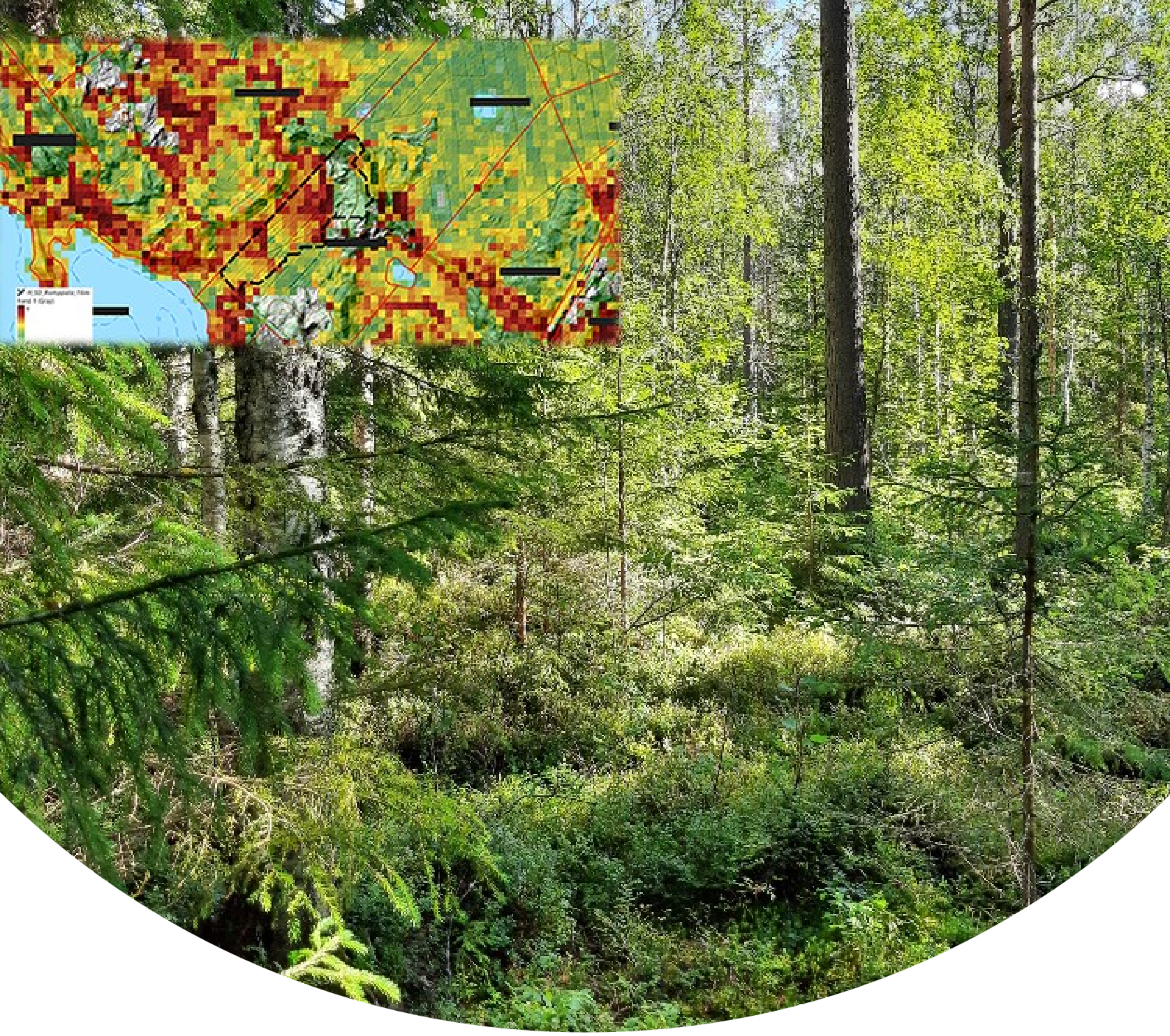

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Abstract

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This study and its developments presented an analysis process to identify forest stands that are suitable for continuous cover forestry harvest, based on tree characteristics and canopy structure. Finnish open forest resource data and national LiDAR were used as input data. Similar input data can be produced in other territories using airborne LiDAR and field reference data.

