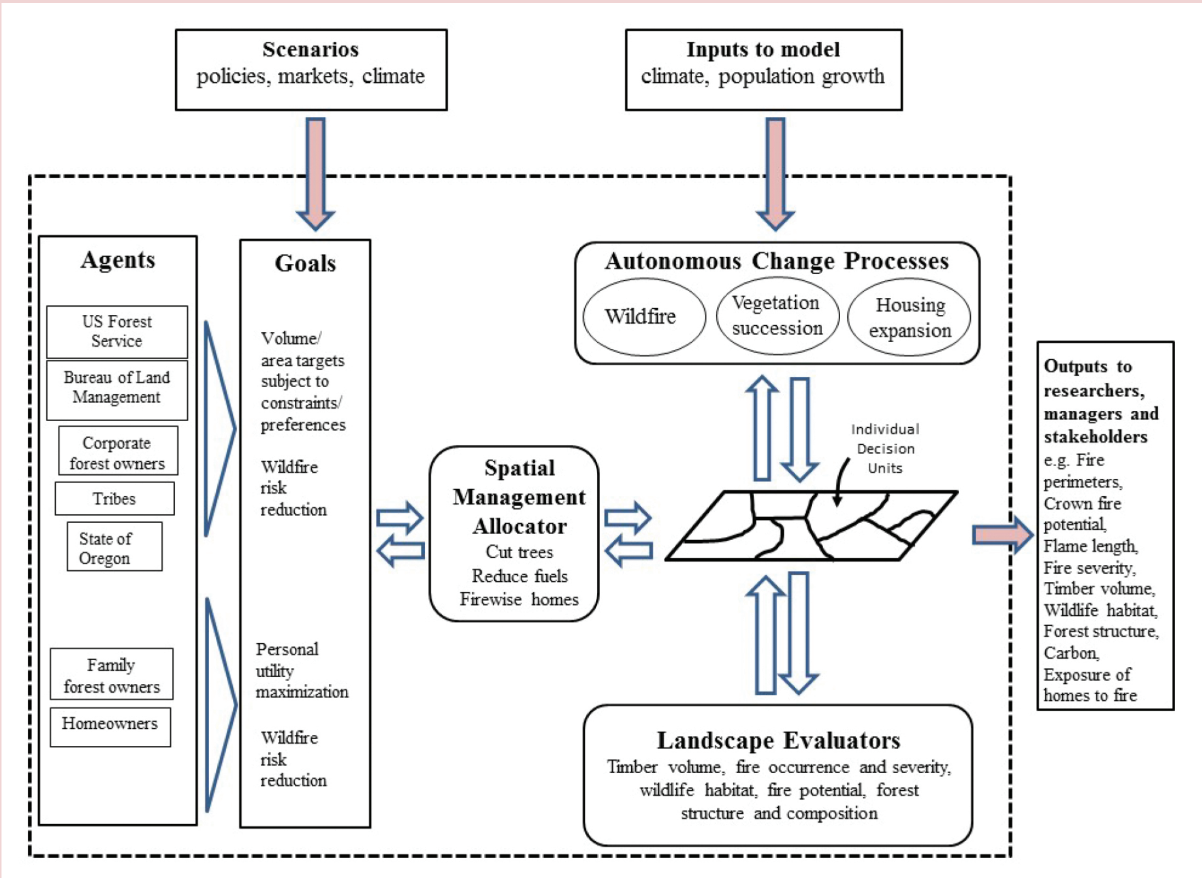
The general pattern of the model is shown in *Fig. 2.*

The agents in the model are large landowners engaged in forestry activities that can influence the changing landscape. Forest fires are simulates using a semiempirical fire spread algorithm that takes into account the composition and structure of forests, and the topography and weather conditions. Changes in the environment that occurred as a result of human activities and natural causes (including fire, windfalls, alternation of tree species), create feedback that influences decisions about future management impacts of man, and the potential threat of forest fires.

Russian experience of agent-based modeling in the forest complex

In Russia, there has been a more widespread development of agent-based modeling in recent years. Scientists work to apply agent-based models in complex social systems, municipal, regional and state management, etc. The research findings include the studies of such authors as V.L. Makarov, A.R. Bakhtizin,

Figure 2.Agent-based model of the interrelated social and natural systems



Source: Spies T.A., White E., Ager A., Kline J.D., Bolte J.P., Platt E.K., Olsen K.A., Pabst R.J., Barros A.M.G., Bailey J.D., Charnley S., Morzillo A.T., Koch J., Steen-Adams M.M., Singleton P.H., Sulzman J., Schwartz C., Csut B. *Using an agent-based model to examine forest management outcomes in a fire-prone landscape in Oregon, USA.* Available at: https://www.ecologyandsociety.org/.../ES-2016-8841.pdf

E.D. Sushko [10, 11, 12], V.I. Suslov [17], M.R. Fattakhov [18], and others. At the same time, the number of agent-based models in the forest sector is sporadic.

For example, the works of P.T. Voronkova et al. [3, 4] raise the general questions of applying simulation modeling in forestry. We can acknowledge the work of Yu.S. Blam [2] as the most comprehensive and system study that makes an attempt to build an integrated architecture of an agent-based model of a regional forest complex represented by several forest harvesting companies (timber industry enterprise) and one comprehensive industrial enterprise that includes forest harvesting and wood processing production (timber industry complex).

