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Handling uncertainties in forest information: the hierarchical forest planning process and its use of information at large forest companies

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This qualitative study aimed to map what information is used in the forest planning process at large forest-owning companies, how it is used, its level of uncertainty and currently employed strategies to handle forest information uncertainty. An additional aim was to assess the status of the paradigm of the forest planning hierarchy in forestry. We used data from semi-structured interviews with representatives of six large forest-owning companies in Sweden, representing 30 per cent of the productive forest land in the country. Our results show that the forest planning process is a hierarchical system of decisions where the information used in the different planning stages is of varying quality and that the traditional hierarchical planning paradigm still plays a vital role in forestry. The most central source of information in the whole forest-planning process is the forest stand database (forest inventory). This includes uncertain information from various sources, including subjective field measurements and aerial image interpretation. However, the use of remote sensing estimates to feed the databases is increasing, which will probably improve the overall quality. Another important finding is that forest companies tend not to use decision support systems or optimization models to solve planning problems outside the scope of strategic planning; thus, most planning is done manually, e.g. in a geographic information system (GIS) environment. Apart from the hierarchical division of the planning process itself, we identified six main strategies that the companies use to control information uncertainty, namely locking the future by making a decision, utilizing a surplus of available harvests, updating information before a decision is made, replanning when the plan is found to be infeasible, planning by looking back and ignoring the uncertainty, either intentionally or unintentionally. The results from this study increase our understanding of contemporary forest-planning practices and will be helpful in the development of decision support systems and methods for information collection.

Introduction

Forest planning is essential for achieving sustainability in forestry (MacDicken *et al.* 2015), and the dominating paradigm of forest planning rests on a planning hierarchy (e.g. Weintraub and Cholaky 1991; Martell *et al.* 1998; Church *et al.* 2000; Sessions and Bettinger 2001; Gautam *et al.* 2017). According to this paradigm, the planning hierarchy consists of three stages, namely, strategic, tactical and operational planning. Strategic planning (the highest stage) deals with company-wide questions such as plans for sustainable harvest levels over more extended time periods and areas (e.g. Gunn 2007). Operational planning (the lowest stage) focuses on the day-to-day scheduling of harvest machines and how to meet delivery demands (e.g. Epstein *et al.* 2007). Finally, the tactical planning (intermediate stage) works as a bridge between the other stages and mainly facilitates the scheduling of what stands (i.e. treatment units) to harvest in what year in order to fulfil the strategic aims (e.g. Church 2007). Traditionally, this stage also includes the planning of road maintenance and the detailed planning of individual harvest areas (e.g. Church *et al.* 2000; Mobtaker *et al.* 2018). Due to the dominance of the paradigm, neither the hierarchy's implementation in forestry nor its effectiveness has been heavily researched. This is especially the case for large forest-owning companies, and there are only a few publications on the forest planning process at such organizations (Tittler *et al.* 2001; Eriksson 2008; Laamanen and Kangas 2011; Nilsson *et al.* 2012). See Figure 1 for a graphical summary of the current paradigm.

Planning on all hierarchical stages relies on information about the forest resource (Nilsson *et al.* 2012). This forest information is structured data about the current and future (modelled) states and properties of forests and related management (Ackoff 1989). In the Nordic countries, forest information for operational use is commonly stored as tabular stand mean values in forest

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stand databases (stand inventories) combined with maps showing boundaries between stands (Nilsson *et al.* 2012). The forest stand databases are a typical case of wall-to-wall information, i.e. they contain information about all stands.

The information in the forest stand databases has historically been collected in large-scale field-based forest management inventories (FMIs, see Kangas *et al.* 2018 for definition) and stand delimitation campaigns where all stands were subjected to measurements of some kind (Maltamo *et al.* 2021). Both objective and subjective (ocular) field-based inventory methods have been used in these inventories, even if the latter has been more common (Ståhl 1992; Koivuniemi and Korhonen 2006). In addition, manual interpretation of aerial and satellite imagery (Hesselman 1939; Åge 1985; Iverson *et al.* 1989) has aided the field inventories during the latter half of the twentieth century. During recent decades, however, estimates from other satellite-based sensors (Holmgren and Thuresson 1998; Reese *et al.* 2002); aerial light detection and ranging (LIDAR) (Næsset *et al.* 2004); terrestrial LIDAR (Maas *et al.* 2008) and digital photogrammetry (Bohlin *et al.* 2012) have emerged as viable alternatives to field-based inventory methods and have been successfully implemented in forestry (Næsset 2014; Nilsson *et al.* 2017). The main strength of these remote sensing (RS) methods is that they produce wall-to-wall forest resource maps for large areas at short intervals with greater spatial and temporal detail than traditional field-based FMI information in forest stand databases (Nilsson *et al.* 2017). However, RS methods also have weaknesses, e.g. some parameters like site index and age are difficult to estimate; estimates for some forest types, for example, young forests, have high uncertainty; and most estimates based on regression or imputation tend towards the mean (Barth *et al.* 2012; Kangas *et al.* 2018).

Depending on the underlying forest information that is used, forest planning can be performed with either an area-based or strata-based approach. Area-based planning (ABP) uses the information in the entire forest stand database as the basis for the planning process (Nelson *et al.* 1991; Murray 1999). However, this approach has some limitations when applied to strategic planning. First, the size of the planning problem for large forest holdings typically includes more than 100 000 stands, making planning problems complex and complicated to solve (Liittschwager and Tcheng 1967). Second, the low or unknown accuracy of the forest stand database information makes it less appropriate as a basis for strategic planning (Duvemo *et al.* 2014). Turning to the strata-based planning (SBP) approach reduces the problem size by aggregating stand-level information into strata based on properties like species, age and timber volume (Daust and Nelson 1993; Church *et al.* 2000). The planning problem is then to find the optimal area of each stratum to be harvested at each time point. An extended version of SBP is to perform a sample-based FMI. Here, a stratified sample of stands is selected (with the forest stand database as the sampling frame), and each sampled stand is surveyed with field plots (Lindgren 1984). Each sample stand thus represents a proportion of the total area of the forest holding. In comparison with ABP, this version of SBP reduces the problem size and avoids uncertainty from forest stand database information. This approach has dominated strategic planning at large forest companies in Sweden since the 1980s (Jonsson *et al.* 1993). ABP, on the other hand, has received more attention outside Sweden (Nelson *et al.* 1991; Murray 1999). Because ABP uses wall-to-wall forest information, it can in contrast to SBP facilitate explicit spatial considerations. These consideration are, however, of higher importance in tactical and operational planning situations (Rönnqvist *et al.* 2015). These planning phases concern economic aspects like the concentration of harvests along roads (Naderializadeh *et al.* 2020) as well as environmental aspects like the spatial allocation of potential habitats for species (e.g. Öhman *et al.* 2011). Ideally, spatial aspects should be considered on the strategic stage too, but the typical long planning horizons and large geographical areas and the consequently large problem sizes make it cumbersome (Næsset 1997; Bouchard *et al.* 2017; Mobtaker *et al.* 2020).

Potentially, ABP can be developed even further in parallel with the development of RS (which nowadays provides information with high resolution), optimization methods (which are becoming more efficient) and recent increases in computation capacity. For example, the dynamic-treatment-unit approach aggregates elements (e.g. forest information in a 10×10 m^2 raster) into temporary treatment units in both time and space without considering traditional (permanent) stand boundaries (Holmgren and Thuresson 1997; Heinonen *et al.* 2007; Magaña *et al.* 2013; Wilhelmsson *et al.* 2021). However, no matter which approach to forest planning one chooses, the uncertainty of information should be considered (Kangas 2010).

Perfect forest information with complete certainty is rare or maybe even impossible, i.e. forest information will always have some degree of uncertainty. We define uncertainty as the incompleteness of the knowledge about something's true state (Ayyub 2010). This uncertainty can be either objectively assessed as a statistical element describing the probability distribution of something's true state (Tannert *et al.* 2007) or as some subjective notion of a decision-maker, depending, for example, on the decision-maker's risk preferences (Pukkala and Kangas 1996; Blennow *et al.* 2014; Rinaldi and Jonsson 2020). Therefore, both the objective and subjective natures of uncertainty must be considered when addressing the impact of uncertainty on forest management.

Pasalodos-Tato *et al.* (2013) give an overview of common sources of uncertainty in forest management, of which two are relevant for this study: uncertainty of measurements or estimations and uncertainty from models. Traditional field-based measurements for central stand attributes, like stand basal area, yield estimation errors of ∼10–20 per cent for subjective methods and ∼2–10 per cent for objective methods (Ståhl 1992). When using field measured ground truths as reference data, measurement errors also affect RS estimates. However, model uncertainty also plays a significant role in RS because most such estimations are modelled from indirect measurements from sensors. One of the more common RS methods is airborne LIDAR, which can produce estimates with errors smaller than 10–20 per cent (Hyyppä *et al.* 2008; White *et al.* 2016). Estimates from airborne LIDAR have similar quality as traditional field-based inventories commonly used in the Nordic countries (Bergseng *et al.* 2015; Nilsson *et al.* 2017) or even better (Persson *et al.* 2022).