Out of 5467 stands analyzed, 925 were identified as having a canopy structure and timber stock suitable for continuous cover logging operations. The resulting maps of this study described standard deviation of tree height, basal area, dominant height and established undergrowth for potential continuous cover forestry logging stands. These maps are digital tools for targeting uneven-aged structured continuous cover forestry logging sites. They enable achieving combined large continuous cover logging blocks which improve wood procurement. Planning of the logging sites in the field also becomes more efficient when the sites are pre-selected with the help of the maps.

Continuous cover forestry can be used on other stands, but the current timber stock does not provide enough logging yield or the canopy structure does not support continuous cover structure without additional alterations or regeneration. Soil type has not been considered in this study, since continuous cover forests can be grown on different soils.

This study focused on finding stands that currently have a suitable canopy structure for continuous cover forestry. In the future, important LiDAR tool development targets for continuous cover forestry logging are terrain maps describing the traversability of a forest machine and integration of the map tools into forest machine information systems. This study focused on presenting a workflow for suitable continuous cover forestry stand identification. The accuracy of the identification should next be assessed using large field data sets.

Keywords: LiDAR, Continuous cover forestry, operation planning, canopy structure, logging planning, uneven-aged structured forest management.

Abbreviations

CCF	Continuous cover forestry
SL	Selective logging
RF	Rotation forestry
ST	Selective thinning
LiDAR	Light Detection and Ranging
CHM	Canopy Height Model

Contents

1. Introduction

1.1. Planning and implementing continuous cover forestry

Continuous cover forestry (CCF) management is a method that avoids clear cuttings, maintaining continuous tree cover. The general common CCF-thinning principle is selective logging (SL), where the parts of the trees of the dominating canopy layer are removed and the densest groups of smallest trees in the lower canopy layer are thinned. CCF SL differs from conventional rotation forestry (RF), which is based on selective thinning (ST) from below, where primarily the smallest trees are removed. In RF, ST is carried out at regular intervals during the rotation period ending with regeneration felling, e.g. clear cutting, seed tree felling, strip felling or shelterwood felling (Lähde et al. 1999, Pommerening & Murphy 2004, Mason 2015, 2022, Rautio et al. 2025, Finnish Forestry Centre 2025).

The strength of CCF is the flexibility to use its different management principles according to the goal. However, in Finland, the current methods for planning the implementation of logging from stump to roadside storage are mainly for RF and knowledge of the practical implementation of CCF is still limited. Therefore, an increase in CCF harvesting volumes requires significant investment in research and development. Training is also needed to transfer the latest information into practice. With this development, CCF can then be targeted towards achieving different forest management objectives (Table 1). More accurate targeted stand specific information is needed to implement logging and for forest owners to meet the diverse goals of forestry. Here, a potential solution is digital information on the stand structure and terrain of the logging area. This information is needed especially to give instructions to the operator (Korpunen et al. 2025). Separate precise thinning instructions are required for each forest; especially on which trees will be removed. The CCF harvesting planner must also consider the different goals and values of forest owners.

According to Luke's recent policy brief (Luke 2025), Finland will not achieve its current climate goals without reducing emissions, strengthening forest carbon sinks and comprehensive guidance on forest management and wood use. The rapid increase of forest use multi-objectives require new forest management and harvesting methods. Choosing the right harvesting method and its high-quality success require good stand-specific preliminary planning, the right technology, working method and skilled implementers. Appropriate forest management guidelines, successful pre-planning of logging as well as technologies and working methods suitable for logging areas ensure the profitability of timber production, recreational use and high biodiversity of a forest.

CCF-forests can be divided into four categories from the point of view of harvesting (Pamerleau-Couture et al. 2015): 1) uneven-aged structured mature forest; 2) even-aged structured mature forest; 3) uneven-aged structured young forest; 4) even-aged structured young forest. However, the stand structure can vary a lot within an individual cutting area (Figure 1), which is why logging implementation does not always succeed in following local forestry management guidelines (Äijälä et al. 2019).

In our study, we concentrate on uneven structured mature forests. Here, Bianchi et al. (2023) classified forest structure in terms of the difficulty of the harvester's SL implementation:

i) "*Advanced CCF*" logging site is already quite irregular in its structure (i.e. height distribution) and has been thinned before by using SL similar to an on-going CCF.

ii) "*Medium CCF*" logging site has more irregular structure than the average RF stand in Finland but has not been selectively thinned before. Therefore, it needs some level of transformation to be fully managed according to CCF principles.

iii) "Beginning CCF" logging site has a quite regular structure and has only been regularly thinned by RF ST. The first SL thinning is needed, to move towards an irregular structure.

