Chapter 5
Forest Planning and Continuous Cover Forestry

Lauri Mehtätalo, Annika Kangas, Jeannette Eggers, Tron Eid, Kyle Eyvindson, Johanna Lundström, Jouni Siipilehto, and Karin Öhman

Abstract

- Forest planning requires unbiased and sufficient information on current forest resources, their anticipated dynamics under different management scenarios, and the objectives of the decision maker.
- Forest planning systems need to be adapted to improve their potential to deal with continuous cover forestry (CCF).
- The current forest planning systems and associated models can be adapted to group systems by treating each group as a separate calculation unit.
- In the selection system, currently available growth models may not realistically describe the growth reaction of trees, which causes additional uncertainty in forest-planning calculations. Furthermore, field-data collection based on airborne laser scanning alone is not sufficient for planning of CCF, and additional field measurements are needed.

L. Mehtätalo (✉) · A. Kangas
Natural Resources Institute Finland (Luke), Joensuu, Finland
e-mail: lauri.mehtatalo@luke.fi; annika.kangas@luke.fi

J. Eggers · J. Lundström · K. Öhman
Swedish University of Agricultural Sciences (SLU), Umeå, Sweden
e-mail: jeannette.eggers@slu.se; johanna.lundstrom@slu.se; karin.ohman@slu.se

T. Eid
Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway
e-mail: tron.eid@nmbu.no

K. Eyvindson
Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway

Natural Resources Institute Finland (Luke), Helsinki, Finland
e-mail: kyle.eyvindson@nmbu.no

J. Siipilehto
Natural Resources Institute Finland (Luke), Helsinki, Finland
e-mail: jouni.siipilehto@luke.fi

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- Tree-level measurements by drones open interesting opportunities for forest planning, which might be especially useful under CCF.

Keywords Decision support · Software · Forest inventory · Simulation · Forest dynamics · Optimization · Forecasting

5.1 Introduction

5.1.1 What Is Forest Planning?

The use of a certain forest area is affected by the available forest resources, their future production possibilities, the objectives of the decision maker (e.g. forest owner, company, stakeholders or society), and restrictions set by laws, agreements and guidelines. Besides wood production, forests provide a multitude of other goods, services and values, including non-wood products such as berries and mushrooms, biodiversity, carbon storage and sequestration, recreation opportunities, and a basis for reindeer husbandry. The objectives include those related to the production of all goods, services, and values. Forest planning can provide valuable information for the decision maker on how to manage the forest to reach the objectives.

From an economic point of view, harvesting decisions are particularly influenced by forecasts of the value of the felled and remaining trees in each stand, as well as the interest rate used by the decision maker. Economic analyses are often based only on the revenues from timber sales and silvicultural costs, but can include markets for other products, such as biodiversity, carbon sinks and recreation. Other goals, such as those related to the timing of harvest revenue, the harvested volume, the structure of the landscape, biodiversity, carbon sinks, and other goods, services and values discussed above have been considered by using different methodological approaches like multi-attribute utility theory (Kangas et al. 2015).

Forest planning can encompass a wide range of time spans and spatial scales. In the narrowest sense, forest planning is the search for a treatment schedule (a sequence of activities for a stand over the entire planning horizon) for an individual stand in the near future. In the broadest sense, forest planning designs long-term scenario analyses about the development of forest resources under different harvest levels at the national level. In tactical forest planning, forest management is planned for a landowner's forest property for the next 10–20 years. From the forest planning situations described above, it is important to distinguish between genuine planning, where the landowner sets the management objectives and accepts and implements the plan, and calculations for public operators which can only be implemented indirectly through various forest policy incentives.

The starting point of forest planning is the clarification of the decision maker's goals. After that, the planning often proceeds in the following steps: (1) Based on the inventory data, a detailed description of the current state of the forest is produced, allowing (2) simulation of alternative treatment schedules for each stand to sufficiently cover the range of acceptable management alternatives, and (3) the optimal combination of treatment schedules for all stands is identified by solving an optimisation problem with mathematical programming or some heuristic method. Steps (2) and (3) could involve interactive processes where new alternative treatment schedules are designed, and updated preference information on the forest owner's goals becomes more precise and integrated into the optimisation approach (Eyvindson et al. 2018). The simulation of alternative treatment schedules in step (2) requires models that can predict the dynamics of all decision variables over time under different management alternatives, as well as realistic algorithms to describe the silvicultural operations.