There is a trade-off between the cost of lowering the uncertainty of forest information and the increased benefit from better decisions based on improved or new information (Duvemo and Lämås 2006). This trade-off can be examined with a Cost-plus-loss analysis that minimizes the sum of the costs of information acquisition and the losses from suboptimal decisions based on that information. Cost-plus-loss is suitable for evaluating information acquisition methods and the value of information before using it in forest planning procedures (Gilabert and McDill 2010). Finding the minimum cost solution can be accomplished through either an analytical (Hamilton 1970; Ståhl *et al.* 1994) or a simulative approach (Sprängare 1975; Larsson 1994; Eid 2000; Holmström *et al.* 2003; Holopainen *et al.* 2010; Mäkinen *et al.* 2012; Duvemo *et al.* 2014). However, utilizing knowledge about information uncertainties when solving actual planning problems can also be approached with other operation research methodologies (Pasalodos-Tato *et al.* 2013). There is a steady flow of suggestions about such methods and how to include them in a decision support system (DSS) (Eyvindson and Kangas 2014; Eyvindson *et al.* 2018; Alvarez-Miranda *et al.* 2019; Alonso-Ayuso *et al.* 2020; Rinaldi and Jonsson 2020). However, few methods appear to be easily implemented in practice, most likely due to the exponentially growing size of the problem and results that perhaps are difficult to understand and interpret for a non-expert.

The development of new methods for forest information acquisition is a highly active field of research (White *et al.* 2016). However, how information is used in practical forest planning, its current value for decision-making and how its quality might be improved to increase its value are also important topics. Kangas (2010) suggested that the actual use of the collected information should be mapped together with what decision-makers need from such information in terms of quality. Such a mapping would help researchers and forest practitioners to focus on the most beneficial development of new information acquisition methods. Unfortunately, only a few studies have examined what (and how) forest information is used in practice in large-scale forestry (Laamanen and Kangas 2011; Nilsson *et al.* 2012; Borges *et al.* 2014).

Sweden has an international reputation for its thriving forest industry sector (Lindahl *et al.* 2017). Furthermore, the country is heavily forested and has a high production of industrial round wood considering its small size and boreal location (Ahti *et al.* 1968; FAO 2020a, b; SLU 2020). Some reasons behind this productivity are the focus of many actors on high forest production through intensive even-aged forest management, combined with a highly developed forest industry, a low degree of regulations (Lindahl *et al.* 2017), a long tradition of computer-aided planning (Stridsberg 1959; Jonsson *et al.* 1993) and a significant share of the forests (~37 per cent) owned by for-profit organizations (Swedish Forest Agency 2018). Studying the implementation of forest planning in Sweden should therefore provide interesting results for the international community.

This study aimed to map the information available for the forest planning processes at large forest-owning companies, how it is used, its level of uncertainty and currently employed strategies to handle forest information uncertainty. An additional aim was to assess the status of the paradigm of hierarchical forest planning, especially concerning the management of information uncertainty. The following research questions guided our study:

- **RQ1:** Is the hierarchical forest planning paradigm implemented in large forest-owning companies? If so, how?
- **RQ2:** What forest information is used by large forest-owning companies, and how?
- **RQ3:** What level of uncertainty does this forest information have?
- **RQ4:** What strategies do large forest-owning companies employ to handle or control the effects of forest information uncertainty?

RQ1 and RQ2 relate to the forest planning process, how it is structured and how it facilitates different uses of forest information. RQ2 and RQ3 relate to the input of information in the process and its quality. RQ4 covers the potential strategies that forest companies use to handle or control the effects of information uncertainty. We argue that we cannot answer RQ4 without first mapping the overall forest planning process with the information used (RQ2), how it is used (RQ2), the level of information uncertainty (RQ3) and how the traditional planning stages relate to each other (RQ1).

Methods

This study employed a qualitative research methodology with semi-structured interviews of representatives from large forest owning companies in Sweden (Miles and Huberman 1994). The sample consisted of six production-oriented forest companies managing more than 200 000 ha of productive forest land (see Figure 2 and Table 1 for a map and an overview). The total area in the sample represented more than 30 per cent (7.8 million ha) of the productive forest land in Sweden. The purpose of this sampling strategy was that the larger companies would have greater incentives for employing a formal forest planning process (Eriksson 2008).

The sampled companies were asked who in their company knew the most about the overall forest planning procedures, from forming strategies to the actual harvesting of a single stand. The suggested persons had titles such as head of forest planning, forest management specialist and head of forest management, and these persons were chosen to be our respondents. We interviewed the respondents in person or via an online video conferencing system (due to covid-19 restrictions). All interviews were recorded and transcribed into written language, averaging 177 min and 24 192 words in length. The interviews were aided by an interview guide that was developed from our research questions with inputs from a read-through of internal documents provided by three of the companies (see supplementary files online). Because the interviews were semi-structured, questions not included in the guide were asked if needed, e.g. for clarification purposes. In addition to answering the questions, the respondent and the interviewer created a process map including all actions and decisions that needed to be made throughout the company's organization before a stand could be harvested (see Figure 3). The map included the information used for each activity or decision, its perceived certainty and how it was used, i.e. in what system or DSS it was used. The respondents categorized all activities and decisions as either strategic, tactical or operational. The interviews did not cover planning related to local timber purchases. All collected information was stored in a

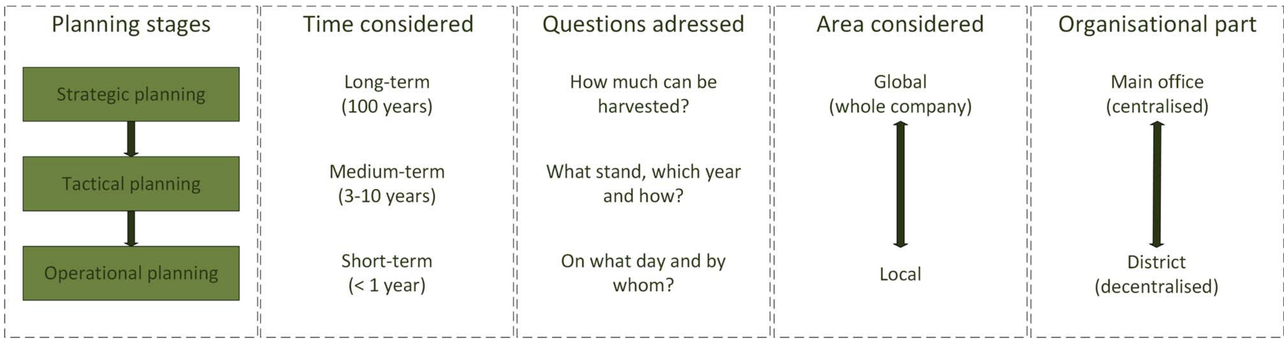

Figure 1 Conceptual summary of how forest planning at large forest-owning companies in the Nordic countries is described in the forest-planning literature. After Eriksson (2008).

Table 1 An overview of the six companies in the study. The numbers indicate in what region of Sweden each company has holdings, from north to south: (1) Norra Norrland, (2) Södra Norrland, (3) Svealand, (4) Götaland. See Figure 2 for a map. The sources of the information in this table are the companies themselves.

Company name	Productive forest land	Connection to industries	Ownership	Geography
BillerudKorsnäs AB	Manages Bergvik Skog Öst's forests, 295 000 ha, and its own forests, 50 000 ha. In total: 345000 ha	Owns multiple pulp and paper mills	Private, primarily institutional owners	Mainly in 3
Holmen AB	1043 000 ha	Owns multiple pulp, paper and sawmills	Private	Mainly in 1 and 2. Some in 3 and 4.
Kopparfors Skogar AB	230 000 ha	Independent. Sells felling rights to harvesting companies. Does not own any industries.	Private. Private foundations own the parent company	2, 3, and some in 4
Stora Enso AB	1139 000 ha	Owns multiple pulp, paper and, sawmills	Private, primarily institutional owners	Mainly in 3. Some in 2 and 4
Sveaskog AB	3050 000 ha	Owns 50% of Setra Group AB, a sawmill company	100% government owned	Mainly in 1 and 2. Some in 3 and 4
Svenska Cellulosa Aktiebolaget SCA	2000 000 ha	Owns multiple pulp, paper and, sawmills	Private, primarily institutional owners	1 and 2

computer-assisted qualitative data analysis software that aided the analysis, which aimed to find general trends and patterns in the material from all companies. The process maps were essential for the analysis, especially in searching for similar or dissimilar practices between companies.

Results

The results are divided according to our research questions. The most important results are summarized in Table 2. See Figure 3 for a graphical summary of the planning process based on the collected process maps.

RQ1: Is the hierarchical forest planning paradigm implemented in large forest-owning companies? If so, how?

The results from our interviews show that the structure of the forest planning process at large forest-owning companies in Sweden is set up as a hierarchy, adhering to the traditional paradigm, with three distinct stages. The stages answer different questions; they use different information (see RQ2), they are the responsibility of different parts of the organization and the lower stages follow the aims and boundaries set by the higher stages.