Figure 1. The thinning treatment and its timing are crucial in successful continuous cover forestry. Left: even-aged structured stand. Right: more irregular uneven-aged structured stand (Figure: Yrjö Nuutinen, Luke).

In Finland, a large proportion of forests of a quite regular stand structure (i.e. Beginning CCF logging site) need the first SL transformation towards a CCF structure. A smaller number of forests already have an uneven-structured or are already being managed by CCF methods (i.e. Advanced CCF logging site) (Finnish Forestry Centre 2025).

Table 1. Tools for planning and implementing continuous cover forestry management, and their impacts.

Tool for planning and implementing continuous cover forestry management	Impact of the tool
Classification of continuous cover forests based on stand structure (diameter, length, stand density of trees). Development of digital tools for the pre-planning and targeting of cutting areas and harvesting.	Continuous cover forestry is targeted more efficient, resulting in increased harvesting volumes and timber supply, increasing both environmental and economic benefits.
Development of thinning models for the harvester's working location level.	The forest management level of continuous cover forests is improved, which over a longer period improves the profitability of timber production and biodiversity.
Development and documentation of harvester work methods.	The efficiency and quality of harvester work will improve which improves the activities of forestry professionals.
Development of calculation models for harvesting resourcing and profitability monitoring in cutting areas and at regional levels.	Planning and cost monitoring of harvesting resources improves. Contractors' budgeting of the workforce and equipment is improving.
Development of networks for the transfer of research and development knowledge to practice.	The research and development output will be shifted to use through cooperation between practical forestry professionals, research and teaching. This expands the knowledge of forestry operators and improves the professionalism of forestry professionals. Productivity differences between operators will decrease and the harvesting quality improves.

Light Detection and Ranging (LiDAR) is a remote sensing technology that uses laser pulses to measure distance with exceptional accuracy (GISGeography 2025). As those pulses bounce off surfaces and return to the sensor, they create millions of data points that map the shape and structure of real-world spaces. LiDAR is a promising tool in the development of digital tools for the pre-planning of logging area targeting and of harvester work.

1.2. Objective

The overall objective of this study is to find out whether uneven-structured stands, which are the most suitable for CCF management, can be identified from laser scanning data.

Open forest resource data is also used to support the search for study stands because many basic tree identifiers, e.g. length, must be used in identifying the stands. Open forest resource data is useful for this purpose because it covers most of the Finnish forest area.

The aim is also to find out whether map layers produced from laser scanning data can be utilized in the planning of CCF harvesting operations.

2. Materials and methods

2.1. Study site and input data

A pilot study examined the delimitation of the study stands by using various background materials. The emphasis was on testing a workflow that could be used for the task in a practical operation. A detailed examination of the accuracy level of each information source is left to future studies.

The study was done in an area around Romppala village, Kontiolahti, Finland (62°57'19.05"N, 29°44'0.34"E). The location of the area is presented in Figure 2.

Figure 2. Location of the Romppala study site.

The study included 5467 forest stands from open forest resource data by the Finnish Forest Centre. The data is organized by forest stand, produced using an automatic stand delineation process where the tree characteristics are the main stand creation criteria. This data contains mean and summary characteristics of the trees in each stand. The production of the data is based on automatic analysis of LiDAR and spectral data on a grid and field training plot data. Corresponding data can be produced in different forest areas around the world. The methods would require adaptation of the species classes, tree sizes etc. to the local conditions in each target territory. A more detailed description of the forest resource data can be found in the Finnish Forest Centre's open forest and nature data (Finnish Forestry Centre).

National airborne laser scanning (LiDAR) data was used in this study as input data. This data is openly available as a thinned version. Limited access full density data was also used in this study (NLS – National Land Survey of Finland). Vegetation height in our study area is presented in Figure 3.

