Overview of the PlanWise application and examples of its use

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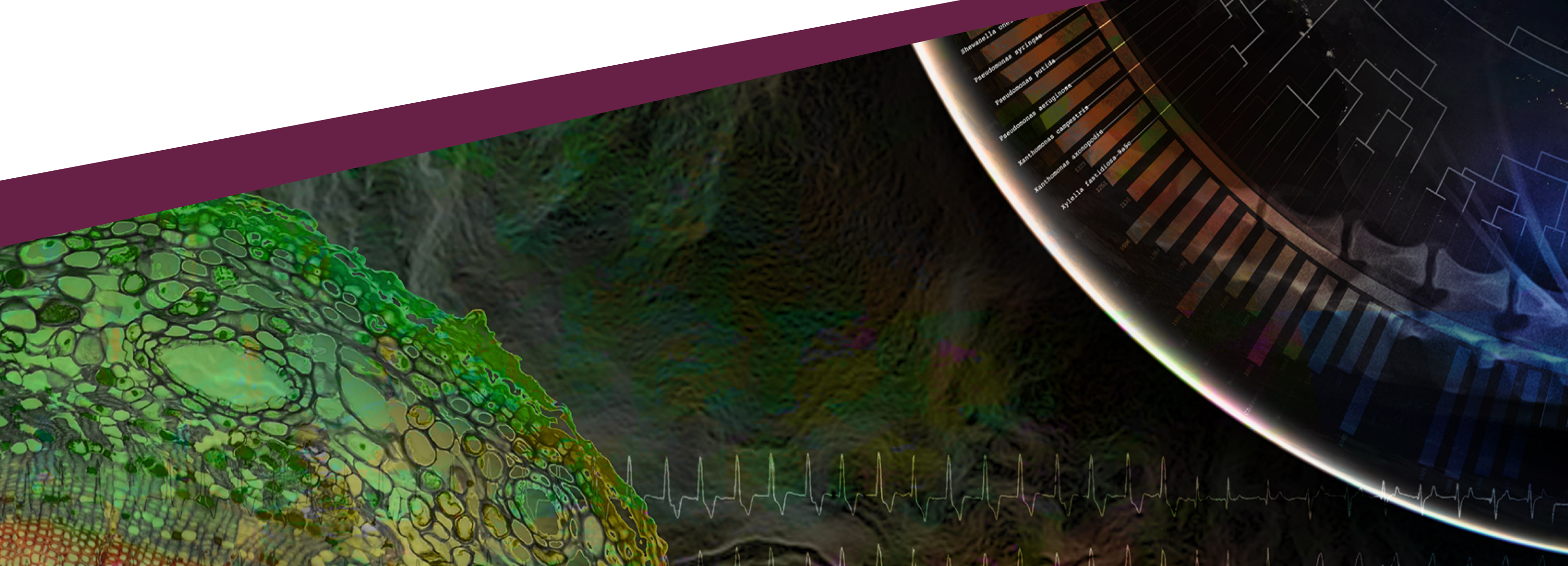

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Preface

The purpose of this document is to present how the PlanWise application within the Heureka forest decision support system can be used for the mapping and valuation of various ecosystem services related to forestry. In the first part a general presentation of the PlanWise application is done and in the second half we give several examples from recent research projects.

The Heureka system is a series of software developed at SLU, allowing user to perform many different analysis and to develop long-term management plans for forestry. All software within the Heureka system is freely available and the system is today managed and developed by the program for Forest Sustainability Analysis, SHa. For more specific information about how to use the system and download instructions please visit the home page of SHa, www.slu.se/sha.

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1. Introduction

There are many demands on forests today, such as producing wood and bioenergy, maintaining biodiversity, providing attractive recreational settings, and mitigating climate. These objectives are partly in conflict with each other, and management strategies differ in how much they contribute to each of these objectives. Therefore, there is a need to assess the long-term consequences of different management strategies on e.g. indicators for different ecosystem services and biodiversity.

One important tool to do such assessments are forest decision support systems (DSS), i.e. 'computer-based systems that help decision makers to analyse and solve ill-structured problems' (Vacik *et al.* 2015). Methodologically, DSS can be classified into three groups: DSS based on simulation, DSS based on optimization, and DSS used for multi-criteria decision analysis (MCDA). In this context, *simulation* means that forest management rules are specified, and the outcome is based on an application of these rules (Nobre *et al.* 2016). The simulator thus projects the likely development of the forest, and the resulting ecosystem services under pre-defined management rules. Simulators are useful for answering "what if" questions, i.e., for assessing the consequences of a limited set of pre-defined management alternatives. The advantage of simulation approaches lies in the relative ease of formulating the problem and interpreting the output. Simulation approaches are useful for projecting the consequences of a limited set of predefined scenarios. DSS based on *optimization*, in contrast, generate a large set of alternatives from which the best alternative is selected using an optimising algorithm based on the goals and constraints of the planning problem. These kinds of DSS can be used for answering "How to" questions, i.e., for finding the optimal way to reach certain objectives. Optimisation problems thus require that the user defines forest management goals and constraints rather than strict management rules. Both simulation and optimization approaches can be used to generate a number of scenarios, which can be used in a *MCDA* approach to identify the solution that best fits decision makers' preference's for different objectives. MCDA is the collective term for a set of mathematical methods and approaches used to find solutions to decision problems with multiple conflicting objectives.

In Sweden, the forest DSS most widely used in research, education and at forest companies for producing long-term plans and making analysis related to forest and forestry is Heureka. The Heureka forest DSS was developed at SLU and the first version was released in 2009 (Wikström *et al.* 2011). The system includes three applications that are designed to be used for different types of analysis and at different spatial levels and one application that helps compare scenarios (such as different long-term forest management plans) using MCDA. *StandWise* is an interactive simulator for stand-level analysis. *PlanWise,* which we focus on in this report, is a system for analyzing a large set of forest management options in order to identify the best alternative using optimization based on user-defined objectives and constraints. *RegWise*, on the other hand, is based on a simulation approach where users pre-define the management for e.g. different forest types and landowners through management rules. The advantage of using PlanWise is the possibility to find the most cost-effective solution among a nearly continuous scale of possible alternatives. On the other hand, problems with a high degree of stochasticity are difficult to formulate and solve with in the PlanWise application. For such problems, RegWise could be a better alternative. Finally, *PlanEval* is a MCDA application designed to evaluate and rank forest plans or scenarios created in *PlanWise* or *RegWise*. PlanEval is also available as a web version intended for participatory planning processes.

The aim of the report is to present how the Heureka PlanWise application can be used in different types of analysis for mapping and valuation of the future state of the forest, and forest-related indicators for ecosystem services and biodiversity. More specifically, we show which indicators can be assessed, how the type of input data determines what kind of analysis can be done, and how to assess trade-offs between conflicting objectives. We give several examples from recent research projects.

2. Overview of the PlanWise application

The PlanWise application consists of a stand level simulator integrated with an optimization tool. When doing an analysis with PlanWise, a number of steps are included. In this report, we have chosen to divide this into five different steps that all influence the analysis (Figure 1). For a complete description of the various steps, e.g. exactly how data is imported to the system, we refer to the Heureka Help and Wiki.[1]

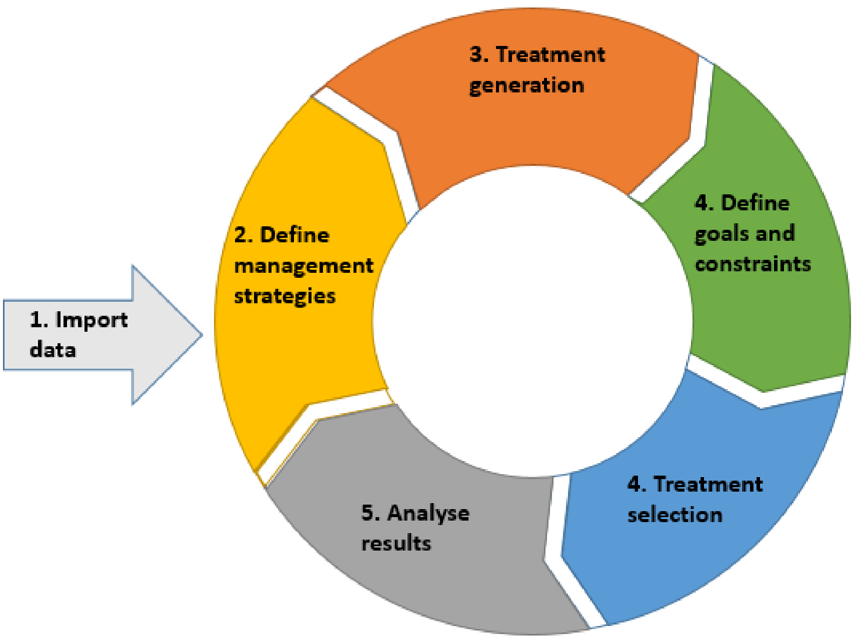


Figure 1: Flowchart of the basic steps for creating a management plan or doing an analysis in PlanWise.

