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Modeling Timber Transport Flows for Forest Quarter-Based Implementation of Logging Operations with Combined Reforestation

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Abstract: The article presents a model for the formation of timber transport flows during the forest quarter-based development of forest plots with combined reforestation. A distinctive feature of the research is the accounting for the need to transport coniferous undergrowth, which must be preserved and transplanted from clear-cutting areas to sites with insufficient natural regeneration. The model optimizes the transport and technological scheme for quarter development by minimizing the movement paths for both harvested timber and viable undergrowth. The methodology is based on the application of geographic information systems and algorithms that enable the rational routing of technological corridors, considering the spatial distribution of forest inventory units. A key feature is the solution of a modified transport problem that accounts for the dynamic role of plots as both sources and consumers of undergrowth. The modeling results make it possible to determine optimal volumes and directions of timber transport flows, reduce the average skidding and undergrowth transportation distances, while ensuring its preservation and survival rate.

1 INTRODUCTION

One form of integrated forest management is the forest quarter and block methods. The essence of the forest quarter method is that all types of work provided for by the forest management plan are carried out within a forest quarter. The forest quarter-block method, in addition to the forest quarter method, involves the concentration of production activities across several forest quarters simultaneously (Rukomoynikov, 2016. Mokhirev & Rukomoinikov, 2022.).

Currently, the Volga State University of Technology, in collaboration with Moscow State University, has conducted research on transplanting coniferous undergrowth from under the forest canopy. The study identified various possible technological schemes for transplanting coniferous undergrowth. The conducted analysis showed that the most effective approach for reforestation work is to carry it out without organizing temporary storage sites, as loading and unloading coniferous undergrowth requires additional labor and financial costs. This option is possible when the digging and planting sites are located close to each other. The currently developed method of forest quarter-based development, which involves the sequential execution of all types of work within a forest quarter (Shirnin et al, 2001, Shirnin et al, 2004), provides an opportunity to maximize the concentration of work sites, and a rational technology for forest quarter development and its infrastructure will reduce the necessary costs for their implementation.

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One of the main tasks, the solution of which allows for increasing the efficiency of implementing the aforementioned method is the development of a rational technological map for forest quarter development (Rukomoynikov, 2015). Solving this task will improve soil cover preservation through the rational placement of transport routes (George et al. 2025, Tampekis, 2025., Zumbo et al., 2025) and increase the efficiency of timber transport flows within the forest quarter network (Makarenko, 2018., Skrypnikov et al, 2016., Vadbolskaya & Azarenok, 2016, Rukomoynikov et al, 2017.).

2 MATERIALS AND METHODS

Such a technological map under the forest quarter-based method of forest fund plot development is created entirely for a forest quarter. Loading decks located along the perimeter are used for developing adjacent forest quarters. When organizing the territory of a forest quarter (or a block of forest quarters) loading points should be placed so that they can be used for all types of work.

Currently, software has been developed for the automated creation of a technological map for the forest quarter-based development of forest fund plots. It involves design based on the geographic information system MapInfo Professional 9.5, which provides the user with characteristics of the forest stand, terrain relief, and the territorial location of the developed forest inventory units within the forest quarter, and is developed using the MapBasic 9.0 programming language embedded in its shell.

The program allows for solving issues of integrated forest quarter development not only when organizing logging and reforestation work on its territory using traditional methods of artificial reforestation but also makes it possible to assess the efficiency of transport route placement within the forest quarter when implementing a variant of logging operations with combined reforestation. This variant involves transplanting coniferous undergrowth from areas where it would be damaged during logging to areas with an insufficient amount of coniferous undergrowth of commercially valuable tree species. The idea of performing work with combined reforestation within a forest quarter is a continuation of joint scientific developments by a team of researchers from the Volga State University of Technology and Moscow State Forest University, which confirmed its relevance and economic feasibility (Lazarev, 1999, Goncharov et al, 1996).

3 RESULTS AND DISCUSSION

Initially, when using the program, the user inputs data related to the technology of work execution in the forest quarter. The information entered by the user includes characteristics of the work performed and the machines and mechanisms used for transport operations.