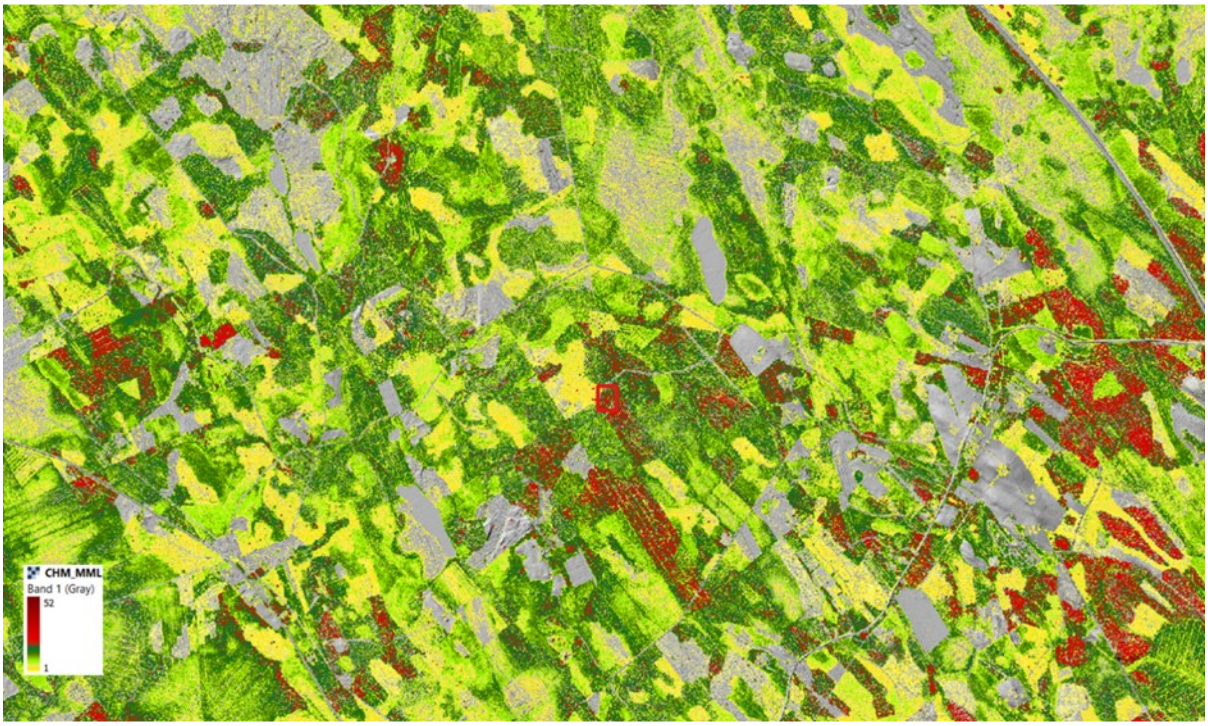

Figure 3. Vegetation height in the Romppala test area. The light and dark green colors describe the good proportion of forests having trees of thinning size class. Red shows the tallest trees, yellow trees have not yet reached commercial thinning height and grey areas are void of vegetation over 1 m in height.

2.2. Method of site selection suitable for continuous cover forestry

The following process aimed to select stands suitable for CCF. The selection was implemented visually by blacking out "unsuitable" stands based on the parameters of the stand level, one parameter at a time.

Professional judgement was used to find reasonable parameter values. The goal was to present a practical selection process and introduce one set of requirements that can be used. Determining optimal values for each selection parameter requires a large amount of training material and is left for further research.

The stand boundaries and stand data are based on the open forest resource data provided by The Finnish Forest Centre (Finnish Forestry Centre).

The key information used in the selection was standard deviation of the Canopy Height Model (CHM) height values, which presents the height variation of the canopy. The idea is that stands with an uneven-age structure tend to have more variable height structure as well.

On stands with tall spruce trees of relatively low density, branches can be found at many altitudes even if they have a uniform age structure. On LiDAR point cloud, the canopy height structure of these stands may also be variable. Thus, stands with tall spruce were excluded from the selection because they are not necessarily suitable for continuous cover forestry. In the case of tall spruce trees, suitability for continuous cover forestry shall be examined using a separate analysis.

It is also possible to alter a stand with a uniform age structure to continuous cover management by creating suitable conditions in harvest. However, this analysis has focused on finding stands where existing trees provide direct prerequisites for continuous cover forestry.

The analysis presented starts with using LiDAR data to identify stands with uneven height structure. The process to produce this layer is presented in Section 2.1.