[1] Help: https://www.heurekaslu.se/help/index.html?introduktion.htm,
Wiki: https://www.heurekaslu.se/wiki/Heureka_Wiki

2.1. Import data

Heureka can deal with different kinds of input data, for example, spatially explicit stand-level information, plot level data (such as information from the national forest inventory (NFI)), or the inventory of a forest company. Even data from airborne laser scanning, describing the forest in raster cells that are much smaller than an ordinary stand, can work as input data as long as all necessary input variables are available.

The type of input data determines the kind of analysis that can be done. *Plot-level data*, e.g. data from the National Forest Inventory (NFI)[2], where each plot represents a certain proportion of the forest landscape, allows for the analysis of the development of the tree layer and indicators coupled to it that are not dependent on exact location. Examples of analysis include: investigating how the area of certain forest types changes over time under different management strategies, determining the maximum harvest level that can be sustained in the long term, or trade-offs analysis between various ecosystem services and biodiversity indicators. Advantages of plot-level data are that they usually have a high data quality and enable users to do analysis for large areas. *Spatially explicit stand-level data* additionally allow for the inclusion of location-specific issues as well as spatial relationships in the analysis, i.e. where the choice of management depends on the exact location of the treatment unit, or on the management or condition of adjacent areas. Examples include the impact of buffer zones around water on the economic outcome from forestry (Tiwari *et al.* 2016), planning for recreational values in peri-urban areas (Eggers *et al.* 2018) or clustering habitat for species in a landscape over time (Öhman *et al.* 2011).

Irrespective of whether the input data is spatially explicit or on plot level, a number of variables are needed to describe the current state of the forest and allow projections of the tree layer. Variables that are needed by the system include several site- and tree layer variables for each stand or plot[3]:

Variables describing the **site**: stand/plot area (and/or the area that the plot represents in the case of plot level input), location (county, altitude, latitude), site index[4], soil moisture, vegetation type of the field layer, and presence of peat. These variables are used to simulate tree growth, but they **remain constant** throughout the simulation.

Variables describing the **tree layer**: mean age, number of stems, basal area, and tree species distribution. Tree-species specific diameters and heights are optional, but it is recommended to include them as they improve the quality of the

[2] https://www.slu.se/centrumbildningar-och-projekt/riksskogstaxeringen/

[3] Hereafter the term treatment unit is used when referring to stands and/or plots.

[4] Site index can also be calculated by the system if all needed site information is available (latitude, altitude, slope, soil texture, soil depth, field vegetation type, soil moisture, soil water regime, presence of peat)

projections. Variables describing the tree layer are projected, i.e. they are **dynamic over time**.

In addition, the user has the option to include information on dead wood volumes, as well as a number of user-defined variables, describing, for example, ownership or management class. The user can also import a forest map and link it to the imported stand register. Retention patches can be imported as separate treatment units or be defined as parts of existing treatment units. Finally, the user has the possibility to import proposals of what management to carry out for example the coming ten years. These proposals could e.g. come from a traditional forest management plan, produced by a planner after on-site assessments. In this case, the system can be forced to simulate the recommended management activities.

During data import, Heureka creates trees (or tree cohorts) for each treatment unit, using a Weibull function.

2.2. Define management strategies

After importing the input data, the next step is to define which management strategies should be applied when projecting the state of the forest into the future. Management strategies can differ in management system (unmanaged, even-aged, and uneven-aged), or details within each system, e.g. in type of regeneration, minimum rotation length, number of thinnings or the proportion of broadleaves retained in thinnings. The user can group treatment units into domains based on their characteristics (e.g. dominant species, management class, location, protection status) and assign these groups one or several different management strategies (Figure 2).

A large number of parameters control how forest management is simulated in each management strategy, and the users can modify many of them. For example, users can specify, in detail, how cleaning, thinnings, selection and final fellings should be performed, how many retention trees and high stumps should be left in final fellings, if and where harvesting residues should be extracted and what type of regeneration should be used. There is also a choice of different fertilization regimes.

Users can also adapt parameters for management costs as well as prices for timber, pulpwood, fuelwood and forest residues.

2.3. Treatment generation

For each treatment unit and their assigned management strategies, several treatment schedules are generated (Figure 2), in five-year time steps spanning the user-defined planning horizon (usually 50 – 100 years). The user defines the maximum number of treatment schedules to be generated for each management strategy, and the interest rate used in the calculation of the net present value (NPV) of each treatment schedule. Each treatment schedule covers the entire planning horizon and differs in the timing of silvicultural activities (Figure 3). The user also defines which result variables should be saved to the result database. These variables will be available in the treatment selection step (optimization), and for the analysis of the results. It is advisable to select only variables that will be needed later on, especially when the analysis includes many treatment units and treatment schedules. The larger the result database, the more time it takes for the optimization and for the extraction of the results.

