AUTOMATED FOREST HARVESTING ALGORITHMS: ECOSYSTEM-BASED ALTERNATIVES TO CLEAR-CUTTING METHODS

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Abstract

This research focuses on developing an innovative, multi-criteria approach to forest harvesting planning, providing an alternative to traditional clear-cutting and selection-cutting methods. The study integrates automated planning algorithms with geospatial analysis to promote more sustainable forest management practices that prioritize ecological integrity and social value, particularly in areas with significant natural and recreational importance. The proposed approach is based on the use of open-source algorithms, enabling individual forest owners or users to select logging areas by weighing ecosystem service indicators and remote sensing criteria specific to each forest stand. By incorporating adaptive harvesting parameters, this method allows for tailored decision-making that reduces the environmental impact of forestry activities while maintaining flexibility in addressing various forest management objectives. The primary objective of this research is to create a scientifically validated framework that balances timber extraction with the preservation of diverse forest ecosystem services. The approach accounts for available biodiversity data, supports recreational use, and considers other social-ecological functions of forests. The study includes the development and testing of data processing and analysis algorithms that optimize forest harvesting strategies based on ecosystem service assessments. The proposed methods are field-tested in managed forest areas to verify their practical applicability in real-world conditions. This research contributes to advancing sustainable forest management by offering data-driven, ecosystem-based solutions that address contemporary challenges in balancing timber production with broader social-ecological values, while also empowering forest owners to make more informed, site-specific harvesting decisions.

Keywords: automated planning algorithms, ecosystem services, sustainable forest management, timber harvesting planning.

Introduction

Forests are managed to fulfil various economic and social objectives, with some areas prioritized for timber production, others dedicated to biodiversity conservation or recreation, and many designed to support multiple functions (Lindenmayer et al., 2012). Achieving these diverse goals while adapting to different environmental conditions requires forest owners to apply a variety of silvicultural practices (Eyvindson et al., 2021). Although several advanced planning systems are available to support multifunctional forest management by integrating eco-geographical variables and optimizing harvesting strategies (e.g., Mason et al., 2018; Marto et al., 2019; Tahri et al., 2021; Lämås et al., 2023), their practical application remains limited. Many rely on region-specific datasets or proprietary data formats, reducing their adaptability in diverse forest conditions (Eriksson et al., 2014). Additionally, the scarcity of open-source solutions and dependence on openly accessible data further restricts access to effective planning tools, particularly for regions seeking flexible, low-cost alternatives or aiming to prioritize ecosystem services alongside timber production.

In Latvia and the broader boreal region, clear-cutting with subsequent stand regeneration by planting is the primary logging practice. This method is widely applied to promote timber production, particularly for key species such as *Pinus sylvestris* and *Picea abies*, ensuring efficient stand renewal and forest productivity (Pach et al., 2018).

The dominance of clear-cutting reflects both economic considerations and the limited implementation of advanced planning tools that account for multifunctional objectives. Expanding the use of data-driven planning approaches that integrate ecosystem services, biodiversity data, and terrain constraints could support a shift toward more sustainable and multifunctional forest management practices (Larsen et al., 2022).

The aim of this paper is to present a workflow for a mixed-method approach to automated small-scale clear-cutting that considers diverse eco-geographical conditions and ecosystem services. The proposed method supports sustainable forest management by modelling logging operations in a way that incorporates site-specific environmental factors, terrain constraints, and ecosystem service values. The workflow integrates multiple open data sources relevant to forest structure, ecological features, and landscape conditions. A customized meta-heuristic algorithm is used to identify harvesting sites while balancing multiple constraints, refining outputs through iterative, randomized search strategies.

The research tasks addressed in this study include:
- developing and implementing an automated algorithm that generates spatially explicit clear-cut units while accounting for ecological and legal constraints;
- integrating remote sensing and ecosystem service

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- indicators with forest inventory data to guide harvesting decisions at the stand level;
- testing the workflow in managed forest areas and evaluating the resulting harvesting phases in terms of spatial balance, consistency of environmental metrics, and operational feasibility.

Materials and Methods

The following methods outline the data sources, processing tools, and workflow steps used to develop an automated small-scale clear-cutting approach that considers eco-geographical conditions and ecosystem services.