2.3. Standard deviation of vegetation height

Forest stands with wide diameter variation are the most suitable for CCF. Such stands have trees of different diameter classes and their general CCF management method is SL. In SL, a generally accepted method is to fell part of the largest trees and thin the densest small-diameter tree groups (Puettmann et al. 2015; Lundqvist 2017). In Advanced CCF SL (Bianchi et al. 2023), the dominant trees that have reached the desired diameter class can be preferred for removal, while still maintaining targeted canopy closure and providing space for the growth of smaller trees of lower canopy layer. In Beginning CCF, the site has a uniform size structure. It may need considerably heavier thinning of the dominant canopy layer to allow regeneration and production of a younger tree generation. In Advanced CCF sites, a suitable canopy structure for continuous cover forestry can be achieved after production of the new tree generation. In this study, the aim was to find sites where different size structures were already present before harvest (i.e. Advanced CCF sites).

To identify stands with variable size structure, a standard deviation raster of vegetation height was tested wherein tree height and diameter had a good correlation. Tree height measurement is relatively easy to produce from LiDAR anywhere in the world and does not necessarily need any local field measurement data, so it was selected as a size measurement variable.

Airborne LiDAR point cloud data from the national LiDAR collection was used as input data, allowing wide usability in Finland. Specifications of the national LiDAR coverage can be acquired from the National Land Survey of Finland (NLS). Data of quite similar characteristics is available in many countries, allowing wide applicability. Ground points and vegetation points were classified into their own classes in the data. More fine-tuned point classification could be used, but since the target areas tend to be forest stands, not many non-natural objects were expected to be found in the data.

Vegetation height standard deviation raster was produced using the following process:

1. The elevation value of the ground surface was removed from the elevation values of the points in the data, leaving the Z-value of the points as the height of the point above the ground surface. This can be done, for example, with TerraScan software.

2. The vegetation and ground points of the point cloud were rasterized into a combined raster with a resolution of 1 meter. TerraScan software can be used in this task. The coordinate system’s origo was defined to be the same as the origo of the other raster data used in the project, so that the pixel boundaries aligned with the other datasets.

3. CHM was classified so that pixels with vegetation height of less than 2 m receive a "no data" value. The GIS tool "reclassify" can be used for this task.

4. A grid of vector polygons was produced for the project area. Cell size of 16 meters is quite commonly used in Finland, so it was recommended here. The co-ordinate system's origo was again defined to be the same as the origo of the other rasters in the project.

5. "Raster zonal statistics" (Standard Deviation) were calculated from the reclassified CHM for cells in the 16 m grid.

6. The values of the 16 m grid were rasterized.

7. The presentation color scheme was adjusted so that the desired range of height variation was emphasized. For example, sample stands known to have uniform canopy height and stands with uneven canopy can be used to find a suitable color scheme that separates these two. Here, green tones were used for objects of uniform canopy and burgundy was used for objects of uneven canopy. The intervening yellow tint provided a slide between the extremes.

The resulting standard deviation raster is presented in Figure 4. This is an input for further analysis.