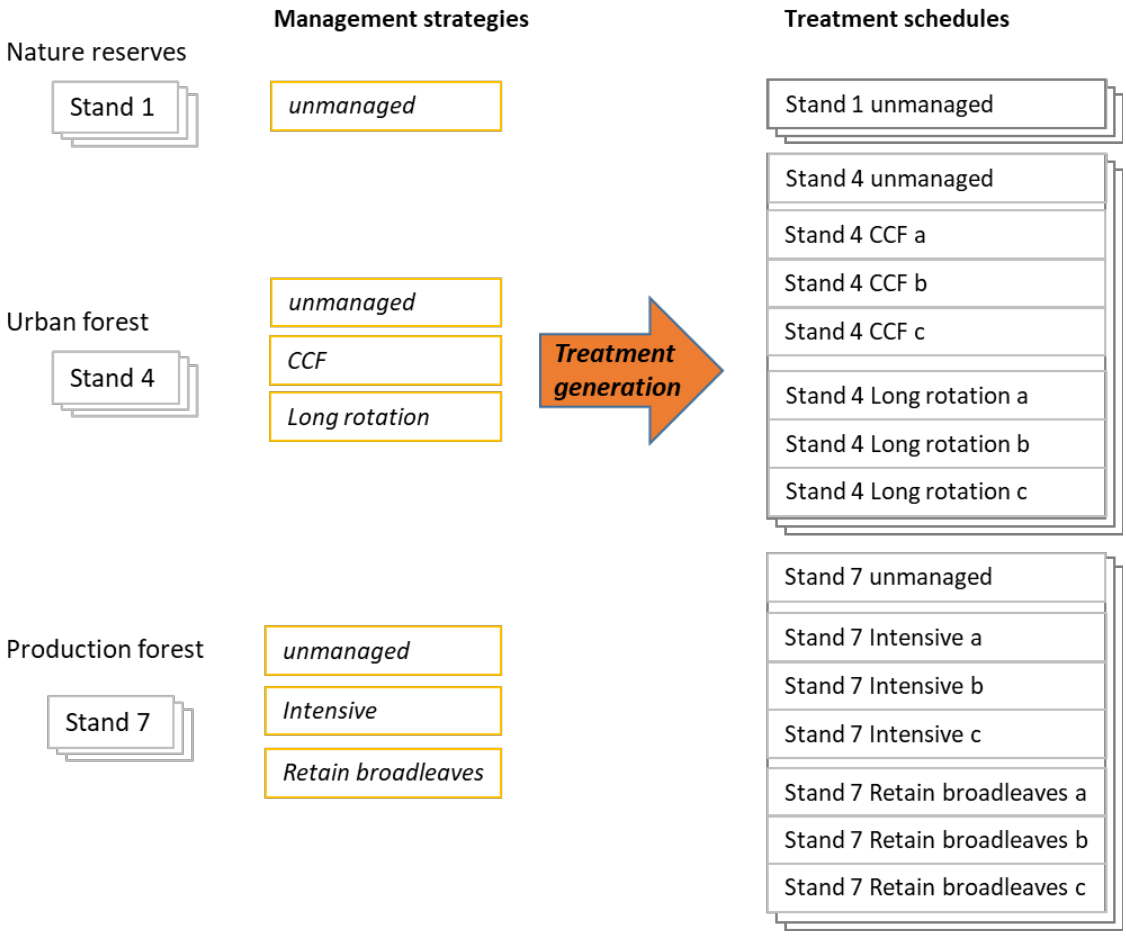


Figure 2: Flowchart of the treatment generation step in PlanWise. In this example, stands are divided into three groups (nature reserves, urban forest and production forest), and each group has been assigned a number of management strategies. Three treatment schedules are created for each management strategy (except for the unmanaged strategy for which only one schedule is possible, i.e. one without any management actions).

		Period															
Mngmt. strategy	Alter-native	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Prod.	1				FF					Cl						Th	
Prod.	2			FF					Cl						Th		
CCF	3			SF			SF			SF			SF			SF	
CCF	4		SF			SF			SF			SF			SF		
	FF – final felling, Cl – cleaning, Th – thinning, SF – selection felling																

Figure 3: Example of treatment schedules, for an even-aged management strategy (Alternatives 1 and 2), and for continuous cover forestry (Alternatives 3 and 4). In this example, the planning horizon is 75 years (15 periods).

The development of the tree layer is simulated for each treatment schedule using a set of empirical growth and yield models that project the development of the tree layer and the resulting ecosystem services. The growth and yield models, which include models for stand establishment, diameter growth, height growth, in-growth, and mortality, are typically developed using regression analysis based on data from the National Forest Inventory, long-term experiments, and yield plots (Fridman & Ståhl 2001; Wikberg 2004; Fahlvik *et al.* 2014). Using results from process-based models, users can adjust the empirical growth models to account for expected climate change effects.

2.4. Define objectives and constraints

After generating a set of different treatment schedules for each treatment unit, the next step is to decide which treatment schedule(s) should be selected. The selection is done using optimization, based on linear programming (LP) or mixed integer programming (MIP).

The built-in optimization tool provides suggestions on the proportion of each treatment unit that should be managed with a certain treatment schedule so that the user-defined objective function is maximized or minimized and the user-defined constraints are fulfilled. This means that the decision variable, i.e. the variable set during the optimization process, is the proportion of each treatment unit that is allocated to a certain treatment schedule. The proportion can be continuous, i.e. take any value between 0 and 1 (LP), or binary, 0 or 1 (MIP).

The objective function can be any Heureka result variable (i.e. any of the variables projected by the system) or a combination of several result variables.

Examples include:

- net present value,
- harvest volume,
- area of old forest (at a certain point in time, or average over time) and
- the maximum relative distance to a set of target levels for several indicators.

Constraints can be used to add additional specifications. Common examples include:

- evenness constraints (the harvest volume should not vary too much over time),
- area proportions that are to be left unmanaged/managed with selection fellings,
- the volume of broadleaves should not decrease and
- the standing volume in the end should not be smaller than in the beginning of the planning period.

There is one constraint that always has to be included and that is a restriction that ensures that all the forest area in each treatment unit is managed with exactly one treatment schedule in total (note, however, that different parts of a treatment unit may be managed with different treatment schedules in the case of LP). This restriction makes sure that no areas are double-counted or left out of the results. [5]

Both the objective function and constraints need to be constructed so that the basic assumptions of proportionality, additivity and certainty are fulfilled:

1. Proportionality: This means that the contribution of any activity to the objective function or the constraints is directly proportional to the level of activity. For example, if you get 100 m^3 if the entire stand is harvested, then you get 50 m^3 if half of the stand is harvested, and the timber price for 1000 m^3 of a certain assortment is ten times the price as for 100 m^3 of the same assortment.
2. Additivity: This means that the combined contribution of the decision variables in the objective function or the constraints can be calculated directly as a sum of the contributions of each individual decision variable. In other words, there can be no interactions between the effects of different treatment schedules; i.e., the outcomes of different treatment schedules for a certain treatment unit are independent of each other. Also the outcomes of treatment schedules for different treatment units are independent of each other, i.e. what happens in one treatment unit does not affect the outcome of treatment schedules in another treatment unit.

[5] This constraint is added automatically when creating a new optimization model in Heureka.

3. Certainty: This means that all model parameters (coefficients), such as the future forest growth or timber prices for each treatment schedule, are known with certainty. Thus, it may be important to do a sensitivity analysis by repeating the analysis a number of times with different assumptions about prices, costs, demand of old forest areas etc.

2.4.1. Trade-off analysis

In many cases when using PlanWise, it is of interest to investigate the trade-off between two conflicting objectives, e.g. maximizing the net present value and maximizing the amount of old forest in the landscape. If you have a trade-off between two objectives, it means that for improving the outcome for one objective you need to sacrifice the outcome of the other objective. One approach for doing that is by creating a set of pareto-optimal plans, i.e. plans where the result for any one of the objectives cannot be improved without compromising the result for the other objective. In PlanWise this can be done by first maximizing (or minimizing) each objective separately, to find out the maximum potential for each of them. In the next step, one of the objectives is maximized (or minimized), and the other objective is included as a constraint. By step-wise changing the required amount of that objective to be reached, a number of pareto-optimal solutions can be found.

For example:

Max (A)
Max (B)
Max (A) subject to $B \geq 0.99\ B_{max}$
Max (A) subject to $B \geq 0.95\ B_{max}$
Max (A) subject to $B \geq 0.9\ B_{max}$ etc.

Where: A, B – indicator values for indicators A and B; B_{max} – maximum potential indicator value for indicator B

Then, the indicator values can be plotted against each other (Figure 4).

Another possibility to create trade off curves is by using weights. For at situation with two different objectives the different objectives are weighted against each other into one single-objective problem with weights such that $w_1>0$ and $w_2>0$ and $w_1 + w_2 = 1$. The problem is then solved a number of times with different weight combinations.

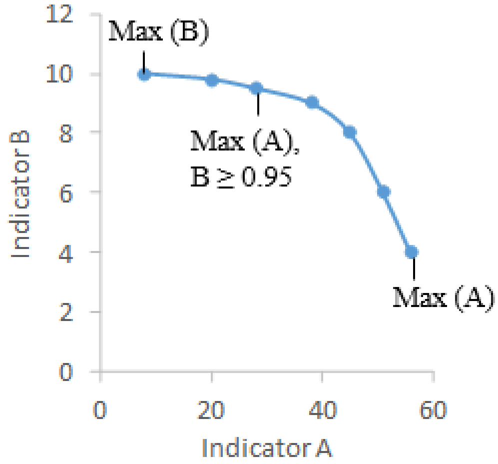


Figure 4: Trade-off curve for indicators A and B. Each mark represents one optimization.