The companies themselves describe their planning processes as consisting of three stages—strategic, tactical and operational. In the strategic stage, the companies set up overall aims and strategies for sustainable use of the forest resource. These strategies are then transformed into sustainable harvest levels with an optimized harvest assessment (see RQ2) conducted by the main office. The final decision about these levels is made by executive management or the company's board. The harvest levels are the only formal connection between the strategic and tactical stages because they function as targets for the lower stages.

The tactical stage's primary purpose is to plan when to perform harvest activities in individual stands in order to fulfil the harvest levels set by the strategic stage. This stage also includes the clustering of harvest areas to road networks and road

Table 2 A summary of the most important results.

	Planning stage			
	Strategic	Tactical	Harvest area planning (part of the operational planning)	Operational
Questions addressed	How much can be harvested sustainably in the coming 100 years?	What stands should be harvested in what year to fulfil the strategic harvest levels?	How should this stand be treated?	What week/day should this stand be harvested, and by whom?
Time considered	100 years	3–10 years	One year	Months
Area considered	The whole company	Regional level or smaller	A small group of neighbouring stands	District level or smaller
Part of the organization	Specialists and managers at the main office	Planners at the regional, district, or planning department	Planners at the district or planning department	Production leaders at the district or production department
Information used	Strata-based: sample-based FMI Area-based: wall-to-wall forest stand database	Forest stand database and information about roads	Forest stand database, public and internal GIS layers about natural, technical and cultural values	Harvest area database, forest stand database, delivery plan and weather forecasts
Main output	Strategic plan, i.e. harvest levels	Tactical plan, i.e. latest date for harvest area planning in individual stands	Harvest instructions. Summarized in the harvest area database	Operational plan, i.e. a list of stands that machine group X should harvest on what day
How the information is used	Optimized harvest assessment in a DSS	Manually in a GIS aided by either a GIS filter or an optimization model	Manually in a GIS	Manually in spreadsheet-based systems
Level of certainty in the information	Strata-based: high Area-based: low, but sufficient	The forest stand database is considered uncertain. The same goes for road information.	Mostly low	Non-relevant due to the manual approach
Main strategies to handle information uncertainty	(1) locking the future, (2) buffering and (3) gathering of new information, and to some extent: (4) replanning	(1) locking the future, (2) buffering, (6) ignoring the uncertainty and to some extent (3) gathering new information and (4) replanning	(2) buffering and (3) gathering new information	(2) buffering, (4) replanning, (5) looking backwards and (6) ignoring uncertainty

maintenance planning. The aims for the extent of the tactical plan vary among the companies but range from 3 to 10 years' worth of timber harvest volumes with a temporal detail of individual years. At the smallest company, the planners make sub-plans for their district (∼25 000–40 000 ha), later aggregated to the company level. With increasing sizes of companies comes more centralized tactical planning, with specialized personnel making plans for larger areas.

The operational stage consists of two parts, namely harvest area planning and operational planning. Harvest area planning produces detailed harvest plans and instructions for individual stands grouped into harvest areas. The organization of this work differs among companies. The larger ones have more specialized processes, with the harvest area planners working most of their time with this detailed planning. When the harvest area planning for an area is finished, the responsibility to fulfil the harvest levels by creating the actual operational plan is transferred from one department (often called the Planning department or District X) to another (often called the Production department). At the same time, there is also a subtle shift of focus from a long-term and silvicultural planning perspective, where the aim is to maximize the utility and production of wood, to a more short-term planning perspective aiming to minimize costs in the production apparatus.

RQ2: What forest information is used by large forest-owning companies, and how?

The companies use many different sources of information throughout the planning process. Most forest information has been either assessed with RS or subjectively estimated in the

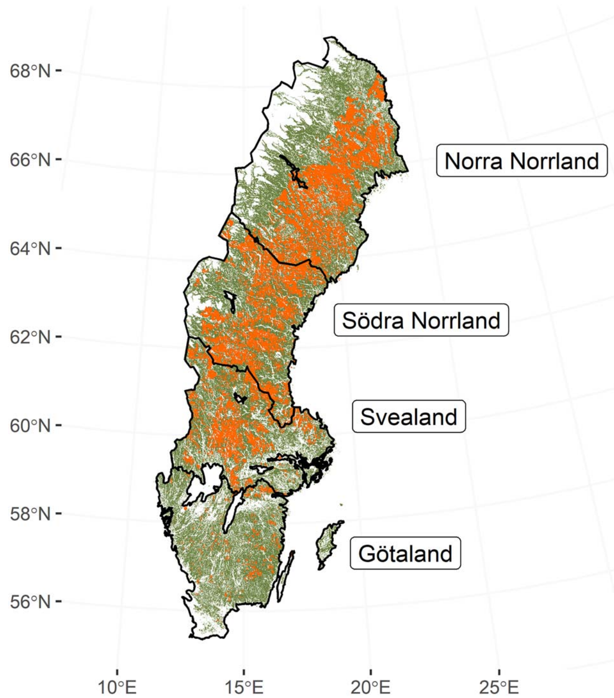

Figure 2 The approximate extent of the forest land managed by the studied companies is shown in orange, while the approximate extent of the additional forest land in Sweden is shown in green. Sweden's regions are indicated by their respective name and black outline.

field. The use of objective inventories is only standard practice in strategic planning.

All companies use Heureka PlanWise, a DSS developed for Swedish conditions, for the optimized harvest assessment on the strategic level (Wikström *et al.* 2011). The system includes a stand simulator with ecological, silvicultural and economic models that produce alternative treatment programmes and an optimization module that assigns treatment programmes to stands. The companies use the system to calculate harvest levels for 100 years with linear or mixed-integer programming with a model I formulation (Johnson and Scheurman 1977) that maximizes the net present value (Arnold 2014) of all future forest management with mathematical restrictions that emulate real-world limitations and aims (Kaya *et al.* 2016). Some examples of these restrictions are requirements of sustainable yield, an even flow of harvested timber volumes, an even geographical distribution of harvest operations, and a demand for a certain surplus of harvestable stands at any given moment in the future (a planning reserve).

The type of information the companies use as input for the optimized harvest assessment depends on their planning approach, i.e. whether they use SBP or APB. For companies using SBP, the input is a sample-based FMI with tree-level surveys in a set of sample stands, each inventoried on ~10 circular field plots per stand (for further details, see Lindgren 1984). Even though this strata-based approach is the most common, there is an increasing interest in using the area-based approach instead. Two companies have already implemented or plan to implement such an approach soon. An overview of the information used in both

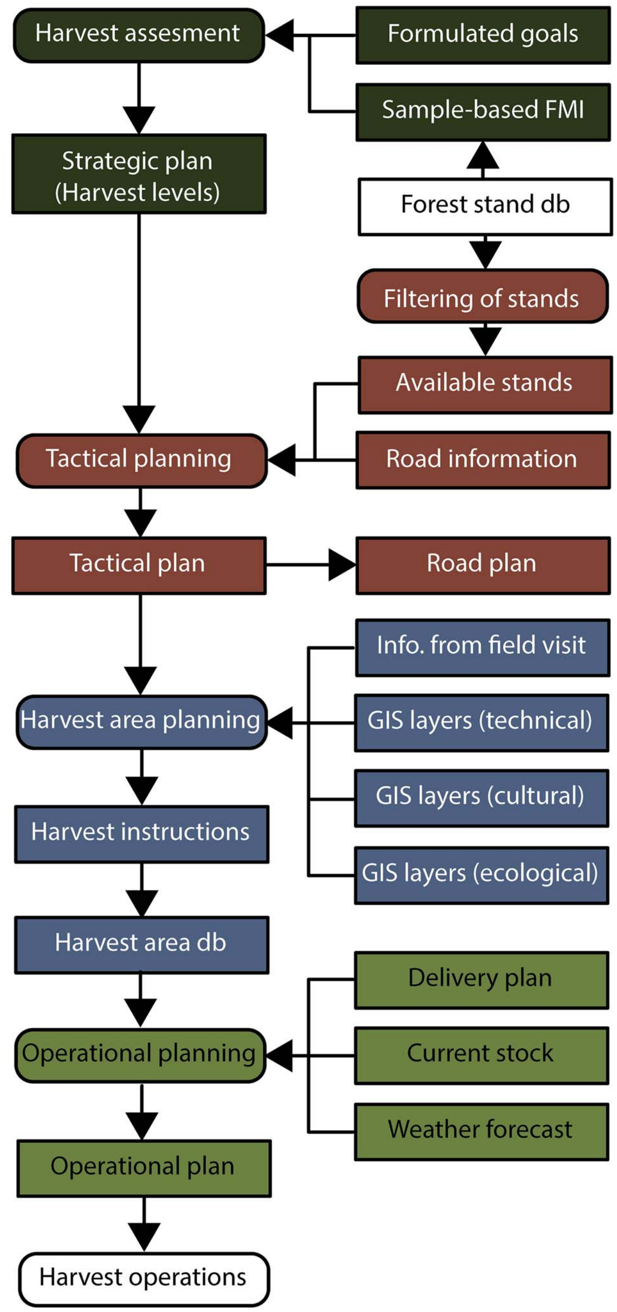

Figure 3 A generalized and simplified example of the process maps created during the interviews. The colours of the boxes indicate the planning stage: dark green for strategic planning, brown for tactical planning, blue for harvest area planning (part of the operational planning) and light green for operational planning. Rounded boxes are activities, while those with sharp corners are information used for these activities.

approaches for strategic planning is found in the supplementary files online.