The formulation of a specific task may cover only the technological characteristics of conducting logging operations on the forest inventory units located within the forest quarter, under the traditional reforestation method. In this case, the issues of finding an effective solution are significantly simplified and represent a special case of solving the general task set for the program and the user. In this formulation, there are no issues related to the transportation of coniferous undergrowth, and the program can be used solely for justifying the direction of technological corridors, main skid trails, and the arrangement of loading points, which significantly expands its scope of application.

The program's task in the general case is considerably more complex. It covers the entire complex of logging and reforestation operations associated with transplanting coniferous undergrowth during reforestation operations and, along with selecting the skidding direction, allows for the selection of the transportation direction for coniferous undergrowth, and quantitative characteristics of its transplantation from each specific unit to the territory of other units within the forest quarter. Digging, transportation, and planting of coniferous undergrowth in this case can be performed by machine, mechanized, or manual methods.

The territorial, qualitative, and quantitative characteristics of the forest stand in the user-marked units, the relief, and the characteristics of soil and ground conditions within the forest quarter are suggested to the user by the MapInfo Professional 9.5 geographic information system based on information obtained from the forest fund plot information maps, which contain the necessary information for the program's functioning. The MapInfo Professional 9.5 system provides access to vast amounts of information. Data is stored in electronic tables about the characteristics of the analyzed forest fund plots, each of the many units located within the forest quarter network of the considered territory. Electronic media contain a multitude of diverse data concerning the natural environment, etc. Information about personnel and equipment can be presented on thematic maps and graphs, as well as other visual forms. One of the main features of the system's operation is ensuring a qualitatively new level of efficiency in designing the technological map for forest quarter development. Desktop cartography uses geographic components of data. This allows the computer to more accurately grasp the meaning of the information presented in tabular form and enables not just data processing but also quick and visual representation. There is a possibility to create one's own maps using either MapInfo or specialized drawing software packages.

After entering numerical technological information, the user, using the functional features of the MapInfo Professional GIS, can indicate on the map sites that may be intended for loading and unloading and other operations during the processing and movement operations of logging, as well as places that can be used for temporary storage of coniferous undergrowth, taking into account the seasonality of work involving its use. Information about the cargo capacity and cargo turnover of such sites must be provided. Sites can be selected by the user as a result of field surveys of cutting areas and identification of places with a minimal amount of coniferous undergrowth and trees of other tiers subject to preservation during felling. The user can indicate all possible locations for them and the cost of arrangement. The program subsequently can automatically select the economically best areas allocated for loading points and temporary storage sites for coniferous undergrowth, considering their territorial location relative to the developed units within the forest quarter. When entering information about a designed technological site, each of them is assigned a separate numerical designation characterizing it, allowing not only the entry of the aforementioned user-defined data of interest but also the identification of its territorial location within the forest quarter in the MapInfo Professional GIS. If the cargo capacity of such sites is insufficient to accommodate the entire volume of removed timber, the user will be notified of a technological error during data entry. If the areas intended for planting and temporary storage of coniferous undergrowth cannot accommodate all the undergrowth that may be damaged during felling, it will be recommended to transport and plant it on the most economically feasible sites to avoid its damage during logging operations. The user has the right to independently decide on the possibility of implementing this option or to balance the task formulation when analyzing the volumes of coniferous undergrowth digging and planting.

When placing transport routes within a forest quarter from the point of view of reducing the costs of transporting coniferous undergrowth between its digging and planting sites and temporary storage sites within the forest quarter one of the primary tasks, standing before the researcher is to justify the rational laying of a network of technological corridors, ensuring minimum distances of transportation of coniferous undergrowth. Solving this task will reduce damage to the forest soil cover and increase productivity during the transportation of coniferous undergrowth. The mathematical solution to this task is possible using the least squares method, which ensures minimum distances between sites and transport routes whose location is specified as a function. As a result of the different locations of sites requiring transplantation of coniferous undergrowth in each individual forest quarter or group of forest quarters, it is impossible to select a universal scheme for the placement of transport routes that is optimal for all possible conditions of performing the complex of logging and reforestation work in the forest quarter. The software designed for creating the technological map of forest quarter development allows for preliminary analysis of the rational location of the technological corridor with the possibility of its further adjustment based on technical and economic calculations of the complex of logging and reforestation operations.