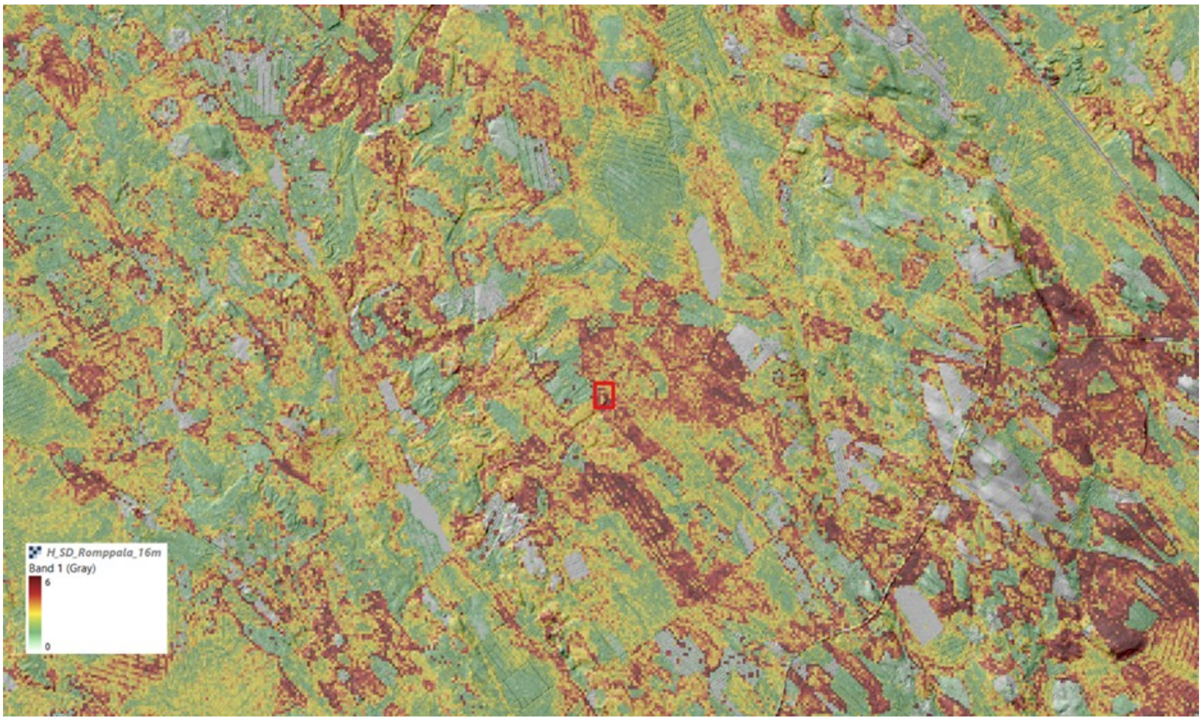

Figure 4. Standard deviation of CHM height on 16m grid, calculated from 1m CHM. The Romppala test site is in the red box in the middle.

2.4. Query to identify stands suitable for continuous cover forestry logging operations

The following criteria were used to find stands where existing trees provide direct prerequisites for CCF logging. Over time, stands of different structures can be transformed towards to uneven-age structure. However, this query was targeted to identify ones that need harvest operations soon.

1. Based on the canopy height standard deviation, the stand has a variable height structure. An uneven age structure will also probably be found on these stands.

2. The basal area is more than 20 m. This was selected as a prerequisite to do a thinning operation. The basal area limitation is made to identify stands with available thinning removal. There are stands that are suitable for continuous cover forestry with lower basal area, but harvest is probably not timely now.

3. Dominant height is over 15 m. This criterion was selected to provide saw timber yield and obviously uneven age structure. The first thinning stands can be selected using a different approach. The vegetation height map on the test area is presented in Figure 3.

4. The percentage of spruce out of the total volume is less than 90%. Pure spruce stands were removed because they have a high standard deviation of height, even on even-aged stands. In the case of pure spruce stands, sites suitable for continuous cover forestry may be identified using other methods.

5. Visibility at human eye level is less than 50 m. This indicates that the stand has an existing understory.

To select the stands, the following selection query was used:

"H_stdev_me" >3.14 AND "G" >20 AND "DOM_H" > 15 AND "V_2" / "V" < 0.9 AND "Visibility" <50

Where the following abbreviations are used:

"H_stdev_me"	Standard deviation of the vegetation height, calculated as presented in Section 2.1.
"G"	Total basal area of all tree species in open forest resource data at stand level.
"DOM_H"	Dominant height of all tree species in open forest resource data at stand level.
"V_2" / "V"	Spruce proportion of total volume in open forest resource data at stand level.
"Visibility"	Visibility calculated in meters at the height of the human eye in a horizontal direction.

3. Results

Standard deviation of vegetation height, generalized for stands, is presented in Figure 5. Results of the query to identify stands suitable for CCF logging operation are presented in Figure 6.