Outside the strategic stage, most planning activities and decisions are not supported by any DSS. The companies use systems that support the process, but no system formally qualifies as a DSS (Vacik *et al.* 2015). When asked why they do not use optimization, one company stated that the manual solution performs better when considering the real world. Alternatively, as the respondent put it: '*An optimizing tool tends to optimize only the thing you ask for and leave the rest unanswered. To really benefit from an optimization, the description of the reality needs to be sufficiently good*'.

According to the respondents, the forest stand database is the most central forest information source in all planning stages. The forest stand database generally consists of a forest map with delineated stands and corresponding tables of information on each stand. The information is primarily made up by traditional forest parameters such as timber volumes, tree height, stem diameter, stand basal area, age and site index. The database also keeps track of previous and planned management activities. The sources of forest information are diverse. Some are from aerial LIDAR and some are from objective inventories, but most are from subjective inventories and ocular estimates by individual forest officers. Most companies have historically updated the forest stand databases with large-scale field-based FMIs at uneven intervals, but none have conducted any during the last decades. Instead, the strategy is to update the database on the go, meaning that forest officers update any information when needed. Updates of the forest stand database with estimates from nationwide LIDAR-based forest resource maps have also been done (Nilsson *et al.* 2017).

The companies use one of two methods in their tactical planning, namely filtering or optimization. With filtering, geographic information system (GIS) models produce subsets of stands from the stand database available for harvest by removing all stands younger than the lowest legal age for harvest and those newly fertilized or thinned. With optimization, Heureka PlanWise, with an area-based mixed-integer model, is used to distribute the harvest levels on the stands in the database, i.e. to decide what stands to harvest in order to fulfil the strategic harvest levels. The settings are similar to the optimized harvest assessment at the strategic stage, with two notable differences: the wall-to-wall forest stand database is used as the underlying information, and a restriction forces the solution to fulfil the harvest levels in the strategic plan. Irrespective of the approach, planners choose stands manually from the resulting GIS layer in order to make up the tactical plan. Thus, a planner following an optimization approach often disregards suggestions made by the optimization or at least tweaks the solution. In addition, the planners can use any other information available in the company's GIS databases for their decisions, e.g. aerial photos and thinning indexes. A thinning index is a wall-to-wall raster data map modelled from LIDAR-estimated forest density and height together with traditional thinning guidelines or growth and yield tables, i.e. for every point in the forest, the map will show the user an estimated need for thinning. The index is one of the most appreciated GIS layers among planners because it is found to be much more accurate than traditional thinning planning based on stand averages. The planners are aided in their work by a business intelligence system that summarizes the tactical plan in a digital dashboard as the work progresses. The dashboard compares the current version of the plan with the harvest levels from the strategic plan.

In the operational stage, the harvest area planning phase consists of preplanning, a field visit, and the compilation of harvest instructions for the machine operators. The first and last are mainly conducted in the office, even if field-adapted software and hardware allow it to be conducted in the field. The harvest area planners manually choose potential stands for field visits from the tactical plan and group them into harvest areas. The resulting harvest instructions include information about the harvest area, with directives for the operations, a map, a yield forecast and instructions for environmental and cultural considerations. There are no DSSs aiding the planners. Instead, they have to interpret a large number of GIS layers manually. A list of information sources used in harvest area planning is found in the supplementary files online. Finally, the finalized harvest instructions are sent to the harvest area database, which makes up the primary information used later in the operational stage.

The creation of the operational plan consists mainly of production leaders manually choosing suitable harvest areas from the harvest area database and assigning them to machine groups on specific dates. The resulting plan indicates what stand should be harvested, by what machine and on what day/week. To create the plan, production leaders need to know what volumes particular customers or internal industries demand. They also use current geographical positions of machine groups, weather forecasts and updated yield forecasts. Additionally, the production leaders use the overall composition of the harvest area database in trying to predict future scenarios.

RQ3: What level of uncertainty does this forest information have?

Even though the respondents considered the general quality of the information to be quite low, they did not think it was impossible to work with, as exemplified by this statement: '*It depends on what you mean with large uncertainties. If one discussed that with a chemist, he or she would think that all we have [in forestry] are large uncertainties. However, the deviations combine in such a way as when looking at the complete picture, it works.*'

The sample-based FMI in the strategic stage is considered certain by the respondents. Even when standard errors for total timber volume estimates are as large as 2 per cent, only the fact that the uncertainty levels are known makes them see it as certain. The harvest levels based on these FMIs are also considered certain. On the other hand, the forest stand database is viewed as uncertain, with the primary reason being the diversity and sometimes unclear origin of its underlying information. Moreover, all companies use growth models to update the information in the database annually, resulting in higher levels of uncertainty (see, e.g. Holopainen *et al.* 2010). One company stated that the information in the database has relatively small systematic errors because of an update with LIDAR estimates a decade ago. However, because the forest stand database is constantly being edited by many forest officers and continuously updated by growth models, the company does not fully trust it for large-scale decisions or analyses, such as the optimized harvest assessment. On the other hand, small-scale decisions and analyses, like the scheduling of harvests in the tactical plan, are heavily dependent on information from the forest stand database. One of the respondents reflected on the lack of maintenance of the database and concluded that it is not surprising that there are many errors in the database when so little focus is set on improving it or on registering high-quality information in the first place. Even if some planners want to improve the information, it is often difficult to do so. For example, at one of the companies, changes regarding stand boundaries have to be made at the main office and cannot be made by the individual planner. There are no plans at any of the companies to do any full-scale field-based FMI to gather new information for all stands. Some companies, however, plan to update their databases with new LIDAR estimates from the second nationwide campaign. Notably, no automatic error detection protocols are included by default in the most commonly used forest stand database system.

A forest stand database with many errors and uncertain, or non-existing, information on positions and quality of nature conservation values is a challenge, especially with a shortage of mature forests. One of the respondents summarized the challenges: *'We are currently harvesting the last remains of the older forests (. . .) and we are doing it with the support of a forest stand database that contains errors (. . .). Proportionally, there are more errors in the small share of remaining semi-natural forests.'* In summary, many of the stands the companies plan to harvest have erroneous information and many nature conservation values to consider, making it challenging to fulfil the strategic harvest levels when parts of or whole stands need to be set aside due to legal or certification reasons.

For tactical planning, the respondents consider the thinning index (see RQ2) much better for identifying stands in need of thinning than the information in the forest stand database (stand averages). One of the respondents explained the preference: *'We have used this [thinning index] and have had great success. We have thinned where thinning was needed instead of where one thought it was needed.'* While the thinning index is viewed as certain, the quality of the information on road status is low, resulting in field visits to ensure that roads fulfil the status requirements before sending harvest machines there.

At one of the larger companies, the harvest area planners have more than 100 internal and external GIS layers available to consider (for an overview, see supplementary files). The respondents saw these information layers as certain, except for the governmental database on cultural heritage sites. Its low quality forces the planners to conduct comprehensive inventories of every harvest area to locate unregistered sites, because they are protected by law. The most significant problem is the database's incompleteness. The same goes for information about nature conservation values. The companies do not know whether the information they have is to be trusted or not because it can be old, incomplete or erroneous. Nevertheless, when the information gathered during the harvest area planning is transformed into the harvest instructions, most companies consider it very certain—at least in the sense that the considerations towards cultural and natural values are precisely documented on a map and marked in the field. The case is similar for information about technical aspects in the instructions, such as harvest road quality, terrain slope class and soil wetness. However, the quality of the information on volumes of timber assortments is low. When considering all these aspects, the general view of the quality of the harvest area database is that it is not to be fully trusted.

RQ4: What strategies do large forest-owning companies employ to handle or control the effects of forest information uncertainty?

The division of the forest planning problem into a hierarchical structure is, in itself, a strategy for controlling the effects of forest information uncertainty. By answering specific questions associated with the different stages, the companies use the information that is best suited for the question and can balance the cost of the information with its utility. When introducing a hierarchical structure, the companies also reduce the problem complexity making it easier to foresee the effects of uncertain information in a more limited problem space. An example of this is the use of information from a sample-based FMI to decide harvest levels at the strategic stage. Of course, the companies could use the forest stand database as a basis for that decision. However, by calculating harvest levels based on an objective sample of inventoried stands, the companies are more confident that the decision is feasible. By deciding the harvest levels in this fashion, with no explicit linkage to what actual stand should be harvested, the companies have, in a sense, created a hierarchical planning process.