However, the method consisting of simulation and optimisation, is not the only planning approach. If the management objectives do not interlink the individual stands' optima, the management plan can be produced by optimising the management of each stand separately, using approaches where simulation and optimisation are integrated into a single step. Stand-level optimisation can also be used when there are management goals that make stand-level decisions interdependent (for instance the requirement of a steady flow of timber or revenue). This requires the stand-level objective functions to be augmented with a penalty function that measures deviations from the forest-level constraints (see Hoganson and Rose 1984; Pukkala et al. 2009). The penalty function is gradually adjusted during the process, and the stand-level optimisations are repeated after every adjustment, until the forest-level constraints or targets are met.

In addition, for large-scale scenario analyses, only one scenario may be simulated for each management unit using a rule-based approach, and optimisation is not used.

5.1.2 Current Forest Planning Approaches

The forest resource data used for planning may be based on sample plots with measured tree diameters and heights. Such data is often used in country-level scenario analyses, where the national forest inventory (NFI) sample plots are commonly used as input data, and not all forest stands need to be covered. When all forest stands of a certain area do need to be covered, tree-level diameter and height measurements and/or tree maps are often considered too costly for the increased accuracy they would provide. In such a case, only stand-level characteristics, such as the basal area or number of stems, mean diameter, mean height and mean tree age by tree species and canopy layer are recorded (either using remote sensing and or field cruising as described below) and used as input for forest planning. However, increased availability of drone- or smartphone-based inventory methods may alter this situation soon by allowing low-cost tree-level inventories.

The stand characteristics of interest are used to generate a tree list using models that predict the parameters of a diameter-distribution model and height-diameter curve (Mehtätalo and Kangas 2005) separately for all species and canopy layers of the stand. Other approaches can be used that estimate all or some of these parameters mathematically (Mehtätalo and Lappi 2020, Chap. 11). Thereafter, a systematic sample of trees can be generated from those models to provide an artificial tree list for the stand or plot.

In the systems used in Sweden and Finland, forest development is described using tree-level growth-model systems (see Chap. 4), which are sometimes calibrated using the most recent NFI plot data. Tree-level models are favoured because they allow flexible simulation of different harvest operations. Based on the tree stocks the models produce, a diverse set of structural indicators can be computed for biodiversity, such as area of mature broadleaf-rich forest, volume of deadwood, etc. (e.g. Kangas and Pukkala 1996). Furthermore, static predictive models have been fitted to various ecosystem services, such as berry (Kilpeläinen et al. 2016) and mushroom yield (Tahvanainen et al. 2018), amenity values, and habitat suitability (e.g. Tikkanen et al. 2007). The inputs for these models are usually ordinary stand characteristics whose values are predictions from the growth simulator. Based on these models, the effects of forest management on various values can be estimated and used in planning calculations. After final felling, a new stand is generated based on the commonly applied guidelines for artificial regeneration and empirical knowledge about the amount of natural regeneration in planted or seeded areas (e.g. Wikberg 2004). If a seed tree or shelterwood method is used, natural regeneration is the only source of the new tree generation.

The collection of stand-level forest resource information for strategic and tactical forest planning in Nordic countries is often based on remote sensing and field data using the area-based approach (ABA, Næsset et al. 2004). In the ABA, the forest stand characteristics of the training plots (usually some 500 plots per campaign) are explained with the features of the remote sensing data (laser scanning and aerial photographs). The models are then used to predict the characteristics for all areas covered by the remote sensing data. Such data is collected using public funding and is made available to the public for free or at low cost. The remote-sensing-based data may be augmented with field assessment, especially to assess the progress of regeneration in different stands.

5.2 Forest-Planning Challenges of Continuous Cover Forestry

Forest planning allows decision makers the opportunity to explore possible outcomes from a wide range of silvicultural methods. Silvicultural treatments that follow the concepts of continuous cover forestry (CCF) and rotation forestry (RF) can be simulated for the forest, and the choice of how the forest is managed should be based on the goals of the decision maker. For example, in thinning a near-mature even-aged stand, the understorey can be spared. The decision on how to continue can be made later, when the decision maker sees what kind of understorey has been created. A slightly different approach is any-aged forestry, where the management schedules are never classified to represent either CCF or RF (Pukkala 2020).