2.5. Treatment selection

Depending on whether the decision variable is defined as continuous or binary, LP or MIP is used for solving the formulated optimization problem, i.e. the selection of treatment schedules for every treatment unit so that the objective function is maximized or minimized and the constraints are fullfilled. If LP is used for solving the optimization problem, the decision variable x_{ij}, (the proportion of each treatment unit that is assigned a certain treatment schedule) is defined as continuous and can take any value between 0 and 1. This means that the treatment unit may be divided and each part be treated with a different treatment schedule. Standard LP is commonly used in problems that are not spatially explicit. For example, when the input data is NFI plots and where each plot represents a large forest area, it makes sense to allow treatment units to be divided.

MIP is on the other hand used when it is important to know where exactly a management intervention happens, e.g. in spatially-explicit planning problems with neighborhood relations. In this case, the decision variable is set to binary, meaning that each treatment unit will be assigned one and only one treatment schedule.

	LP	*MIP*
Decision variable	continuous	binary
Potential division of treatment units	yes	no
Solution time	fast	slow

In MIP, if a treatment schedule is chosen that involves harvesting in a certain period, you know that the entire treatment unit is harvested. If you have continuous variables and half of the treatment unit is managed with a treatment schedule that involves harvesting for a period and the other half is managed with another schedule that does not include harvesting in the same period, you do not know which part of the treatment unit is harvested. You only know that somewhere within the treatment unit there will be a felling.

The drawback with MIP is that the solution times for solving the problem increase considerably and in some cases, it may even be impossible to solve the stated optimization. As an alternative to solve a problem as an MIP-problem with binary decision variables, the problem can be formulated and solved as an LP problem with subsequent rounding. In this case, for each treatment unit, the treatment schedule that has been assigned to the largest proportion of the treatment unit in the LP solution is selected. <u>However, the rounding function should be used with care</u> since the constraints may be violated when rounding is applied, i.e. it could be the case that the constraints you specified in the optimization model are no longer met. Moreover, the rounding function should not be used if the optimization model is truly combinatorial, which is the case in spatial problems with neighborhood relations (e.g. when the treatment schedule of one stand depends upon how a neighboring stand is treated).

Irrespectively if LP or MIP is used, the optimization problem is solved using an external third-party solver. Currently, the solver that is included when PlanWise is installed is LPSolve. However, it is only possible to use LPSolve for very small problems in terms of number of treatment units and number of restrictions, especially if binary decision variables are used. For larger problems, it is recommended to use a commercial solver, such as Gurobi, Cplex or MOSEK. These solvers are supported by Heureka and academic licenses are available for researchers and students.

It is also possible to solve the optimization problem outside of Heureka, after exporting the required variables from the results of the treatment generation process. This can be an option for large optimization problems that are not feasible to solve within Heureka or if you want to solve the optimization problems with Heuristic methods.

The possible results of an optimization in PlanWise include:

- One optimal solution
- No feasible solution is found. In this case, either the constraints are too tight, there are some errors in the optimization model or the size of the optimization problem exceeds the computing capacity.[6]

[6] To identify why no feasible solution is found, exclude all constraints (except for the area treatment unit constraint) and then include the constraints again, one by one, in a systematic order. Try to solve the problem after including each constraint.

Note that even if you do not use the optimization tool, a default solution is always generated, i.e. a suggestion on a treatment schedule for each stand. In the default solution, the treatment schedule with the highest net present value (from the treatment generation) is selected for every stand. The results for this solution are given names that start with "Max NPV".

2.6. Analyse results

Once an optimal solution has been found, its results can be analysed. The future forest development and its effects on ecosystem services and biodiversity can be studied using a large number of result variables that are available for each five-year period over the entire planning horizon. These include:

- Basal area, diameter, height, age, number of stems, and volume, per species
- Above- and belowground biomass and carbon stocks of trees, per species
- Soil carbon stock
- Deadwood volume per decay class and tree species (pine, spruce, broadleaved species)
- Detailed information on silvicultural treatment performed (e.g. type of treatment, thinning form, thinning grade, treated area, biomass of cut trees, regeneration method)
- Harvest volume (timber, pulpwood, and fuelwood, per tree species and harvest type)
- Diameter distribution of cuttings
- Residue extraction
- Current and mean tree growth (both net and gross)
- Natural mortality, per species and diameter class
- Recreation index (stand-level)
- Means and standard variation for age, diameter, height, stems and volume
- Structural diversity (whether a stand is even- or uneven-aged, tree size diversity)
- Costs and revenues, net present value, soil expectation value

Note that only the tree layer is projected and changed over time. Site-level information (e.g. field layer, site index) remain constant throughout the simulation!

The user can either export all result variables per treatment unit that are of interest and analyse them externally, or use the built-in reporting functionality to get summaries of result variables. A number of standard report templates are available, but it is also possible to create new report templates. The reporting templates also allow users to combine several result variables through the use of conditions. Examples where such combinations are needed include the sum of forest area with certain volumes of deadwood, the volume harvested in final fellings, or the area of forest managed with a certain management strategy. Heureka also provides basic GIS functionality, allowing users to view results over time in maps.

3. Examples of the use of PlanWise

The examples below provide short summaries of research in which Heureka PlanWise was applied to analyse the forest management impact on ecosystem services and/or biodiversity. These examples are meant to illustrate various ways in which PlanWise, together with different types of input data, can be used.

3.1. Impacts of wood fuel harvesting on forest ecosystem services

3.1.1. Research question

The aim of this study was to investigate the long-term trade-offs between biofuel extraction on the one hand, and indicators for biodiversity and forest ecosystem services on the other hand. The study area was the county of Västerbotten.

3.1.2. Material and Methods

Import data

The input data for the analysis were the NFI plots for the county of Västerbotten inventoried during the years 2008-2012, i.e. in total 2738 plots representing more than 3 million ha productive forest. NFI plot field measurements are imported to Heureka in a standardized way, and in this case, we used an existing database that was created for the Forest Impact Analysis 2015 (Claesson *et al.* 2015). Thus, no separate import was needed.

Define management strategies

First, we defined a number of alternative management strategies for each NFI plot over a simulation period of 100 years, for two different biofuel extraction settings: with the potential for residue removal in final fellings (BAU), and with the potential for intensive biomass extraction, including options for stump removal, residue removal in thinnings and final fellings, and biofuel thinnings (bioE). Biofuel thinnings were implemented as whole-tree harvest in early thinnings, optionally after omitting cleanings. In contrast to standard thinnings, in biofuel thinnings all the aboveground tree biomass is used for biofuel, i.e. including the stems. For both management settings, we included a number of management strategies:

- Production-oriented management
- No thinning
- Retaining 40% broadleaves in (pre-)commercial thinnings
- Long rotations
- Continuous cover forestry (selection fellings, only in spruce-dominated forests)
- Unmanaged

Treatment generation

We generated treatment schedules for a planning period of 100 years, divided into 20 5-year periods. For each NFI plot and management strategy, up to 20 treatment schedules were created, with an interest rate of 2.5% for calculating the net present value.

Define objectives and constraints

We used the following indicators for biodiversity and ecosystem services:

- Biofuel production (Energy content (TWh/year) of the extracted biomass of residues, stumps and whole trees (above stump, in biofuel thinnings), assuming that 1 t of biomass (dry weight) corresponds to 4.9 MWh)
- Area potentially suitable for reindeer pasture (basal area below 20 m^2/ha, tree density below 1600 stems/ha, not dominated by *Pinus contorta*)
- Carbon storage (Total forest carbon stock including carbon in above- and belowground tree biomass and forest soil, Mg C/ha)
- Recreation (Index between 0 and 1 describing a plots' suitability for recreation, with higher index values denoting a higher suitability for recreation)
- Old forest (Area of forest with age > 140 years)
- Mature broadleaf-rich forest (Area of forest with age > 80 and broadleaves >= 25% of basal area)
- Large diameter trees (Number of trees with a diameter in breast height > 40 cm (trees/ha))
- Deadwood (Total deadwood volume, m^3/ha)

First, we determined the maximum potential indicator level (average for the whole simulation period), by maximizing each indicator separately. Then, we analysed the trade-offs between residue extraction and each of the other indicators, using a set of linear models. Finally, we used goal programming (a special case of linear programming to include multiple objectives) to find a compromise solution, using the maximum potential indicator levels as target levels and minimizing the maximum relative deviation from these targets for all indicators simultaneously. In all optimization models, we included harvest constraints that required roundwood harvest to correspond to reference levels based on national level analysis (SKA15, Claesson *et al.* 2015), and evenness constraints for biofuel extraction.