Apart from the hierarchical division of the planning process, we found six additional main strategies that forest companies employ to control or handle uncertainties in forest information: (1) locking the future by deciding on a plan that should be followed, which means that the company can forget about the uncertainties and pretend that the plan is certain, (2) utilizing a buffer of available stands, thus making the plan more implementable, (3) controlling or updating forest information that highly impacts the downstream planning process, which can be done automatically, for example, with LIDAR-estimates, and manually, as in the inventory by harvest area planners, (4) replanning the actions in the immediate future to make up for differences between the plan and the realized outcome, i.e. the same concept as adaptive planning (Eyvindson and Kangas 2018), (5) looking backwards to decide the future, with the best example being how the companies procure harvesting resources by looking at the previous years' harvest levels instead of the contents of the tactical plan and (6) ignoring the uncertainty, either intentionally or un intentionally.

Strategy 1 (locking the future) is used by companies when they make decisions and create plans to handle information uncertainty. One of the respondents exemplified this in the reasoning behind conducting an optimized harvest assessment and sample-based FMIs: *'That is how we have done it, anyway. It feels safe, and the reason is that we want objectively measured data, some kind of momentary truth, that we will not deviate from. This is the world, this is how it looks, and we will manage it in this way. And then we use that truth for a couple of years until we realize that the world has changed compared with the models and that we have to create a new starting point.'*

Strategy 2 (using buffers) is common throughout the planning process. The companies use the optimized harvest assessment on the strategic stage to account for forest stand database errors on the tactical stage by ensuring a surplus of stands available for harvest at any given moment in the future, i.e. a planning reserve. A respondent exemplified the reason for the reserve: *'If we have enough slack in the system, we can cope with quite large errors'*. The planning reserve gives the planners more stands to choose from, thus increasing the likelihood of creating a complete and feasible plan. Incidents not easily forecasted, such as storms or agreements with reindeer herders, would otherwise lead to unrealizable plans. Even though most companies implement a planning reserve, they aim to minimize it because maintaining a surplus of unharvested stands restricts the total harvest and income, especially when having a shortage of mature forests. Tactical planning has a similar strategy. As with the planning reserve, the tactical plan includes extra volumes to make it easier for the harvest area planners to reach their targets on the planned volume for harvest. At one company, this extra volume amounts to 30 per cent of the total volume in the plan. The reason is that the companies do not trust the forest stand database information and cannot be entirely sure that a planned harvest is possible to do.

Strategy 3 (controlling or updating forest information) is used by companies when they perform controls of the information they use or gather new information (or update it). In the strategic stage, for example, most companies conduct sensitivity analyses of the optimized harvest assessment by performing multiple reruns with varied settings to assess the robustness of the original solution. These sensitivity analyses also investigate consequences for various uncertainty-related scenarios, like climate change acceleration or increased demand for set-asides.

Harvest area planning in the operational planning stage (see RQ2) is a great example of an activity that handles information uncertainty, or the complete lack of information, by gathering new information. One of the respondents described the situation: "*When talking about uncertainties, it is so fascinating that we, in fact, judge all the information we utilize to be of such an insufficient quality that we have to verify everything out in the forest. This means that everything we do before we have been to the forest to gather information in the harvest area planning is very much a guessing game*". Moreover, because the companies are heavily incentivized not to make any mistakes regarding natural and cultural values due to legal and certification concerns, the harvest area planning focuses on planning considerations for these values. Not much time is spent on improving estimates on standing timber volume compared with the time spent finding cultural heritage sites or trees with high nature conservation values. None of the companies routinely measure the tree layer, but if they do, they use subjective methods.

Strategy 4 (replanning) has its best example in operational planning. During the creation of the operational plan, the focus is on minimizing costs, such as avoiding the high cost of sending expensive forest machines to harvest areas that are not harvestable. In principle, the whole forest planning process is a strategy to prevent this from happening in the operational stage. When the planning in the higher stages fails to acknowledge aspects relevant to forest operations, the operational plan needs to be adapted. For example, if there are significant uncertainties in the information in the harvest area database, e.g. on road quality, soil wetness or soil bearing capacity, the production leaders face challenges in periods of thawing or heavy rain. In addition, errors in harvestable volume estimates from yield forecasts affect operational planning. If volume estimates are too high, the companies need to either increase the production pace or reschedule planned harvests to stands that can fill the gaps in the delivery plan. If the estimates are too low, the companies have to handle the surplus of wood instead.

Strategy 5 (looking backwards) is used, for example, when companies decide the levels of procurement of machine resources and future sales of harvested volumes. Rather than trusting their plans, the companies tend to lean more on historic outcomes. If the companies had trusted their plans, these two examples could have been decided by only looking at the plan. Instead, many companies look at the outcome from previous years and determine current levels accordingly.

Discussion

In this study, we wanted to assess the role of forest information uncertainty in practical forest planning and how forest companies try to mitigate the effects of that uncertainty. We also investigated how the information is used and the relevance of the theory of a planning hierarchy in this context.

According to our results, the three-level hierarchical planning paradigm appears valid when describing practical forest planning. There could be several reasons for the persistence of hierarchical planning, like organizational inertia (Ashok *et al.* 2021) and the possibility of withholding sensitive information (Eriksson 2008). Furthermore, decision-making and planning may benefit from dividing the problem into sub-problems, i.e. into a hierarchy, or *'to be departmentalized and sub-departmentalized'*, in order to increase solvability (Simon 1960). Solving forest planning problems in this hierarchical fashion has proven to be a good compromise when the size of the problem grows too large to be efficiently handled as one single model, even if doing so may lead to suboptimal or infeasible solutions (Eyvindson *et al.* 2017). Furthermore, the hierarchical structure helps to deal with information uncertainty.

It is not a surprise that using an SBP approach with Heureka PlanWise and a sample-based FMI is standard procedure for strategic planning since this set-up has been the norm in Sweden since the 1980s (Jacobsson and Jonsson 1991). The dominance of SBP is probably best explained by how the predecessor of Heureka PlanWise, the Forest Management Planning Package, functioned (Jonsson *et al.* 1993). Therefore, all actors in large-scale forestry in Sweden are familiar with how the FMI gathers information of a certain quality, how that information can be used in a DSS and how the results should be interpreted. However, this dominance might change in the future.

Our results indicate a trend for large forest-owning companies to move towards an ABP approach for their strategic planning instead of SBP. This change opens up the development towards a more integrated planning process where the same wall-to-wall information and models are used to decide harvest levels in the long term and simultaneously what stands should be harvested, and when, in the short term (Andersson 2005; Bouchard *et al.* 2017). Such development can reduce the risk of suboptimality, e.g. by including spatial concerns in forest planning (Bettinger and Sessions 2003; Baskent and Keles 2005; Öhman and Eriksson 2010; Öhman *et al.* 2011; Paradis *et al.* 2013). Furthermore, it might make the planning process less hierarchical or at least remove one of the three stages, for example, by uniting strategic and tactical planning.

Our results show that the companies use forest information of relatively low quality in many procedures, at least according to their own standards and perceptions. Due to this study's qualitative approach, we could not assess the uncertainty of the information in a statistical sense, but our respondents were generally unhappy with the quality of the information they used. This knowledge is important for ongoing research for improving forest information acquisition methods, like RS and data assimilation (Lindgren *et al.* 2022).

Many RS studies report LIDAR-estimates to have objectively as good quality as traditionally field-measured forest information like stand basal area (Bergseng *et al.* 2015; Nilsson *et al.* 2017; Persson *et al.* 2022). Therefore, we see no apparent reason not to increase the use of RS information in forest planning. It is comprehensive, has a better-known error structure compared with the commonly used subjective forest information, has relatively low uncertainty and can be gathered with higher frequency for large areas than traditional FMIs. However, future research is needed on how the errors in various information sources interact when forest information is gathered with multiple acquisition methods at different points in time (cf. Lindgren *et al.* 2017).

Companies show little interest in using DSS and optimization. One argument from our respondents was that they could not trust an optimized solution to be truly optimal when implemented in practice. The reluctance to use optimization seems to stem from the fact that optimization models simplify real-world problems and are based on uncertain information. We see two possible actions to address this, namely to decrease the uncertainty in forest information, e.g. by better information acquisition methods and improved growth and yield models, or to employ problem-solving techniques that address information uncertainty, e.g. stochastic or robust optimization. The first is currently ongoing, not only within the research community but also in forestry, with an example being the implementation of RS estimates in the forest stand databases. On the other hand, the second is still primarily a topic for ongoing research (Eyvindson and Kangas 2014; Alvarez-Miranda *et al.* 2019; Alonso-Ayuso *et al.* 2020; Rinaldi and Jonsson 2020). Having access to both would probably develop the planning process in many ways, leading to better decisions and improved sustainability in forest management. Based on our gathered material, we think of the following areas for potential improvement when higher quality forest information and uncertainty-handling DSSs are available: (1) less extensive planning reserves on both the strategic and tactical stages, resulting in increased profits, (2) less and easier work for forest planners due to more comprehensive information, resulting in reduced costs but improved quality of plans, (3) automated harvest area planning, resulting in reduced costs, (4) improved considerations towards nature conservation values due to comprehensive information, (5) less need for short-notice replanning, resulting in lower harvesting costs, (6) lower risk for unsustainable harvest levels, (7) better timing for silvicultural treatments, leading to higher production and lower costs and (8) better adaptability towards climate change.