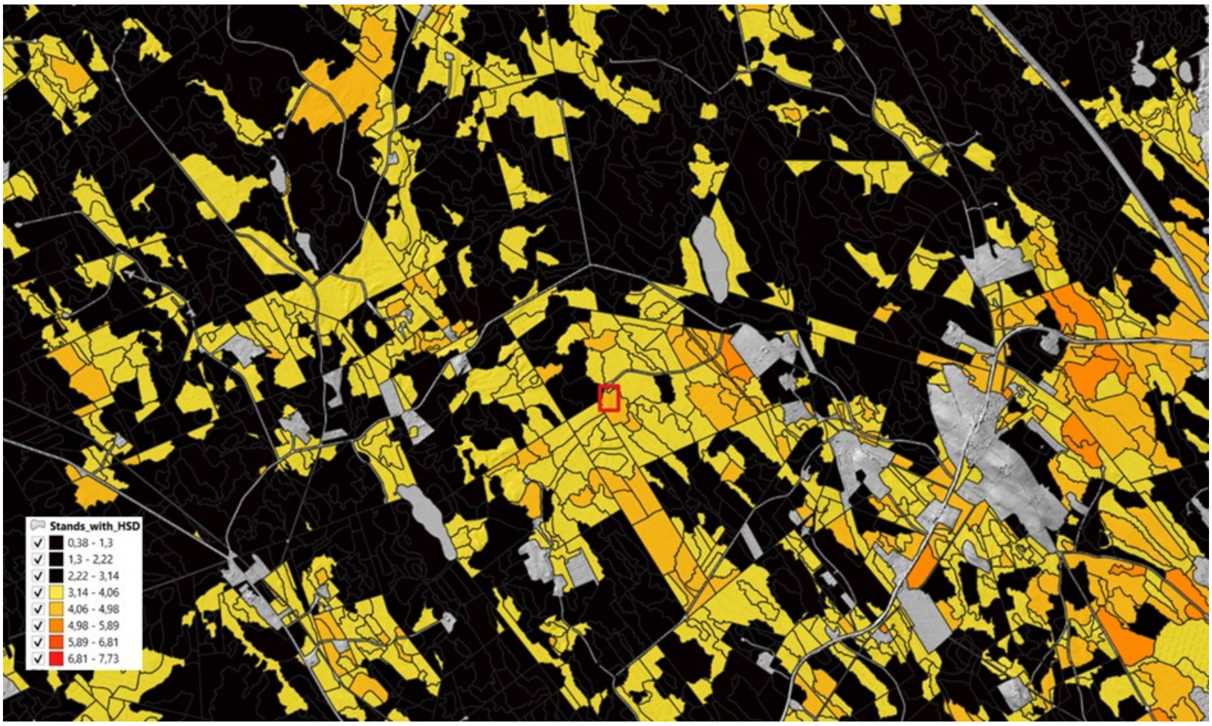

Figure 5. Standard deviation of vegetation height generalized for stands. Stands with low standard deviation of vegetation height are presented with black hues. Yellow and orange colors indicate more uneven canopy structure. The Romppala sample site is in a red box in the middle.

This presentation highlights the stands of interest and allows a glimpse over the landscape, zeroing the user's eye to the stands that would be good candidates for harvest. It still allows for indication of stands where some criteria are not met but may still be of interest, for example when combined into a suitable timber sale. Property boundaries are not shown on this map but can be overlaid if the conversation is ongoing with a given landowner.

When logging individual stands as one harvesting block, a significant part of the harvester's time is wasted in equipment transit from site to site. Achieving combined large harvesting blocks improves logging efficiency. The Figure 6 map is an effective tool to iteratively build harvesting blocks that would be economical to operate. Actual evaluation of each selected stand would be useful, after suitable packaging to maximize the harvestable area in one operation is achieved. After stand selection, the work planning can be complemented with actual harvest plan for the entire packaged harvest block. There are datasets designed for the pre-planning of harvest work.

Figure 6 shows that quite a few stands came out as potential candidates. The partial blackened areas allows flexibility in decision-making. The user can still see the stand and understand that some of the criteria are not quite met but the stand may still be practical to operate in one working block for improved work efficiency.