The choice between CCF and RF can also be made as a categorical decision. In this case, the selection of the silvicultural method itself does not require more detailed calculations: when preparing the forest plan, only treatment options that relate to the chosen silvicultural method are simulated. Such a decision can also take into account how well the consequences of the decision are currently thought to be known. RF has prevailed in the Nordic countries for the last 70 years, so its productivity and risks are quite well known, at least under past conditions. There is less empirical information about the productivity and risks of CCF. However, some risks (e.g. disturbances under a changed climate) may be large and are poorly known for both forest management regimes.

In Chap. 2, the CCF management approaches were classified into selection systems, shelterwood systems and group systems. Because all these approaches may require natural regeneration, a realistic description of ingrowth is essential for planning in all cases. In addition, the selection and shelterwood systems require implementation of the specific thinning operations and a description of their effects on the growth of remaining trees. The group systems can be implemented by treating the gaps as separate management units when simulating growth and harvests. Furthermore, specific models for describing forest-stand structure, such as diameter distributions and height-diameter curves, are needed for the selection system. The challenges set by CCF to different parts of forest planning are discussed in detail in the next subsections.

5.2.1 Challenges for Field Data Collection

The canopy structure of stands managed according to selection systems is different compared to RF (Bianchi et al. 2020). However, in the practical implementation of ABA for forest inventories, only a small share of training plots typically originates from forests managed using selection systems. Therefore, remote sensing may not provide very good estimates of stand characteristics for such forests (Maltamo et al. 2000). However, currently it is even more important to be able to detect forests with an understorey that allows switching to CCF. Such forests do exist in the training data, but the estimation methods may not be sufficiently well optimised for detecting them. Jarron et al. (2020) were able to predict the structure of understorey trees with reasonable accuracy for a study area in British Columbia. Bollandsås et al. (2008a) also obtained similar results from uneven-aged forests in Norway. In Finland, understorey characteristics could be estimated from laser scanning data, but the accuracy of the assessment depended on the density of the dominant tree layer (Maltamo et al. 2005). In general, forest planning for CCF requires either information on the diameter distribution in the form of several differently defined diameters (i.e. moments or percentiles) or information by tree storey. Neither is well supported by the currently implemented ABAs; field-measured forest resource information is needed. The situation might change over time as methods for the aerial inventories develop.

Attempts are being made to efficiently obtain tree-level forest inventory data for planning purposes. The potential methodologies include smartphone applications (e.g. Trestima, Katam) and individual-tree detection from remote sensing data (e.g. Kostensalo et al. 2023). These methods produce either a tree list (diameter distribution) or true tree-level data where the location of each tree in the stand is known. The latter case makes it possible to take the spatial distribution of trees into account in growth prediction and harvest planning. It is also possible to optimise harvest decisions at the tree level, at least for the next cutting.

5.2.2 *Challenges Describing Stand Structure*

Predicting diameter distributions and height-diameter curves is often based on regression models from existing datasets which are mainly based on even-aged forest management. The diameter distribution is usually narrower and the height-diameter curve flatter compared to uneven-aged stands that include several cohorts (Siipilehto et al. 2023). Therefore, using the models developed for even-aged stands in CCF leads to insufficient variation in tree diameter and height.

A theoretically sound way to predict the diameter distribution is using parameter recovery methods based solely on the mathematical relationships of the stand characteristics (Siipilehto and Mehtätalo 2013, Mehtätalo and Lappi 2020; Chap. 11), or calibrating the models using field-measured tree samples or diameter quantiles (Mehtätalo et al. 2006). These methods require additional information besides mean diameter. If this information is not available, but characteristics measured by tree strata in the field are available, the models developed for even-aged stands can be used for each stratum separately. In both cases, the diameter distribution can be further rescaled based on other field-measured quantiles such as the maximum and minimum diameters and the Gini coefficient derived from them (Valbuena et al. 2017). The height model can also be calibrated separately for each canopy layer using the layers' field-assessed mean diameters and heights. Siipilehto et al. (2023) developed separate models based on uneven-aged stands. They also found that stand-level calibration of the height-diameter curves based on even-aged stand data will work if sufficiently many height-sample trees are used for calibration.