However, we believe that while waiting for new and implementable uncertainty-handling methods the companies might try already available optimization tools and DSSs for problem-solving to save some effort and money in the planning process. There are already models available for various forestry-related problems, like forest machine scheduling (Frisk *et al.* 2016; Santos *et al.* 2019), optimized placement of harvest roads (Bont *et al.* 2018; Flisberg *et al.* 2021) and integration of road maintenance and clustering in tactical planning (Flisberg *et al.* 2014; Mobtaker *et al.* 2020), even if none of them fully address information uncertainty.

Apart from the hierarchical division of the planning process itself, we identified six strategies companies employ to control or handle forest information uncertainties in forest planning. The strategies we found were (1) locking the future by deciding on a plan that should be followed, (2) utilizing buffers, (3) controlling or updating forest information, (4) replanning, (5) looking backwards to decide the future and (6) ignoring the uncertainty. Reports from central Europe show somewhat similar strategy patterns (von Detten and Hanewinkel 2017), but with a broader focus than forest information uncertainty. The strategies we found can all be placed in the spectrum of uncertainty, from total determinism via statistical uncertainty (strategy 3), to scenario uncertainty (strategies 4 and 5) and recognized ignorance (strategies 1, 2 and 6), to total ignorance (Walker *et al.* 2003). In the future, we hope that the companies can employ a seventh strategy, namely using formal problem-solving methods that handle uncertainties (Pasalodos-Tato *et al.* 2013).

Our results are based on qualitative data from semi-structured interviews, which is not uncommon in forest planning research (Laamanen and Kangas 2011; Nilsson *et al.* 2012; Meo *et al.* 2013; Wurtzebach *et al.* 2019). With our method, we quickly gathered large amounts of information that provided deep insights into how the companies organize their work internally and their reflections on that. The sample was small but should still be a good representation of the case for forest planning in Nordic countries, at least in industrial and large-scale forestry. Nevertheless, similar studies in other jurisdictions and climate zones are needed to increase the generalizability of the results. Moreover, because our analyses were limited to the perceived information uncertainties in practical forestry, i.e. we did not estimate the uncertainty with measurements and statistical methods, such endeavours are also encouraged.

Conclusions

We can conclude that the forest planning process is a hierarchical system of decisions where the information used in the different planning stages is of varying quality. All of our data supported that the traditional hierarchical planning paradigm still plays a vital role in large forest-owning companies. The forest stand database (stand inventory) is the most central source of information in the forest planning process, but it contains uncertain information primarily based on subjective field measurements or other estimates with unknown errors. However, the use of RS estimates to feed the databases is increasing, which will probably improve the overall quality of the databases, at least compared with the current standard of subjective and ocular estimates. Large forest-owning companies tend not to use DSSs or optimization models to solve planning problems outside the scope of strategic planning; thus, planning on the tactical and operational stages is done by hand, e.g. by manually selecting stands on a map in a GIS. Apart from the hierarchical division of the planning process itself, we identified six main strategies that companies employ to control or handle uncertainties in forest information in forest planning: (1) locking the future by deciding on a plan that should be followed, (2) utilizing buffers, (3) controlling or updating forest information, (4) replanning, (5) looking backwards to decide the future and (6) ignoring the uncertainty. Few activities in the planning process improved the basis for the decision, like gathering better information, with harvest area planning as a notable exception. Furthermore, no company used tools that formally incorporated uncertainty in the decision-making process. We hope that the results from this study increase the understanding of contemporary forest planning practices and will be helpful in the development of forest DSSs and methods for information collection.

Data Availability

The data underlying this paper consists of transcribed interviews and cannot be shared publicly due to privacy concerns.

CRediT author statement

Conceptualization: TL (lead), KÖ, LOE; Methodology: PU, DSW, TL; Formal Analysis: PU (lead), KÖ, LOE, DSW, TL; Writing—Original Draft: PU; Writing—Review & Editing: PU (lead), KÖ, LOE, DSW, TL; Project administration: PU; Funding acquisition: TL (lead), KÖ; Supervision: TL (lead), KÖ, LOE, DSW.

Supplementary material

The following supplementary material is available at *Forestry* online: (1) the interview guide, (2) a table with an overview of the forest information used in strata-based and area-based strategic planning and (3) a table with an overview of forest information in harvest area planning.

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Conflict of interest statement

During his work with this study, PU was employed part-time by Holmen Skog AB, one of the participating companies that also funded the study.

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References

Ackoff, R.L. 1989 From data to wisdom. *J. Appl. Syst. Anal.* **16**, 3–9.

Åge, P.-J. 1985 Forest inventory - Photo interpretation. *LMV-Rapport [LMV-Report] No. 1985:13*. Lantmäteriverket [National Land Survey].

Ahti, T., Hämet-Ahti, L. and Jalas, J. 1968 Vegetation zones and their sections in northwestern Europe. *Ann. Bot. Fenn.* **5**, 169–211.

Alonso-Ayuso, A., Escudero, L.F., Guignard, M. and Weintraub, A. 2020 On dealing with strategic and tactical decision levels in forestry planning under uncertainty. *Comput. Oper. Res.* **115**, 104836.

Alvarez-Miranda, E., Garcia-Gonzalo, J., Pais, C. and Weintraub, A. 2019 A multicriteria stochastic optimization framework for sustainable forest decision making under uncertainty. *For. Policy Econ.* **103**, 112–122.

Andersson, D. 2005 *Approaches to integrated strategic/tactical forest planning*Licentiate thesis. Swedish University of Agricultural Sciences.

Arnold, T. 2014 *How Net Present Value Is Implemented*. In A Pragmatic Guide to Real Options, Palgrave Macmillan.

Ashok, M., Al, B.A.D.M.S.M., Madan, R. and Dzandu, M.D. 2021 How to counter organisational inertia to enable knowledge management practices adoption in public sector organisations. *J. Knowl. Manag.* **25**, 2245–2273.

Ayyub, B.M. 2010 On uncertainty in information and ignorance in knowledge. *Int. J. Gen. Syst.* **39**, 415–435.

Barth, A., Lind, T. and Ståhl, G. 2012 Restricted imputation for improving spatial consistency in landscape level data for forest scenario analysis. *For. Ecol. Manag.* **272**, 61–68 (Emerging Methods for Handling Missing Data in Forest Ecology and Management Applications).

Baskent, E.Z. and Keles, S. 2005 Spatial forest planning: A review. *Ecol. Model.* **188**, 145–173.

Bergseng, E., Ørka, H.O., Næsset, E. and Gobakken, T. 2015 Assessing forest inventory information obtained from different inventory approaches and remote sensing data sources. *Ann. For. Sci.* **72**, 33–45.

Bettinger, P. and Sessions, J. 2003 Spatial forest planning: To adopt, or not to adopt? *J. For.* **101**, 24–29.

Blennow, K., Persson, J., Wallin, A., Vareman, N. and Persson, E. 2014 Understanding risk in forest ecosystem services: implications for effective risk management, communication and planning. *For. Int. J. For. Res.* **87**, 219–228.

Bohlin, J., Wallerman, J. and Fransson, J.E.S. 2012 Forest variable estimation using photogrammetric matching of digital aerial images in combination with a high-resolution DEM. *Scand. J. For. Res.* **27**, 692–699.

Bont, L.G., Fraefel, M. and Fischer, C. 2018 A Spatially Explicit Method to Assess the Economic Suitability of a Forest Road Network for Timber Harvest in Steep Terrain. *Forests* **9**, 169.

Borges, J.G., Nordström, E.-M., Garcia Gonzalo, J., Hujala, T. and Trasobares, A. 2014 *Computer-based tools for supporting forest management: the experience and the expertise world-wide*. Department of Forest Resource Management, Swedish University of Agricultural Sciences.

Bouchard, M., D'Amours, S., Rönnqvist, M., Azouzi, R. and Gunn, E. 2017 Integrated optimization of strategic and tactical planning decisions in forestry. *Eur. J. Oper. Res.* **259**, 1132–1143.

Church, R.L. 2007 Tactical-Level Forest Management Models. In *Handbook Of Operations Research In Natural Resources*. A., Weintraub, C., Romero, T., Bjørndal, R., Epstein, J., Miranda (eds.). Springer, US.

Church, R.L., Murray, A.T. and Barber, K.H. 2000 Forest planning at the tactical level. *Ann. Oper. Res.* **95**, 3–18.

Daust, D.K. and Nelson, J.D. 1993 Spatial Reduction Factors for Strata-Based Harvest Schedules. *For. Sci.* **39**, 152–165.

von Detten, R. and Hanewinkel, M. 2017 Strategies of Handling Risk and Uncertainty in Forest Management in Central Europe. *Curr. For. Rep.* **3**, 60–73.