Table 1

Summary of the data used

Dataset	Description	Link
State Forest Service Forest Compartment Data	Boundaries and attributes (stand composition, age, tree species etc.), of forest compartments. Vector data	https://data.gov.lv/dati/lv/dataset/meza-valsts-registra-meza-dati.jsonld
Latvian Geospatial Information Agency LiDAR Data	4 p/m² LAS data (base for DSM, DTM, TRI, TPI, slope, aspect, roughness, DTW)	https://s3.storage.pub.lvdc.gov.lv/lgia-opendata/las
Ministry of Agriculture Drainage Cadastre Data	Vector data of ditch networks, drainage pipes, and related infrastructure. Vector data	https://www.melioracija.lvhttps://lvm geoserver.lvm.lv/geoserver/zmni/ows
Nature Conservation Agency Data …	OZOLS system data – information on protected nature territories, species distributions, and habitat data. Vector data	https://ozols.gov.lv/arcgis/services/OZ OLS_DABASDATI_PUB_INSPIRE/ MapServer/WFSServer
	Species Protection Plan data. Vector data	https://www.daba.gov.lv/lv/sugu-un-biotopu-aizsardzibas-plani
Information System 'Heritage' Data	Protected sites, landmarks, and areas of cultural significance and their protection zones. Vector data	https://geoserver.mantojums.lv/geoser ver/ows
Latvian State Forest Research Institute 'Silava' Research data …	Data on ecosystem service assessments, SQL qyery	Lībiete et al. (2023)
	LIFE Programme Study – 'Demonstration of Climate Change Mitigation Potential in Fertile Organic Soils in the Baltic States and Finland' (LIFE OrgBalt, LIFE18 CCM/LV/001158). Raster data	https://silava.forestradar.com/data/rast ra-dati/DTW/DTW_10ha_ https://silava.forestradar.com/data/rast ra-dati/DTW/DTW_30ha_
OpenStreetMap data	road and trail network data with the option to supplement it with custom data for improved detail or accuracy	https://download.geofabrik.de/europe/ latvia-latest-free.shp.zip

Table 1 summarizes key datasets, including forest compartments, LiDAR terrain models, drainage networks, biodiversity, cultural heritage, ecosystem services, and road data, ensuring broad coverage for forest planning. Table 2 lists data processing tools.

Table 2

Data Processing and Analysis Tools

Tool	Description	Purpose
Python >= 3.12	Programming language used as the foundation for data loading and processing code.	Core programming environment.
Geopandas	Library for analyzing and processing geospatial data, including geostatistics.	Geospatial data analysis and processing.
Pygro	Library for high-performance reading and writing of vector data in GDAL/OGR-supported formats.	Efficient vector data I/O operations.
Fiona	Library for spatial manipulation and querying of vector data.	Vector data manipulation and selection.
Rasterio	Library for processing and manipulating raster/image data.	Raster data handling and analysis.

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Tool	Description	Purpose
Py7zr	Library for processing data archives in formats such as 7z, rar, and ZIP.	Archive extraction and compression.
Python-PDAL	Python API for PDAL (Point Data Abstraction Library) to manage and process point clouds and LAS data.	Point cloud and LiDAR data processing.
GDAL (gdaldem)	Command-line tool for terrain derivative generation (slope, aspect, TPI, TRI).	Terrain metric derivation from DEMs.
Shapely	Library for manipulation of geometric objects (polygons, lines, points).	Geometry operations and spatial filtering.
JSON / JSONschema	Configuration and validation format for pipeline execution.	Parameter definition and structured automation.
Requests	HTTP library for querying data services and downloading open geospatial data.	Automated access to online spatial data.
Pandas	Library for tabular data handling and analysis.	Attribute table processing, filtering, and statistics.

The data processing workflow begins with the user defining the area of interest, which triggers automated data acquisition from open sources. The core of the system is a modular Python library that handles data import, preprocessing, spatial analysis, and output generation. It operates through a sequence of defined steps that allow reproducibility and customization.

Preprocessing includes format harmonization, spatial alignment, and derivation of additional variables from primary data sources. Terrain metrics such as slope, aspect, roughness, topographic position index (TPI), and depth-to-water (DTW) are calculated from LiDAR-based digital elevation models using the GDAL 'gdaldem' utility and PDAL library. Canopy height is derived from LiDAR point clouds and normalized height models. Vector datasets, such as forest compartments, protected areas, and drainage networks, are filtered, cleaned, and clipped to the area of interest using Fiona, Pyogrio, and Geopandas.

Data access and model execution are managed through a JSON-based configuration structure. This allows the user to define which datasets are downloaded, reused, excluded, or converted, as well as set key parameters such as spatial resolution, masking thresholds, and classification rules. Cached downloads and standardized folder structures improve reproducibility and computational efficiency.

The core algorithm is a customized meta-heuristic routine that generates and refines spatially explicit clear-cutting units. Candidate polygons are created by constrained Voronoi tessellation (Oar et al., 2016) within forest compartments. Each unit is evaluated with a scoring function combining canopy height, slope, and ecosystem service values derived from species distribution layers. Unsuitable units are filtered out based on thresholds (e.g., slope >10°, DTW <0.2 m, overlap with protected zones).

Harvesting units are grouped into three cutting phases. A distance-based adjacency constraint prevents spatial clustering by excluding neighboring polygons from being scheduled in the same phase. The algorithm iterates through randomized orderings and filtering steps until the spatial and ecological balance across phases is maximized.