The stand characteristics commonly used in RF poorly describe the condition of the uneven-aged stands generated by selection systems, but work well for forests under transition. They give means and totals of (more or less) even-aged cohorts. In selection systems, characteristics that describe means, variance and distribution of uneven-aged tree stocks may be of interest, as well as methods using such information. One essential difference is that the age of a CCF forest cannot be defined. In this respect, the field inventory is simpler than in RF forests, but on the other hand, stand age cannot be used in models of stand structure and development. Other commonly used stand-level characteristics, such as mean diameter or height, also become less meaningful because they do not vary much between truly uneven-aged stands. Therefore, in addition to the traditional mean variables, characteristics that can describe differences between the stands, for example the variation in diameter, may be useful in CCF stands. If both the basal area and number of stems are known, the mean height and diameter combined with this information might describe the trees well enough (Mehtätalo et al. 2007). The advantage of such sample-tree measurements is that they can be chosen based on the desired accuracy of the stand description.

5.2.3 Challenges for Predicting Stand Dynamics

Technically, the growth models used in forest planning should be suitable for both continuous cover and rotation forestry, as discussed in Chap. 4. In CCF, it is essential to be able to predict the establishment of new trees. Since the survival of small seedlings is very uncertain, usually only seedlings that have exceeded the set minimum height or diameter (known as ingrowth) are considered. Ingrowth modelling has proven very challenging. Correctly predicting average ingrowth is not enough. The model must be able to describe (1) whether ingrowth occurs, (2) how much ingrowth occurs, if it does occur, and (3) whether ingrowth is distributed sufficiently evenly over the forest (Lappi and Pukkala 2020).

It is also worth distinguishing whether the model realistically describes these three aspects of ingrowth regionally, or whether it can also reliably assign forecasts to different target stands. The latter is hardly possible without field checks even though laser scanning gives reasonably good information about the existence of undergrowth. In large-scale scenario analyses, treatment schedules are not allocated to specific stands. For planning calculations, it is therefore sufficient to have a model that accurately predicts the proportion of forest stands where sufficient ingrowth takes place, by site condition, age group, and region, with continuous cultivation in mind.

Even though the models can technically be used in both forest management systems, it is possible that not all factors affecting the differences between the even-aged and uneven-aged forestry are appropriately taken into account. For example, information describing the health status of the trees and the condition of the canopy is not currently used in the growth models. Therefore, there may be systematic differences in these factors favouring one of the silvicultural methods.

In general, ideal data for modelling stand structure and dynamics in continuous cover forests is not available. Stands in Nordic countries have high variety in tree size, and there is plenty of empirical information on the growth of both suppressed and dominant trees in them. However, there is not enough knowledge on the growth reaction of trees after a strong thinning treatment. Existing experimental datasets are highly valuable for that purpose, even though they do not fully represent all spatial distributions, sites and species. However, extensive highly representative data will not be available in the near future, especially for growth modelling that requires repeated measurements. Therefore, it seems that forest planning in CCF requires more field information than RF, and would benefit greatly from approaches combining remote sensing data and predictions with local field data (e.g., Myllymäki et al. 2024).

5.2.4 *Challenges for Optimisation*

Optimisation does not differ between CCF and RF if all relevant factors affecting growth and yield are described with a simulator suitable to describe both silvicultural methods. However, if the simulator systematically over- or underestimates the development of one of the methods or response to a specific treatment, the problem will be further exacerbated in the optimisation. This is because optimisation, by its very nature, chooses extreme solutions, and even the smallest advantage in favour of one method can produce a plan in which treatments according to this method are chosen significantly more often than others (e.g., Kangas and Kangas 1999).

An optimisation method that recognises stochasticity is needed to consider the different uncertainties between uneven-aged and even-aged forestry (Eyvindson and Kangas 2014; Pukkala 2015; Malo et al. 2022). The stochastic method can take into account, for example, the methods' different risks for regeneration. Other damage risks that may differ between the methods (such as wind, bark beetles or root rot) should be accounted for in a similar way. If different risks are not considered, the planning system inevitably favours the silvicultural system that produces a better result on average, regardless of the differences in risks.