Duvemo, K. and Lämås, T. 2006 The influence of forest data quality on planning processes in forestry. *Scand. J. For. Res.* **21**, 327–339.

Duvemo, K., Lämås, T., Eriksson, L.O. and Wikström, P. 2014 Introducing cost-plus-loss analysis into a hierarchical forestry planning environment. *Ann. Oper. Res.* **219**, 415–431.

Eid, T. 2000 Use of uncertain inventory data in forestry scenario models and consequential incorrect harvest decisions. *Silva Fenn.* **34**, 89–100.

Epstein, R., Karlsson, J., Rönnqvist, M. and Weintraub, A. 2007 Harvest Operational Models in Forestry. In *Handbook Of Operations Research In Natural Resources*. A., Weintraub, C., Romero, T., Bjørndal, R., Epstein, J., Miranda (eds.). Springer, US.

Eriksson, L.O. 2008 The forest planning system of Swedish forest enterprises: A note on the basic elements. In *Arbetsrapporter från Institutionen för skoglig resurshushållning [Work Reports from the Department of Forest Resource Management] No. 232 2008*. Swedish University of Agricultural Sciences.

Eyvindson, K., Hartikainen, M., Miettinen, K. and Kangas, A. 2018 Integrating risk management tools for regional forest planning: an interactive multiobjective value-at-risk approach. *Can. J. For. Res.* **48**, 766–773.

Eyvindson, K. and Kangas, A. 2014 Stochastic goal programming in forest planning. *Can. J. For. Res.* **44**, 1274–1280.

Eyvindson, K. and Kangas, A. 2018 Guidelines for risk management in forest planning — what is risk and when is risk management useful? *Can. J. For. Res.* **48**, 309–316.

Eyvindson, K., Rasinmäki, J. and Kangas, A. 2017 Evaluating a hierarchical approach to landscape-level harvest scheduling. *Can. J. For. Res.* **48**, 208–215.

FAO 2020a *FAO Yearbook of Forest Products 2018*, FAO.

FAO 2020b *Global Forest Resources Assessment 2020: Main report*, FAO.

Flisberg, P., Frisk, M. and Rönnqvist, M. 2014 Integrated harvest and logistic planning including road upgrading. *Scand. J. For. Res.* **29**, 195–209.

Flisberg, P., Rönnqvist, M., Willén, E., Frisk, M. and Friberg, G. 2021 Spatial optimization of ground-based primary extraction routes using the BestWay decision support system. *Can. J. For. Res.* **51**, 675–691.

Frisk, M., Flisberg, P., Rönnqvist, M. and Andersson, G. 2016 Detailed scheduling of harvest teams and robust use of harvest and transportation resources. *Scand. J. For. Res.* **31**, 681–690.

Gautam, S., LeBel, L. and Beaudoin, D. 2017 A hierarchical planning system to assess the impact of operational-level flexibility on long-term wood supply. *Can. J. For. Res.* **47**, 424–432.

Gilabert, H. and McDill, M.E. 2010 Optimizing Inventory and Yield Data Collection for Forest Management Planning. *For. Sci.* **56**, 578–591.

Gunn, E.A. 2007 Models for Strategic Forest Management. In *Handbook Of Operations Research In Natural Resources*. A., Weintraub, C., Romero, T., Bjørndal, R., Epstein, J., Miranda (eds.). Springer, US.

Hamilton, D. 1970 *Precision requirements for some information in timber management decisions*PhD thesis. Iowa State University.

Heinonen, T., Kurttila, M. and Pukkala, T. 2007 Possibilities to aggregate raster cells through spatial optimization in forest planning. *Silva Fenn.* **41**, 89–103.

Hesselman, H. 1939 En på flygrekognoscering grundad karta över bokskogens utbredning i Sverige. En kritisk granskning [A map of the distribution of the beech forests in Sweden based on aerial reconnaissance. A critical review]. *Geogr. Ann.* **21**, 72–87.

Holmgren, P. and Thuresson, T. 1997 Applying Objectively Estimated and Spatially Continuous Forest Parameters in Tactical Planning to Obtain Dynamic, Treatment Units. *For. Sci.* **43**, 317–326.

Holmgren, P. and Thuresson, T. 1998 Satellite remote sensing for forestry planning—A review. *Scand. J. For. Res.* **13**, 90–110.

Holmström, H., Kallur, H. and Ståhl, G. 2003 Cost-plus-loss analyses of forest inventory strategies based on kNN-assigned reference sample plot data. *Silva Fenn.* **37**, 381–398.

Holopainen, M., Mäkinen, A., Rasinmäki, J., Hyytiäinen, K., Bayazidi, S. and Pietilä, I. 2010 Comparison of various sources of uncertainty in stand-level net present value estimates. *For. Policy Econ.* **12**, 377–386.

Hyyppä, J., Hyyppä, H., Leckie, D., Gougeon, F., Yu, X. and Maltamo, M. 2008 Review of methods of small-footprint airborne laser scanning for extracting forest inventory data in boreal forests. *Int. J. Remote Sens.* **29**, 1339–1366.

Iverson, L.R., Graham, R.L. and Cook, E.A. 1989 Applications of satellite remote sensing to forested ecosystems. *Landsc. Ecol.* **3**, 131–143.

Jacobsson, J. and Jonsson, B. 1991 *The Forest Management Planning Package: Experience from Applications*. Department of biometry and forest management.

Johnson, K.N. and Scheurman, H.L. 1977 Techniques for prescribing optimal timber harvest and investment under different objectives—discussion and synthesis [monograph]. *For. Sci.* **23**, S1–S31.

Jonsson, B., Jacobsson, J. and Kallur, H. 1993 *The forest management planning package. Theory and application. Studia Forestalia Suecica No. 189*. Swedish University of Agricultural Sciences.

Kangas, A., Astrup, R., Breidenbach, J., Fridman, J., Gobakken, T., Korhonen, K.T. *et al.* 2018 Remote sensing and forest inventories in Nordic countries – roadmap for the future. *Scand. J. For. Res.* **33**, 397–412.

Kangas, A.S. 2010 Value of forest information. *Eur. J. For. Res.* **129**, 863–874.

Kaya, A., Bettinger, P., Boston, K., Akbulut, R., Ucar, Z., Siry, J. *et al.* 2016 Optimization in Forest Management. *Curr. For. Rep.* **2**, 1–17.

Koivuniemi, J. and Korhonen, K.T. 2006 Inventory by Compartments. In *Forest Inventory: Methodology and Applications*. A., Kangas, M., Maltamo (eds.). Springer, Netherlands.

Laamanen, R. and Kangas, A. 2011 Large-scale forest owner's information needs in operational planning of timber harvesting - some practical views in Metsähallitus, Finnish state-owned enterprise. *Silva Fenn* **45**, 711–727.

Larsson, M. 1994 Betydelsen av kvaliteten i skogliga avdelningsdata för skattningar av volymtillväxt och inoptimalförluster : en studie av norrländska slutavverkningsavdelningar [The significance of data quality in compartmental forest registers in estimating volume growth and non-optimal losses: A study of findal felling compartments in northern Sweden]. *Rapport från Institutionen för biometri och skogsindelning [Report from the department of Biometry and Forest Management] No. 26*. Sveriges lantbruksuniversitet [Swedish University of Agricultural Sciences].

Liittschwager, J.M. and Tcheng, T.H. 1967 Solution of a Large-Scale Forest Scheduling Problem by Linear Programming Decomposition. *J. For.* **65**, 644–646.

Lindahl, K.B., Sténs, A., Sandström, C., Johansson, J., Lidskog, R., Ranius, T. *et al.* 2017 The Swedish forestry model: More of everything? *For. Policy Econ.* **77**, 44–55.

Lindgren, N., Olsson, H., Nyström, K., Nyström, M. and Ståhl, G. 2022 Data Assimilation of Growing Stock Volume Using a Sequence of Remote Sensing Data from Different Sensors. *Can. J. Remote. Sens.* **48**, 127–143.

Lindgren, N., Persson, H.J., Nyström, M., Nyström, K., Grafström, A., Muszta, A. *et al.* 2017 Improved Prediction of Forest Variables Using Data Assimilation of Interferometric Synthetic Aperture Radar Data. *Can. J. Remote. Sens.* **43**, 374–383.

Lindgren, O. 1984 *A study on circular plot sampling of Swedish forest compartments*. PhD thesis. Swedish University of Agricultural Sciences.

Maas, H.-G., Bienert, A., Scheller, S. and Keane, E. 2008 Automatic forest inventory parameter determination from terrestrial laser scanner data. *Int. J. Remote Sens.* **29**, 1579–1593.

MacDicken, K.G., Sola, P., Hall, J.E., Sabogal, C., Tadoum, M. and de Wasseige, C. 2015 Global progress toward sustainable forest management. *For. Ecol. Manag.* **352**, 47–56.

Magaña, S.d.M., Pukkala, T. and Tato, J.P. 2013 Dynamic treatment units: flexible and adaptive forest management planning by combining spatial and optimization methods and LiDAR. *Cuad. Soc. Esp. Cienc. For.* **37**, 43–48.