Treatment selection

We solved the optimization problems within Heureka, using Gurobi as a solver, with linear programming and continuous variables, i.e. allowing plots to be divided and each part to be managed with a different treatment schedule.

3.1.3. Results

The maximum available amount of woody biofuel from Västerbotten was 1.0 TWh/year when biofuel removal was limited to tops and branches from final fellings (BAU extraction settings), and 4.3 TWh/year when biofuel removal also included stumps, residues from normal thinnings and whole-tree biofuel harvest from early thinnings (bioE). Maximizing biofuel resulted in relatively low values for several of the ecosystem service and biodiversity indicators analyzed (Figure 4a), for both the BAU and bioE management settings. In the compromise solutions, 80% or more of the maximum potential of each indicator could be reached, resulting in a biofuel potential of 0.8 Twh/year under the BAU settings, and 3.3 TWh/year under the bioE settings (Figure 6). This is considerably higher than the current extraction rate of approximately 0.4 TWh/years[7]. Under the bioE settings, a major proportion of the potential comes from biofuel thinnings, which is an assortment that is hardly used currently.

[7] *The current extraction rate is based on the average annual area where biofuel extraction after final felling has been notified (years 2015-2018, circa 2000 ha/year in study area) and an assumed average extraction rate of 38 ton dry matter/ha, and one ton dry matter corresponding to 4.9 MWh.*

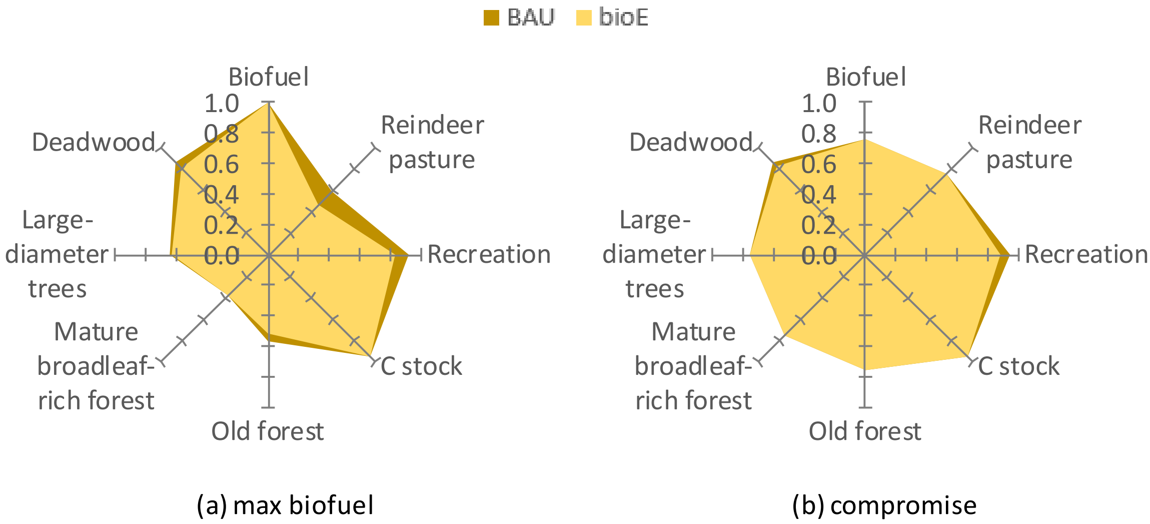


Figure 5: Relative indicator outcome (1.0 = maximum potential) when maximizing biofuel (a) and for the compromise solution (b), for the BAU and bioE biofuel extraction settings.

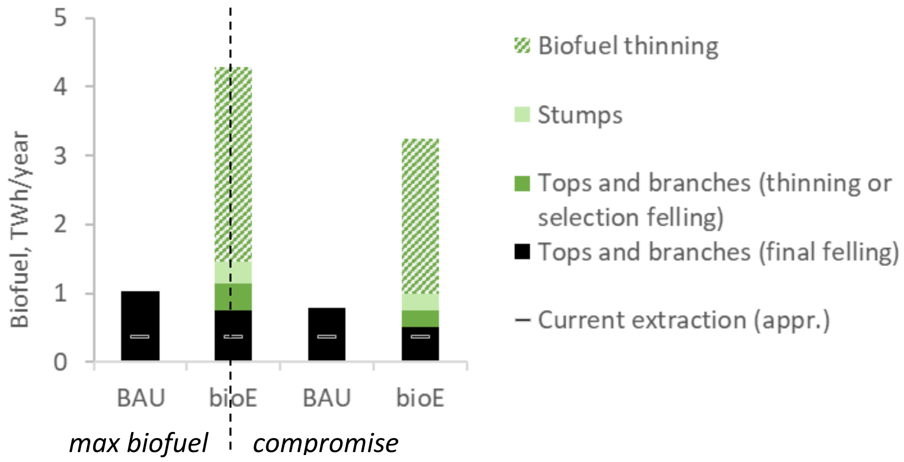


Figure 6: Average annual biofuel extraction potential in different biofuel assortments, in the BAU and bioE scenarios, when maximizing for biofuel (max biofuel) and in the compromise solution.

The trade-off curves (Figure 5) indicate that biofuel extraction can have a negative impact on other ecosystem services and biodiversity, but that potential conflicts can be alleviated through strategic planning. The indicator values of other ecosystem services and biodiversity can be increased substantially without big losses in woody biofuel extraction, up to a certain point. At the same time, future forest conditions can result in higher ecosystem service and biodiversity levels compared to the current situation, except for reindeer pasture and recreation, which are projected to decrease. This is because all scenarios result in denser forests, which has a negative impact on ground lichen occurrence and visibility.