5.3 Continuous Cover Forestry in Currently Available Decision Support Systems

5.3.1 *Tools in Sweden*

Heureka is a forest decision support system widely used in Sweden with different modules applicable for analysis at stand, estate, landscape and national levels (Lämås et al. 2023). The system includes both a simulator for generating treatment schedules using tree- and plot-level growth and yield models and an optimisation tool based on linear and integer programming. Heureka can generate treatment schedules with uneven-aged forestry. However, the growth functions have not been fully designed or properly validated for uneven-aged forestry. Therefore, results for uneven-aged forestry are less certain compared to even-aged forestry. A serious drawback of the current growth function for uneven-aged forestry is that it includes age as variable. There are indications that the current growth function underestimates long-term growth in uneven-aged forestry and thus introduces a bias in the simulation and optimisation results (Fagerberg et al. 2022).

While the empirical experience from uneven-aged forestry in Sweden is limited, long-term field experiments do exist and more data is now available compared to 15 years ago, when Heureka was initially developed. There are ongoing research efforts to validate and improve or replace the current growth models for uneven-aged forestry in Heureka.

Heureka includes functionality for patch cutting. However, no edge effects are included, which means that the new stand in the gaps is not affected by competition from the adjacent mature forest. The remaining mature forest is also unaffected by release from the gap felling. The models for shelterwood management in Heureka also need to be validated and improved.

5.3.2 Tools in Finland

MELA and MOTTI are area-level and stand-level decision-support systems developed at Luke for assessing the effects of alternative forest management practices on growth, yield and profitability (Salminen et al. 2005). Previously, MOTTI was used mainly as a test platform for new growth and yield models as well as for formulating and comparing stand-level forest management alternatives to develop silvicultural guidelines. MELA has been used for large-scale analyses since the 1980s (Siitonen 1983). These systems currently include the same growth and yield models which can predict growth responses to silvicultural practices. Both simulators produce growth and yield information covering the development and structure of growing stock and deadwood by tree species, the amount and structure of cutting removals and natural mortality, and predictions of the biomass dynamics of different tree strata. The main difference between the systems is currently in the simulation of treatment schedules: MELA automatically simulates all treatment options that are acceptable according to the silvicultural guidelines, while in MOTTI treatments tailored specifically for a problem at hand can be simulated. In the future, the best properties of both systems will be merged to form a next-generation planning system.

In both simulators, optimisation can be done using JLP, a system to handle large-area calculations using linear programming (Lappi 1992). Spatial description of the forested area and spatial optimisation are not available in JLP.

Development of the young even-aged stands is based on stand-level models until a stand reaches an 8-m dominant height. Thereafter, tree-level models are used, which are fitted separately for mineral soils (Hynynen et al. 2014) and peatlands (Repola et al. 2018). For uneven-aged stands and CCF, models by Eerikäinen et al. (2007) are implemented based on the permanent experimental ERIKA plots which represent single-tree selection in Norway-spruce-dominated uneven-aged stands. Models cover regeneration establishment, and height development of the established seedlings. For larger trees, calibration functions for diameter and height growth for CCF are under development (Lee et al. 2024).

The Monsu forest planning system has been developed for multi-objective forest planning at the University of Eastern Finland. It has been widely used in education and research for more than 20 years, and is also used in practical forest planning. Monsu allows both automatic and manual simulation of management alternatives. Optimisation is based on multi-attribute utility functions using heuristic methods. Spatial optimisation is also possible, which could be useful in CCF based on a group system. CCF using selection systems became possible in Monsu already in 2014 when growth models that allow both RF and CCF were implemented (Pukkala 2014). Several growth models are available for the simulation, including those of Pukkala et al. (2021). The management schedules can be simulated according to both RF and CCF, and the optimisation selects the one that best meets the management objectives. Alternatively, the simulation can be restricted to RF, CCF, or any-aged management where treatment schedules cannot be classified as RF or CCF (Pukkala 2020). Beyond the models that describe the dynamics of living trees, Monsu includes models for the dynamics of deadwood, soil carbon, wood products, and biodiversity which enable additional analyses. These include the effects of forest management on forest carbon balance and wood-based products (Heinonen et al. 2018), on water systems (Nieminen et al. 2023), and a responsibility report of the applied forest management (Pukkala 2022).