The model considers various options for harvesting (clear-cut and selective) and sales of harvested wood; it takes into account seasonal factors and direct and indirect costs associated with timber harvesting. The conditional annual profit is considered as the main criterion.

Yu.Sh. Blam in the first stage formalizes the economic formulation of the problem in the form of optimization linear production-transport model and then converts it into a complex of agent-based models that describe the behavior of forest-harvesting enterprises and the timber industry complex, "other" agents of the regional level that define the external parameters of functioning of the regional timber industry complex and describes the logic and sequence of their interaction.

The author distinguishes the following types of agents: Forest Harvesting Companies Agents and Timber Industry Complex Agents presented by the optimization linear production-transport models, Administration Agents, Markets Agents, and Finances Agents, represented by simulation units, and management decisions for these types of agents are formed in the model taking into account external influences.

At the debugging stage, these agents represent an information base generated by the scenario calculations of the basic model and generate for the first four calculating quarters the estimated parameters that coincide with the optimal solution to the original complex model. The inputs in the model, when moving to the next accounting period, are recorded taking into account the related decisions for the previous period and the information from external agents.

In continuation of the study, it is planned to develop further the scheme of interaction between the agents, to clarify the model description of functioning of enterprises in the current institutional and economic conditions, as well as to clarify the functional representation of external agents of the branch-wise subsystem of the region.

Similar to foreign works, of definite interest are the studies of the possibilities of application of mathematical modeling to fight forest fires. Here we can mention the works of D.O. Morozov, A.A. Dekterev et al. [13, 14], G.V. Sokolova [16], A.N. Razdayvodin and D.Yu. Romashkin [15]. But the possibilities of agent-based models are reflected most comprehensively in the work of S.V. Yarovoi and G.A. Dorrer [19, 20] that considers the problem of simulating forest fire situations. It is recommended to use the agent-based approach in conjunction with the technology of geographic information systems (GIS), which allows for combining the advantages of both directions. A multi-agent model implemented on the basis of nested Petri nets enables to predict the spread of the edge of a forest fire, and imitate the direct method of fighting ground forest fire with the help of non-mechanized fire-fighting units.

The simulation environment in this study is represented by a section of the map of the real area coated with a layer characterizing the flammability of vegetational combustible materials, which is determined on the basis of a pyrological description of areas on the map of forests. Thus, for each location on the map a type of surface is set that determines the presence of major conductors of burning and their type, depending on which the base speed of propagation of the edge of the fire and the heat of ignition of the layer are defined.

The data on the speed and direction of the wind and the fire danger class are also taken into consideration as main indicators of the environment.

In the model under consideration, agents of two types are used. The agents of the first type represent sections of the front of fire spread and are used to model a forest fire, representing, in the aggregate, the outline of a fire on the map. The model allows for the simultaneous presence of several such contours propagating independently from each other in different parts of the map.

The agents of the second type simulate the actions of the firefighting forces and influence the agents of the first type.

The study describes in sufficient detail the parameters characterizing the agents of both types, their purpose, possible states, conditions and algorithms of transition from one state to another. The simulation results make it possible to solve a number of related tasks: first, to get a picture of the spread of forest ground fire in real terrain and under certain weather conditions; second, to determine the required number of fire extinguishers for the localization of ground fire in these conditions.

Conclusion

Having studied the existing experience of agent-based modeling in the forestry sector, we can point out the following:

– the range of contemporary research on the application of agent-based modeling in various branches of forestry is quite diverse, but to date there is no scientific developments in the field of building integrated models for the forest complex for the level of large territorial formations, intended for its prospective analysis and development planning;

– the range of domestic studies on this subject is more modest in comparison with foreign research;

– most models have the following feature: they use certain groups as the main agents: private households, municipalities, commercial organizations, etc., and the forest is considered as one of the resources with a simple algorithm of development, which does not require complex simulation;

– both foreign and Russian researchers studying the application of agent-based modeling in forestry note the high complexity of the forest complex as object of study due to the large number of interdependent and often unpredictable factors, such as instability and changes in climatic conditions, possibility of natural disasters (fires and windfalls), and the need for long-term forecasting;

– due to the high complexity of the real system of relations in the forestry sector, the classic methods of analytical and simulation modeling traditionally used for modeling individual elements of the work of timber and logging companies are unable to ensure compliance with the requirements of modern systems for support of managerial decision-making in the regional forestry complex;

– the use of the agent-based approach in modeling the regional forest complex will help solve the issue of complexity and scalability of the model. The possibility of constructing multi-level and embedded agents and the individuality of the agents are most convenient for simulating such complex systems.

The most important task when building agent-based models in forestry is to determine common approaches to the formation of composition of agents and creation of environment for their functioning. The simultaneous complexity and openness of the system provides for multiple architectures of such systems. Therefore, there is a need to elaborate the processes of identification of model elements, address the issues of their abstract representation, which will help describe the mechanisms of their interaction and formation of input impacts and obtaining the desired results [6]. It is necessary to consider the influence of spatial factors in the positioning of elements, and a multi-role aspect in the models of their behavior. An important task is to choose the scale of the model that allows efficient obtaining of the results that confirm adequacy; it will signify the possibility of its use in regional management systems.

So far, there has been no research on the general problems of building agent-based models for the forest complex. The results we have obtained in the analysis of agent-based models in the forest sector allow us to estimate the prospects of applying the agent-based approach to modeling the regional forest complex, to use the existing experience, and formulate directions of further research.

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