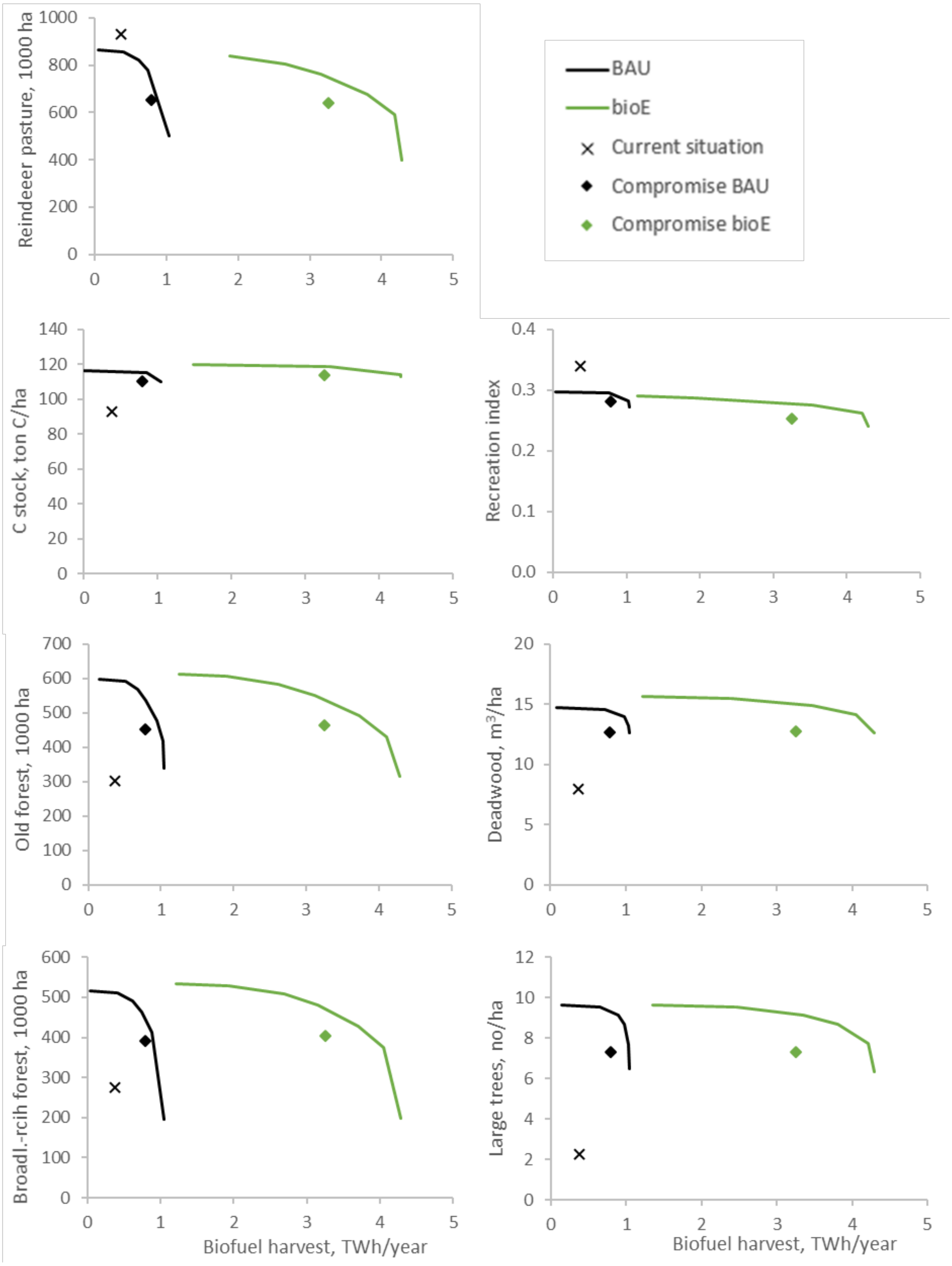


Figure 7: Trade-offs between biofuel production and indicators for other ecosystem services and biodiversity. Markers show current conditions as well as average values for the compromise solutions.

3.2. Landscape planning in Östra Vätterbranterna

3.2.1. Research question:

The objective of this study is to examine the consequences on a number of indicators linked to the sustainable development goals (SDG's) if an increased investment in nature conservation is distributed across all properties in a forest landscape or if the property boundaries are ignored. The SDG's are a collection of 17 global goals that were adopted in 2015 by all United Nations Member States in 2015 and intended to be achieved by the year 2030. The selected indicators are: Harvest volume, Total carbon stock, Standing volume, Dead wood, Mature broadleaf-rich forest, Large trees, Old forest and Recreation (Table 1).

Table 1. Included indicators

Indicator	Explanation
Harvest volume	This is the total harvest volume from the landscape measured in m^3fub per period
Total carbon stock	This is the total forest carbon stock including carbon in above- and belowground tree biomass and forest soil measures in ton C per hectare
Final felling	This is the total area of final felling each period measured in hectare
Recreation	This is an index between 0 and 1 describing the suitability of the forest for recreation, with higher index values denoting a higher suitability for recreation
Dead wood	This is the total area (measured in hectare) with dead wood more than 20 m^3 per hectare
Mature broadleaf-rich forest	This is the total area of forest older than 60 years and where at least 30% of the basal area is deciduous forest
Large trees	This is the total number of large trees. For pine, spruce, beech, oak and other noble broadleaves (ädellöv) this means trees 45 cm or more in diameter. For other broadleaved trees, at least 35 cm in diameter
Old forest	This is the total area (measured in hectare) of forest older than 120 years

The different consequences were investigated using three different quantitative future scenarios for Östra Vätterbranterna, an area of national interest for nature conservation and a biosphere reserve, which extends from Omberg in the north to Tenhult in the south. Each scenario consists of a description of how the forest is managed 100 years ahead and the consequences this will have on selected indicators.

Scenario A (*Business as usual*) is a reference alternative that should mimic the way forestry is conducted today. This means that nature reserves or key habitats are left for free development and forest outside existing reserves is managed with even aged forestry. The total final felling area on each forest holding is limited so that the legal requirements are met, i.e. the area consisting of young forest is limited for each property. The volume harvested from the entire area is expected to increase over time, i.e. the harvesting volume in a period should be higher or equal to the period before.

In scenario B (*Everyone is responsible*) every forest owner takes responsibility for an increased consideration to nature conservation. In this scenario, on top of the area that today is nature reserve, an additional 12% of the forest area is left for free development on each property and 10% of each forest holding is managed with "forestry adapted for nature conservation". All other things are equal to scenario A.

In scenario C (*A few are responsible*) only some forest holdings take responsibility for an increased consideration to nature conservation. In this scenario, it is simulated that on top of the area that today is nature reserve, an additional 12% of the forest area in the landscape are left for free development and 10% of the landscape is managed with "forestry adapted for nature conservation", i.e. no consideration is taken to the forest holding border. All other things are equal to scenario A.

3.2.2. Material and methods

All three scenarios were simulated with Heureka PlanWise using the steps described in section 2.

Import data

In the first step, the forest data describing the initial condition of every stand in the forest was imported to PlanWise. The landscape contains 46 184 ha of productive forest divided into 1406 properties and 4840 stands. The mean standing volume is 170 m^3/ha.

Define management strategies:

The forest stands were divided in two different domains. The first domain consisted of nature reserves and key habitats and the second domain consisted of forest outside the reserves. For each domain different management strategies were defined. For reserves and key habitats, only one strategy was defined, free development. In this strategy no management is simulated, i.e. the forest is left for free development. For the stands outside existing reserves, three management strategies were defined, free development, even aged forestry and forestry adapted for nature conservation. Even aged forestry includes planting with 1-2 thinnings and final felling between 10-40 years after reaching the lowest accepted final felling age according to the law (SKFS 993). At final felling, about 5% of the standing volume is left in the form of retention trees. Cleaning and planting is done according to current rules. In forestry adapted for nature conservation, the rotation age is increased, more deciduous trees are left in the forest in thinnings and cleanings and seed trees are used for regeneration.

Treatment generation

In the third step up to a maximum of 15 treatment schedules were generated for each stand and management strategy. Each treatment schedule covers the development of the stand for all indicators in five-year steps over the 100-year planning horizon. For calculating the net present value, an interest rate of 3 % was used.

Define objective and constraints

In step 4 three different optimization problems were defined, one for each scenario.

Scenario A: The objective function in scenario A was to maximize the net present value from the forest. Except for the area restriction, two additional constraints were formulated. Constraint 1 regulated the amount of young forest for each property in each period (in accordance with the legal requirement that limits the proportion of forest younger than 20 years on property-level, 'ransoneringsregeln') and constraint 2 forced all forest outside reserves to be managed with management strategy "even aged forestry".

Scenario B: The objective function used in scenario B maximized the area of mature broadleaf-rich forest in total over all periods. To increase the importance of forest with high nature conservation values in the beginning of the planning horizon, a discount factor of five percent was used. Except for the area restriction, three additional constraints were formulated. Constraint 1 (which was the same as in Scenario A) regulated the amount of young forest for each property in each period. Constraint 2 forced 10% of the forest outside reserves for each property to be managed with management strategy "forestry adapted for nature conservation". Constraint 3 forced 12% of the forest outside reserves for each property to be left for free development.

Scenario C: The objective function in scenario 3 was the same as in scenario 2. Except for the area restriction, three additional constraints were formulated. Constraint 1 was the same as in scenario A and B and regulated the amount of young forest for each property in each period. Constraint 2 forced 10% of the forest outside reserves in total in the landscape to be managed with management strategy "forestry adapted for nature conservation". Constraint 3 forced 12% of the forest outside reserves in total in the landscape to be left for free development.

Treatment selection

All three optimization problems were solved within Heureka, using Gurobi as a solver, with linear programming and continuous variables, i.e. allowing the stands to be divided and each part to be managed with a different treatment schedule.