An Operational Guidance Map is generated by combining raster and vector constraints into a unified planning layer. Wet areas (DTW <0.2 m) are classified as no-go zones, moderately wet soils (0.2–1.0 m) as caution zones, and accessible terrain as suitable. Additional exclusion layers include species habitats, cultural heritage zones, and terrain barriers.

The final output is packaged as a ZIP archive for integration with forest management systems. Users can select which background variables and classifications to include in the export. The processed units are transferred into operational maps and machine-readable plans to support harvesting logistics and ecological compliance.

The processing environment is implemented in Python (v3.12) and utilizes the following libraries: Geopandas, Fiona, Pyogrio, Rasterio, python-pdal, Requests, and Py7zr. Data interactions are managed via standardized protocols (e.g., HTTP, WFS), ensuring compatibility with Latvian national open-data services and spatial metadata frameworks.

Results and Discussion

The cutting sequence results 'Figure 1' illustrate a structured approach to timber harvesting, designed to achieve a balanced distribution of clearings over time. Each forest compartment was subdivided into tessellated planning units and scheduled for harvesting in three successive phases, with a 20-year interval between phases and a cumulative harvest share of 60% of the total area. These phases represent spatial batches designed to maintain ecological continuity and avoid operational overlap. The algorithm allocated each unit to a phase while avoiding adjacency and balancing ecological and terrain characteristics. The map visualizes this phase allocation, showing how

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openings are spatially arranged to minimize the risk of large contiguous clear-cuts while ensuring gradual and distributed timber extraction.

To evaluate the performance of the spatial allocation algorithm, the model was configured to run 50 randomized iterations. Each iteration generated a different tessellation and harvesting phase assignment based on varying random seeds, while applying consistent ecological scoring and spatial constraints. This iterative setup allowed exploration of variability in polygon layout and indicator distribution. The result was selected based on achieving (i) minimal intra-phase variance in canopy height, depth-to-water, and ecosystem service values, and (ii) maximal spatial separation between cutting units within the same phase, as measured by adjacency index and unit dispersion. While no formal validation against field data was performed, all iterations adhered to legal and ecological constraints (e.g., exclusion of steep slopes and protected areas, non-adjacency rule). The consistency of ecological scoring and spatial constraints across runs

suggests that the algorithm reliably produces feasible, ecologically balanced solutions. These internal checks serve as proxies for performance assessment in the absence of ground-truth validation.

Although precise estimation of timber volume is not directly possible, a wide range of metrics was calculated for each tessellation unit to support informed decision-making. These include canopy height model (CHM) values as a proxy for stand structure and biomass potential; depth-to-water (DTW) as an indicator of site accessibility and soil moisture conditions; and ecosystem service (ES) values representing ecological and social forest functions. For each harvesting phase, average and standard deviation values of these metrics are summarized in Table 4, providing an overview of how environmental conditions are distributed across the spatial schedule. Additionally, the Operational Guidance Map supports harvester and forwarder navigation by classifying terrain into suitable, caution, and no-go zones, based on combined constraints.

Figure 1
Harvesting phases

Tables 3 and 4 show that topographic conditions, canopy height, and ecosystem service potential are consistently distributed across all harvesting phases. Table 3 provides a summary of the spatial and environmental properties of the generated cutting units, including their area distribution and mean values for terrain and canopy structure indicators, which are relevant for planning feasibility and ecological

balance. The low variation in average values and standard deviations between phases suggests that the algorithm maintained spatial balance and avoided front-loading of high-value or environmentally sensitive stands. This outcome supports the intended goal of distributing ecological and operational characteristics evenly across the planned harvesting timeline.

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Table 3

Summary of area distribution and selected environmental metrics across harvesting phases

	Area (ha)	Mean area (ha)	DTM (mean)	SLOPE (mean)	CHM (mean)	hCHM (mean)
Total processed area	157.09	0.14	9.49	4.19	10.71	16.32
Area in Phase 1 (0–20 yrs)	66.15	0.12	9.64	4.25	10.60	16.37
Area in Phase 2 (20–40 yrs)	30.53	0.17	9.23	4.09	10.78	16.22
Area in Phase 3 (40–60 yrs)	30.77	0.16	9.41	4.20	10.98	16.36
No-harvest area	29.64	0.15	9.38	4.12	10.67	16.23

The developed workflow integrates eco-geographical data, ecosystem service values, and terrain constraints, offering a flexible, data-driven approach to sustainable forest management. This method supports mitigation of trade-offs between bioeconomy goals, biodiversity conservation, and ecosystem service provision by explicitly embedding ecological and spatial criteria in the scheduling process. Unlike conventional planning approaches that prioritize timber yield or compartment-based rotation, this workflow emphasizes spatial distribution of ecological value. The results show a balanced phase allocation that promotes gradual extraction while maintaining stable forest conditions and minimizing concentrated disturbance. While these outcomes are illustrative and not predictive, they demonstrate the workflow's ability to integrate complex spatial data into harvest planning. Further real-world evaluation is necessary to assess long-term ecological outcomes, particularly with respect to biodiversity, landscape connectivity, and changing environmental conditions.