Mäkinen, A., Kangas, A. and Nurmi, M. 2012 Using cost-plus-loss analysis to define optimal forest inventory interval and forest inventory accuracy. *Silva Fenn.* **46**, 211–226.

Maltamo, M., Packalen, P. and Kangas, A. 2021 From comprehensive field inventories to remotely sensed wall-to-wall stand attribute data — a brief history of management inventories in the Nordic countries. *Can. J. For. Res.* **51**, 257–266.

Martell, D.L., Gunn, E.A. and Weintraub, A. 1998 Forest management challenges for operational researchers. *Eur. J. Oper. Res.* **104**, 1–17.

Meo, I.D., Ferretti, F., Hujala, T. and Kangas, A. 2013 The usefulness of Decision Support Systems in participatory forest planning: a comparison between Finland and Italy. *For. Syst.* **22**, 304–319.

Miles, M.B. and Huberman, A.M. 1994 *Qualitative data analysis: an expanded sourcebook*. 2nd edn. Sage.

Mobtaker, A., Montecinos, J., Ouhimmou, M. and Rönnqvist, M. 2020 Integrated forest harvest planning and road-building model with consideration of economies of scale. *Can. J. For. Res.* **50**, 989–1001.

Mobtaker, A., Ouhimmou, M., Rönnqvist, M. and Paquet, M. 2018 Development of an economically sustainable and balanced tactical forest management plan: a case study in Quebec. *Can. J. For. Res.* **48**, 197–207.

Murray, A.T. 1999 Spatial Restrictions in Harvest Scheduling. *For. Sci.* **45**, 45–52.

Naderializadeh, N., Crowe, K.A. and Pulkki, R. 2020 On the Importance of Integrating Transportation Costs into Tactical Forest Harvest Scheduling Model. *Croat. J. For. Eng.* **41**, 267–276.

Næsset, E. 1997 A spatial decision support system for long-term forest management planning by means of linear programming and a geographical information system. *Scand. J. For. Res.* **12**, 77–88.

Næsset, E. 2014 Area-Based Inventory in Norway – From Innovation to an Operational Reality. In *Forestry Applications of Airborne Laser Scanning: Concepts and Case Studies*. M., Maltamo, E., Næsset, J., Vauhkonen (eds.). Springer, Netherlands.

Næsset, E., Gobakken, T., Holmgren, J., Hyyppä, H., Hyyppä, J., Maltamo, M. *et al.* 2004 Laser scanning of forest resources: the nordic experience. *Scand. J. For. Res.* **19**, 482–499.

Nelson, J., Brodie, J.D. and Sessions, J. 1991 Integrating Short-Term, Area-Based Logging Plans with Long-Term Harvest Schedules. *For. Sci.* **37**, 101–122.

Nilsson, M., Nordkvist, K., Jonzén, J., Lindgren, N., Axensten, P., Wallerman, J. *et al.* 2017 A nationwide forest attribute map of Sweden predicted using airborne laser scanning data and field data from the National Forest Inventory. *Remote Sens. Environ.* **194**, 447–454.

Nilsson, M., Wasterlund, D.S., Wahlberg, O. and Eriksson, L.O. 2012 Forest Planning in a Swedish Company - a Knowledge Management Analysis of Forest Information. *Silva Fenn.* **46**, 717–731.

Öhman, K., Edenius, L. and Mikusiński, G. 2011 Optimizing spatial habitat suitability and timber revenue in long-term forest planning. *Can. J. For. Res.* **41**, 543–550.

Öhman, K. and Eriksson, L.O. 2010 Aggregating harvest activities in long term forest planning by minimizing harvest area perimeters. *Silva Fenn.* **44**, 77–89.

Paradis, G., LeBel, L., D'Amours, S. and Bouchard, M. 2013 On the risk of systematic drift under incoherent hierarchical forest management planning. *Can. J. For. Res.* **43**, 480–492.

Pasalodos-Tato, M., Mäkinen, A., Garcia-Gonzalo, J., Borges, J.G., Lämås, T. and Eriksson, L.O. 2013 Review. Assessing uncertainty and risk in forest planning and decision support systems: review of classical methods and introduction of new approaches. *For. Syst.* **22**, 282–303.

Persson, H.J., Olofsson, K. and Holmgren, J. 2022 Two-phase forest inventory using very-high-resolution laser scanning. *Remote Sens. Environ.* **271**, 112909.

Pukkala, T. and Kangas, J. 1996 A Method for Integrating Risk and Attitude Toward Risk into Forest Planning. *For. Sci.* **42**, 198–205.

Reese, H., Nilsson, M., Sandström, P. and Olsson, H. 2002 Applications using estimates of forest parameters derived from satellite and forest inventory data. *Comput. Electron. Agric.* **37**, 37–55.

Rinaldi, F. and Jonsson, R. 2020 Accounting for uncertainty in forest management models. *For. Ecol. Manag.* **468**, 118186.

Rönnqvist, M., D'Amours, S., Weintraub, A., Jofre, A., Gunn, E., Haight, R.G. *et al.* 2015 Operations Research challenges in forestry: 33 open problems. *Ann. Oper. Res.* **232**, 11–40.

Santos, P.A.V.H.d., Silva, A.C.L.d., Arce, J.E. and Augustynczik, A.L.D. 2019 A Mathematical Model for the Integrated Optimization of Harvest and Transport Scheduling of Forest Products. *Forests* **10**, 1110.

Sessions, J. and Bettinger, P. 2001 Hierarchical planning: Pathway to the future? In *Proceedings of Proceedings of the first international Precision Forestry Cooperative symposium*. D., Briggs, J., Haukaas, and D., St. John, (eds).

Simon, H.A. 1960 *The New Science of Management Decision*. Harper.

SLU 2020 *Forest statistics 2020*. Swedish University of Agricultural Sciences, Umeå, Department of Forest Resource Management.

Sprängare, B. 1975 A method for analysing the sensitivity of the long-range planning which depends on errors in stand data. *Rapporter och uppsatser [Reports and theses] No. 87*. Institutionen för skogsteknik, Skogshögskolan [Department of forest technology, Royal College of Forestry].

Ståhl, G. 1992 A study on the quality of compartmentwise forest data aquired by subjective inventory methods. *Rapport No. 24. Department of Biometry and Forest Management*. Swedish University of Agricultural Sciences.

Ståhl, G., Carlsson, D. and Bondesson, L. 1994 A Method to Determine Optimal Stand Data Acquisition Policies. *For. Sci.* **40**, 630–649.

Stridsberg, E. 1959 *Linjär planering som hjälpmedel vid planläggning av ett skogsbruksprogram [Linear planning as tool for plannning of forestry]*. Skogshögskolan [Royal College of Forestry].

Swedish Forest Agency 2018 Strukturstatistik: Statistik om skogsägande 2017 [Structural statistics: Statistics on the owning of forests 2017]. *Rapport [Report] No. 2018/12*. Skogsstyrelsen [Swedish Forest Agency].

Tannert, C., Elvers, H.-D. and Jandrig, B. 2007 The ethics of uncertainty. In the light of possible dangers, research becomes a moral duty. *EMBO Rep.* **8**, 892–896.

Tittler, R., Messier, C. and Burton, P.J. 2001 Hierarchical forest management planning and sustainable forest management in the boreal forest. *For. Chron.* **77**, 998–1005.

Vacik, H., Borges, J.G., Garcia-Gonzalo, J. and Eriksson, L.-O. 2015 Decision Support for the Provision of Ecosystem Services under Climate Change: An Editorial. *Forests* **6**, 3212–3217.

Walker, W.E., Harremoës, P., Rotmans, J., van der Sluijs, J.P., van Asselt, M.B.A., Janssen, P. *et al.* 2003 Defining Uncertainty: A Conceptual Basis for Uncertainty Management in Model-Based Decision Support. *Integr. Assess.* **4**, 5–17.

Weintraub, A. and Cholaky, A. 1991 A Hierarchical Approach to Forest Planning. *For. Sci.* **37**, 439–460.

White, J.C., Coops, N.C., Wulder, M.A., Vastaranta, M., Hilker, T. and Tompalski, P. 2016 Remote Sensing Technologies for Enhancing Forest Inventories: A Review. *Can. J. Remote. Sens.* **42**, 619–641.

Wikström, P., Edenius, L., Elfving, B., Eriksson, L.O., Lämås, T., Sonesson, J. *et al.* 2011 The Heureka forestry decision support system: an overview. *Math. Comput. For. Nat.-Resour. Sci.* **3**, 87–94.

Wilhelmsson, P., Sjödin, E., Wästlund, A., Wallerman, J., Lämås, T. and Öhman, K. 2021 Dynamic treatment units in forest planning using cell proximity. *Can. J. For. Res.* **51**, 1065–1071.

Wurtzebach, Z., Schultz, C., Waltz, A.E.M., Esch, B.E. and Wasserman, T.N. 2019 Adaptive governance and the administrative state: knowledge management for forest planning in the western United States. *Reg. Environ. Chang.* **19**, 2651–2666.