3.2.3. Results

Increasing the ambition for nature conservation had a clear effect on most of the selected indicators, see Figures 8 and 9. In addition, it also seems to be possible to improve the outcome for the indicators connected to biodiversity if the increased ambition is fulfilled by only some forest holdings.

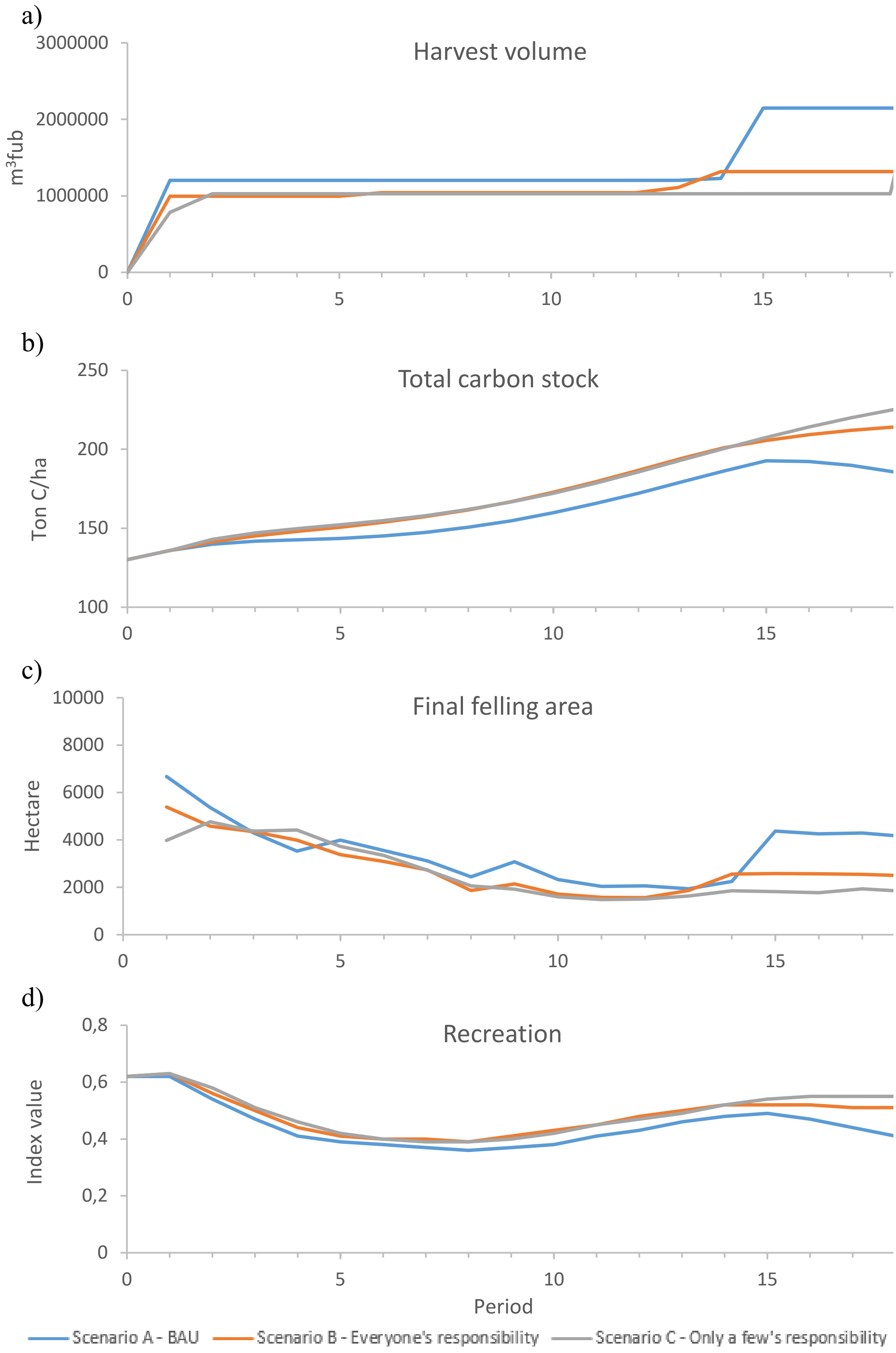


Figure 8. The development of the indicators for a) harvest volume b) total carbon stock c) final felling area and d) recreation over time for the three different scenarios. One period corresponds to five years.

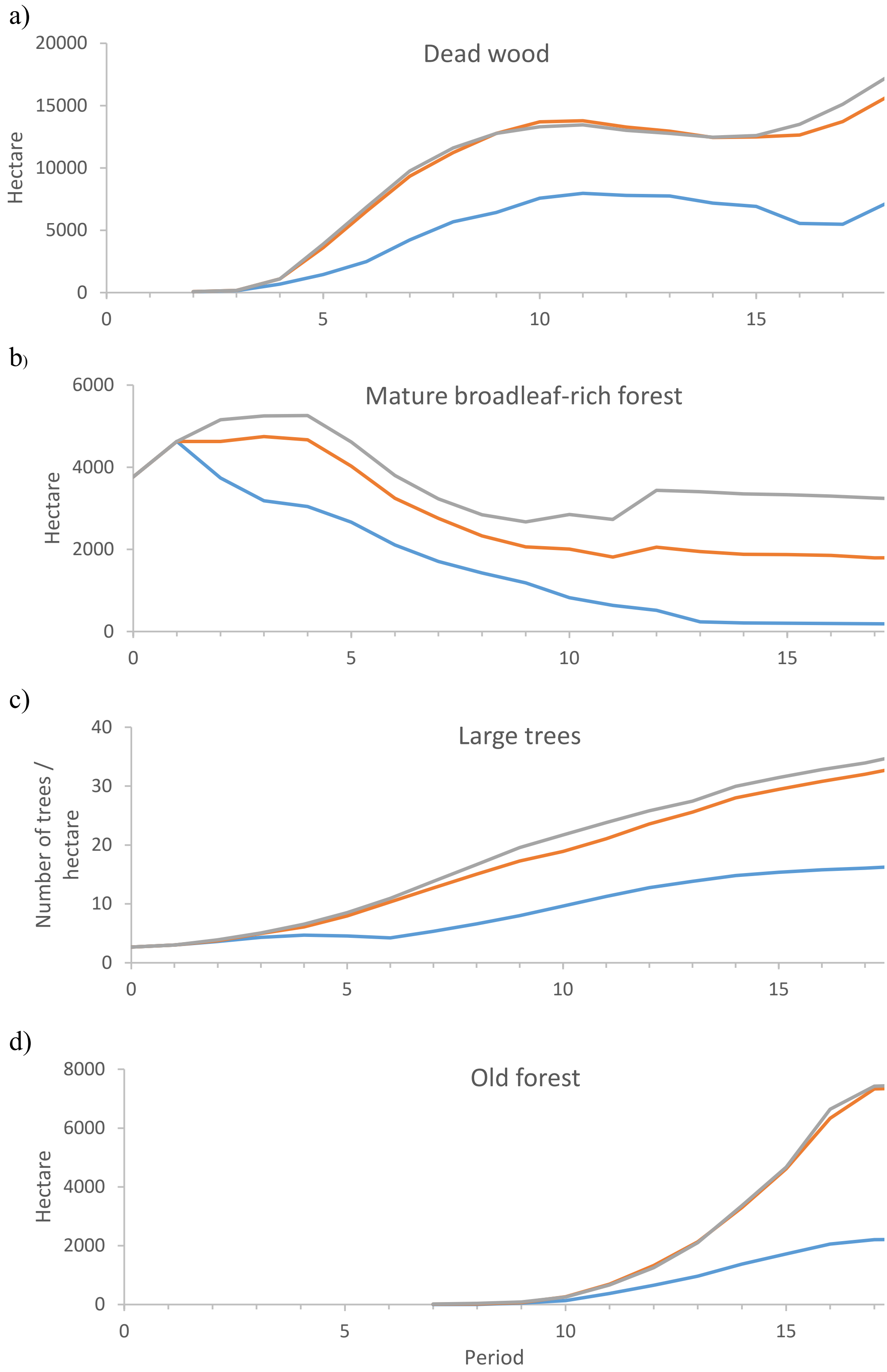


Figure 9. The development of the indicators for a) dead wood b) mature broad leaf rich forest c) large trees and d) old forest over time for the three different scenarios. One period corresponds to five years.