The scheme for placing a technological corridor can include not only straight-line but also curved sections and should be coordinated with the specific conditions of territorial growth of coniferous undergrowth in the forest quarter, as well as the technical and technological aspects of felling, determining the volumes of coniferous undergrowth requiring transplantation. In a forest quarter, there can be either one or several mutually agreed-upon technological corridors used for both logging and reforestation work, which allows for reducing the average skidding distance and decreasing the labor intensity of work execution. In this regard, the user performs the adjustment of the preliminary trajectory of the technological corridor.

When searching for options for laying technological corridors and main skid trails in a forest quarter, the user has the option of independently choosing their placement. This option can be proposed to the program at the stage of entering technological data. The user independently marks on the map in the MapInfo environment the most rational options from their point of view, and each unit can have several options for transport routes. When selecting options, the user draws technological corridors and main skid trails on the map using MapInfo tools. The program automatically determines the average skidding distance (movement of coniferous undergrowth) across the unit's territory and corrects the starting point of the transport route, placing it in the center of gravity of the figure bounding the analyzed unit, loading point, or temporary storage site for coniferous undergrowth. Using this capability provides the user with the fastest calculation option, as the user, based on their own experience and intuition, can preliminarily discard options they deem irrational and reduce the number of possible combinations already at the initial data entry stage. At the same time, the transport routes indicated by the user can have a curvilinear form and consequently, this option allows for maximum consideration of the presence on the ground of artificial and natural obstacles that prevent movement operations along the shortest distance between endpoints.

The variety of options for laying transport routes does not imply their mandatory use during transportation. The final decision on the advisability of using the most effective combination of transport routes should be made based on subsequent calculations.

The units marked on the map can be subdivided by the user using MapInfo tools into small plots of various shapes, for example, in case of their significant sizes or elongated shape, allowing for a decision on the advisability of either:

- performing timber skidding or transportation of coniferous undergrowth in different directions respectively to loading points and coniferous undergrowth planting sites located in different areas;
- dividing the cutting area into sections with the necessity of laying different main skid trails and skidding timber to different loading points.

Solving transport tasks when analyzing the volumes of transport operations between units and loading points with the determination of rational volumes of timber placement on them, and analyzing the volumes of transport operations between units with excess and insufficient amounts of coniferous undergrowth and (or) its temporary storage sites is the next stage of the program's work. Moreover, solving the transport task when moving commercially valuable coniferous undergrowth requires a non-traditional approach to its solution, as it involves transporting coniferous undergrowth both to the territory of the forest plot (temporary storage sites for coniferous undergrowth) and from the aforementioned territory to already developed plots. Thus, each of the plots can be both a supplier and a consumer of products in the form of commercially valuable coniferous undergrowth at different stages of its development (unlike the traditional formulation of the transport task, where each of the analyzed points can be either only a supplier or only a consumer of products)

The program for selecting options for transport and technological development of a forest quarter iterates through all variants of timber and coniferous undergrowth transportation along all possible directions specified by the user, having calculated the best volumes of movement operations for each of them, and outputs the best variant for the placement of transport routes and technological corridors with indication of the volumes and sequence of technological process operations.

4 CONCLUSIONS

The developed model for the formation of timber transport flows during forest quarter-based development demonstrates an integrated approach to optimizing logging and reforestation operations. The key achievement is the integration of transport operations for both harvested timber and coniferous undergrowth requiring transplantation from cutting areas to sites with insufficient natural regeneration.

The model enables:

- justification of rational routing of technological corridors and main skid trails considering the spatial distribution of forest inventory units;
- minimization of average skidding and undergrowth transportation distances;
- solution of a modified transport problem with dynamic redistribution of undergrowth between plots;
- preservation of soil cover through transport network optimization.

The practical significance of the results lies in the creation of technological maps that ensure efficient forest quarter development while maintaining biodiversity through the transplantation of coniferous undergrowth.

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