5.3.3 *Tools in Norway*

Norway has long traditions of developing decision-support systems for forest management, but they have mainly focused on RF in even-aged stands and used area-based growth models (e.g., Eid and Hobbelstad 2000; Strimbu et al. 2023). A few attempts have been made to adapt the area-based growth models for selective cutting in uneven-aged stands, but these solutions have been based on rather subjective considerations due to a lack of empirical data from experimental research plots (Eid and Hobbelstad 2005).

The only decision-support system developed for Norwegian conditions based on individual tree-growth models aiming for selective cutting in uneven-aged stands is T (Gobakken et al. 2008). T is a bio-economic forest simulator that can be applied to stand-level analyses. The simulator produces alternative treatment schedules with all feasible combinations of user-defined treatment and regeneration options, which were supposed to cater for both even- and uneven-aged forestry. The system has no functionality related to large-area (forest holding) analyses. The simulator relied on distance-independent diameter growth and mortality models, and area-based recruitment models (Bollandsås et al. 2008b; Bollandsås and Næsset 2009) calibrated to Norwegian NFI plots. The economic features of the simulator include timber values and cost calculations (harvesting, forwarding) for different harvesting methods (clearcutting, seed tree establishment and cutting, and selective cutting) based on individual trees. The simulator also provides costs related to silvicultural treatments such as planting and young growth tending, and calculates a net present value (NPV) for all treatment schedules over an infinite planning horizon.

Gobakken et al. (2008) evaluated and demonstrated the performance of the simulator. At the time of development, the simulator was judged to work appropriately, meaning vital silvicultural treatments under different conditions were handled reasonably, yielding logical and consistent biological and economic results, in accordance with previous experience and research. Fifteen years later, it has become clear that the biological and economic empirical data the simulator relies on is both uncertain and outdated.

In Norway we have seen two recent forest-simulator initiatives facilitating analyses of selective cutting through SiTree (Antón-Fernández and Astrup 2022) and TreeSim (Nabhani and Sjølie 2022). These initiatives are interesting as frameworks and technical solutions, but the simulators, as they are now, still rely on old biological models (Bollandsås et al. 2008b), and incorporate no or very limited economic features. An ideal decision-support system covering both even-aged and uneven-aged forestry developed for Norwegian conditions will require significant long-term research. Among other features, such a system should probably include a simulator based on distance-dependent tree growth (diameter and height) and mortality models for a more accurate description of horizontal and vertical variations in tree growth (Sharma and Brunner 2017). Such models could possibly be calibrated based on a combination of NFI plots and research plots from experiments where selective cuttings have been followed over time.

5.4 Conclusions

From a technical point of view, forest planning does not differ between CCF and RF. Forest planning has similar stages of data collection, simulation and optimisation, and also similar information needs about decision makers, forest resources and their dynamics under different treatments. For forest planning, a strict difference between RF and CCF is not very useful. Treatment schedules can be simulated and selected that best serve the management objectives of the decision maker. These may include a variety of management alternatives, including CCF, RF, extended rotations and other intermediate approaches.

Incorporation of CCF into forest planning involves a variety of challenges to the specific application of models. These challenges involve natural regeneration, description of forest structure, and reactions of forests to types of forest management operations that have not been extensively applied during the last 70 years.

Some tools for planning CCF are already available in the Nordic countries, but further development is still needed for better decision support. Fulfilling some of the requirements will take time because long-term datasets on CCF are scarce. The planning of CCF management might benefit from approaches combining model predictions with local field data from stands of interest.

The development of remote sensing methods for tree-level mapping of forests opens exciting possibilities for forest planning. First, models are no longer needed to generate the initial tree list for simulation. In addition, a spatial description of the stands could be used, allowing distance-dependent growth models and simulating tree extraction in a spatially and temporally explicit manner. These new possibilities will be especially useful under forest management like CCF that does not follow previously used RF practices.

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