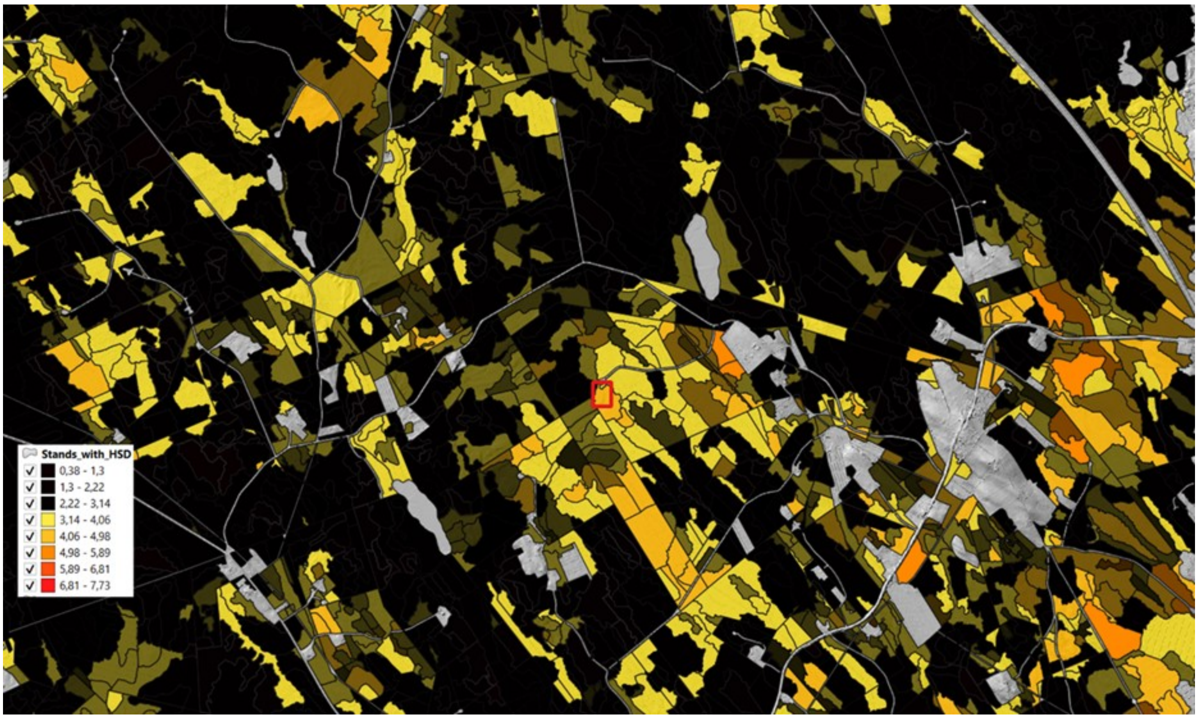

Figure 6. Standard deviation of tree height, basal area, dominant height and established undergrowth. The red and yellow hues indicate more uneven canopy structure. Stands excluded by some criteria of the query receive the coal shadowing. Stands excluded by several criteria are in black. The visualization has been implemented by blacking out the patterns that were not selected. The red-yellow theme shows the standard deviation of vegetation height.

4. Discussion and conclusions

This study demonstrated that digitalization (i.e. laser scanning datasets) has the potential to improve the finding of sites suitable for CCF and the pre-planning of logging work. Forests suitable for CCF can be identified from the Finnish open forest resource data. Various map level indices produced from laser scanning material (e.g. tree species, density of undergrowth, topography and moisture of terrain) can be utilized in the planning of CCF.

With the criteria used, quite a lot of stands were found around the Romppala test area. In the test area were a total of 5467 stands where the query was applied. Out of these stands, 925 (18.4%) were identified as being potentially suitable for CCF based on the given search criteria. These stands are promising candidates for CCF logging by SL in the next few years because the basal area allows for a reasonable thinning removal. A more detailed analysis of these stands can be done in the field.

The Romppala test site was identified in the selection process, as expected. It was chosen as a sample stand for CCF logging with field inspection.

It is recommended to do a field pre-verification for the logging sites, since the selection method is new and wide experience of the reliability needs to be gathered before moving to planning. However, the field work is more efficient when it can be focused on the pre-selected potentially suitable stands.

However, the use of the methods of this study is multi-stage and they are not yet directly accessible to forest service companies, as they require special software and their expertise. This will require further development work. The map data still leaves open the quality factors of the removed trees and the value of the accumulated timber assortments. This is important information for standing trees to maximize saw log yield with longer rotation period. Also, soil type has not been considered in this study, since CCF forests can be grown on different soils.

This study focuses on finding stands that currently have a suitable canopy structure for CCF. There are cases where CCF is especially desirable even if the canopy structure is currently not optimal. This is the case, for example, on drained peatlands where an adequate amount of remaining canopy provides evapotranspiration that keeps the soil drained without drainage ditch maintenance. Identification of these stands was left for other studies.

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