Table 4

Summary of ecosystem service potential across harvesting phases

	Medical plants	Forest berries	Fito-remediation	Cosmetics	Wind resistance	Aesthetics	Recreation	Noise reduction	Fire resistance	Bioremediation	Filtration/accumulation	Flood mitigation	Climate control
Total processed area	3.08	2.84	3.98	2.97	4.38	3.48	4.31	4.24	1.00	2.10	2.10	1.11	2.06
Phase 1 (0–20 yrs)	3.07	2.83	3.98	2.97	4.32	3.48	4.27	4.25	1.01	2.08	2.08	1.12	2.06
Phase 2 (20–40 yrs)	3.10	2.85	3.99	2.98	4.44	3.48	4.31	4.21	0.99	2.12	2.12	1.12	2.06
Phase 3 (40–60 yrs)	3.10	2.85	3.96	2.95	4.43	3.46	4.34	4.21	0.99	2.11	2.11	1.09	2.05
No-harvest area	3.10	2.84	3.98	2.97	4.42	3.48	4.39	4.28	1.01	2.13	2.13	1.12	2.06

Recent developments in spatial forest planning have emphasized the need to find a way to fulfill both timber production goals and ecological integrity goals, particularly through the use of optimization algorithms that can handle spatial constraints and multiple objectives. Borges et al. (2014) highlight how simulated annealing and related heuristics have become essential tools for spatial harvest scheduling, especially when seeking to avoid fragmentation, ensure connectivity, or control block sizes. This view is echoed in Bettinger et al. (2009), who stress that heuristic planning must be transparent in its assumptions and evaluated for spatial realism rather than pure computational output. While Borges' work focuses on simulated annealing in a context of minimizing habitat fragmentation and maximizing economic returns, the structure of the algorithm presented here shares the core principle of balancing spatial objectives through randomized and iterative allocation. However, our approach departs from theirs by prioritizing ecological indicators - such as canopy height, depth-to-water, and ecosystem service potential - rather than economic net present value. This shift reflects a broader move in forest planning toward embedding ecological constraints directly into the spatial allocation logic, rather than treating them as secondary filters. Schooler et al. (2023) demonstrate how multi-objective optimization can be used to balance timber yield with habitat suitability, using species-specific models as proxies for ecological value. While their focus is on single-species habitat dynamics, our method generalizes ecological considerations

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through terrain metrics and ecosystem service indicators, allowing broader applicability across diverse stand types.

Moreover, the evaluation of cutting unit properties in our study - including shape complexity and adjacency index - resonates with Borges et al. (2014) emphasis on spatial feasibility and implementation cost. Our workflow ensures that harvested units remain compact, ecologically balanced, and non-adjacent within each phase. This supports both biodiversity retention and smoother field logistics, aligning with Janová et al. (2024), who argue that planning systems must account for how and when harvesting occurs, not just what is harvested. Wing et al. (2019) emphasize that the real value of spatial decision support lies in its adaptability to different data availability and management goals - something our open-source, data-driven design also enables. Finally, the spatial parity achieved across phases, as shown in Table 4, demonstrates that heuristic spatial scheduling can be guided by ecological value distributions rather than solely by timber yield or infrastructure constraints. This represents a practical contribution to ecosystem-based forest management, where spatial planning is responsive to both ecological integrity and operational needs.

Conclusions

1. The presented method demonstrates that it is possible to allocate small-scale clear-cutting phases in a way that maintains spatial balance across ecological indicators and minimizes spatial clustering. The results show low intra-phase variation in canopy height, terrain accessibility, and ecosystem service values, supporting the claim that spatially structured harvesting can be ecologically and operationally coherent.

2. Although developed for the Latvian context, the workflow's reliance on modular inputs and open geospatial tools makes it technically adaptable to other regions with compatible data layers. This positions the method as a prototype for broader applications in contexts where fine-resolution environmental data are available.

3. Future development should focus on adding dynamic components such as connectivity indices, temporal stand development, and cost-based constraints. This would extend the method from spatial prioritization toward full-scale operational forest planning under multi-objective criteria.

4. By embedding ecosystem service values into the decision logic, the method anticipates future policy directions such as payments for ecosystem services and biodiversity credits. While markets for such instruments remain emergent, this design enables alignment with incentive-based governance models that are increasingly discussed in European and global forest policy frameworks.

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