3.3. Optimizing landscape-level management for biodiversity and wood production

3.3.1. Research question

The aim of this study was to investigate the trade-offs between nature conservation and wood production, and to identify combinations of forest management strategies that balance wood production and nature conservation in a boreal forest landscape.

3.3.2. Material and methods

Import data

The input data for this study was a stand register for a forest landscape of 100 000 ha productive forest in boreal Sweden. It was created based on segmented satellite data (SLU forest map[8]), combined with information from the Swedish forest inventory, as well as auxiliary information such as the location of nature reserves and woodland key habitats. The landscape is situated in Vilhelmina municipality in the county of Västerbotten, and is representative of forest conditions in boreal Sweden. Only productive forest (mean annual increment > 1 m^3/ha/year) was included. More information on how the input data was created is available in Eggers et al. (2020).

Define management strategies

Nature reserves and key habitats were left unmanaged. For the forest available for wood supply, we applied up to seven different management strategies (Table 2). The continuous cover forestry (CCF) strategy was only applied in spruce-dominated forests.

Treatment generation

For each management strategy, up to 12 treatment schedules were simulated, spanning a time period of 100 years, divided into 20 5-year periods. The interest rate for calculating the net present value (NPV) was 2.5%.

Define objectives and constraints

As biodiversity indicators, we chose indicators that are used to follow up the Swedish Environmental Quality Objective Sustainable Forests. These are:

[8] https://www.slu.se/en/Collaborative-Centres-and-Projects/the-swedish-national-forest-inventory/forest-statistics/slu-forest-map/

- Deadwood-rich forest: forest area with more than 20 m^2 deadwood/ha, with a minimum deadwood diameter of 20 cm
- Large trees: forest area with at least 60 large-diameter trees, with a minimum diameter of 45 cm for pine and spruce), and 35 cm for broadleaves
- Mature broadleaf-rich forest: forest that is older than 80 years, with a broadleaf proportion of at least 30% of the basal area
- Old forest: forest older than 140 years
- Set-asides: Forest set-aside from management, including formally protected, voluntary set-asides and retention patches)

Net present value (NPV) and harvest volume (average over the entire planning horizon) were used as indicators for wood production.

First, we determined the maximum potential indicator level (average for the whole simulation period), by maximizing each indicator separately. Then, we analysed the trade-offs between harvest level and each of the biodiversity indicators, using a set of linear models. Finally, we used goal programming (a special case of linear programming to include multiple objectives) to find a compromise solution, using the maximum potential indicator levels as target levels and minimizing the maximum relative deviation from these targets for all indicators simultaneously. In all optimizations, we implemented a minimum harvest level. The minimum harvest level was set to reflect average harvest levels during the past 20 years (1996-2006) in the county of Västerbotten, 1.9 m^3/ha/year (under bark, ub) on average on forest available for wood supply, i.e. productive forest outside nature reserves and woodland key habitats.

Table 2: Management strategies

	Pro-duction	No thinning	Broad-leaves	Long rotations	Close-to-nature	CCF	Un-managed
Regeneration	Planting	Planting	Spruce: plantin g Pine: natural	Spruce: planting Pine: natural, seed trees retained	Natural, seed trees retained	Natural	-
Broadleaf admixture after cleaning	10%	10%	40%	20%	40%	-	-
Broadleaf admixture after thinning	10%	-	40%	20%	40%	Higher thinning grade for conifers in selection fellings	-
Delay in final felling after reaching minimum final felling age	At most 30 years	At most 20 years	20 – 50 years	35 – 60 years	35-60 years	-	-
Retention practices in final felling							
Number of single retention trees	10	10	20	20	70	-	-
Number of high stumps	3	3	6	6	3	-	-

Treatment selection

All optimization models were solved within Heureka using Gurobi 8.1 as a solver, with linear programming and subsequent rounding to an integer solution.

3.3.3. Results

There was a large variation in indicator outcomes between the scenarios maximizing one indicator at a time (Figure 8). Maximizing NPV or harvest volume resulted in low relative values for the biodiversity indicators (Figure 9). Also maximizing one of the biodiversity indicators at a time does not automatically result in high values for the other biodiversity indicators, illustrating that focusing on just one aspect of biodiversity is not enough, but that a comprehensive approach is needed.

In the compromise solution, at least 71% of the maximum potential indicator value could be reached for each of the indicators. It is worth noting that in this case, all indicators were given equal weight, including the forest area set-aside from wood production. The compromise solution resulted in 39% of the productive forest area being set-aside without management (Figure 9). Other solutions, giving indicators varying weights, would result in different outcomes. For example, abolishing the set-aside target would allow reaching 79% (instead of 71%) of the maximum indicator values, while the area left unmanaged would be 15%.

In all the scenarios, the minimum harvest level corresponded to the current average harvest level in the region. Given the large variation in potential indicator outcome while sustaining current harvest levels, there is a large leeway for forest management in reaching management objectives that combine wood harvest and biodiversity conservation.

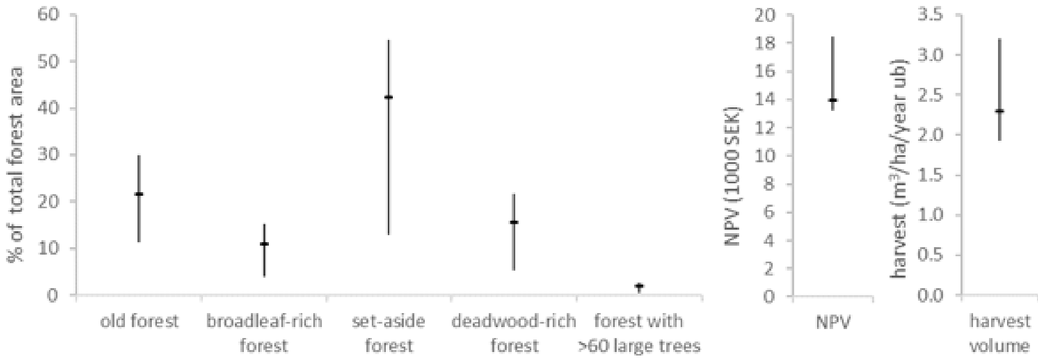
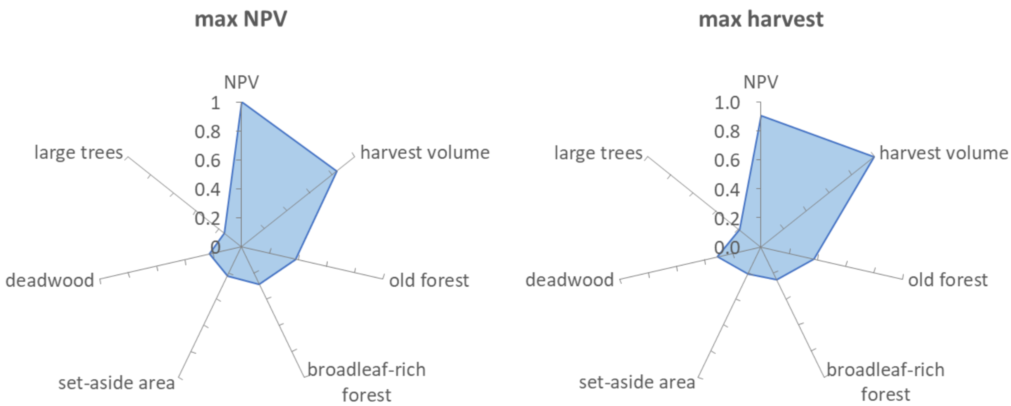


Figure 10. Range of potential outcomes for the analyzed indicators in the scenarios maximizing one indicator at a time. The compromise scenario values are marked with a horizontal line.



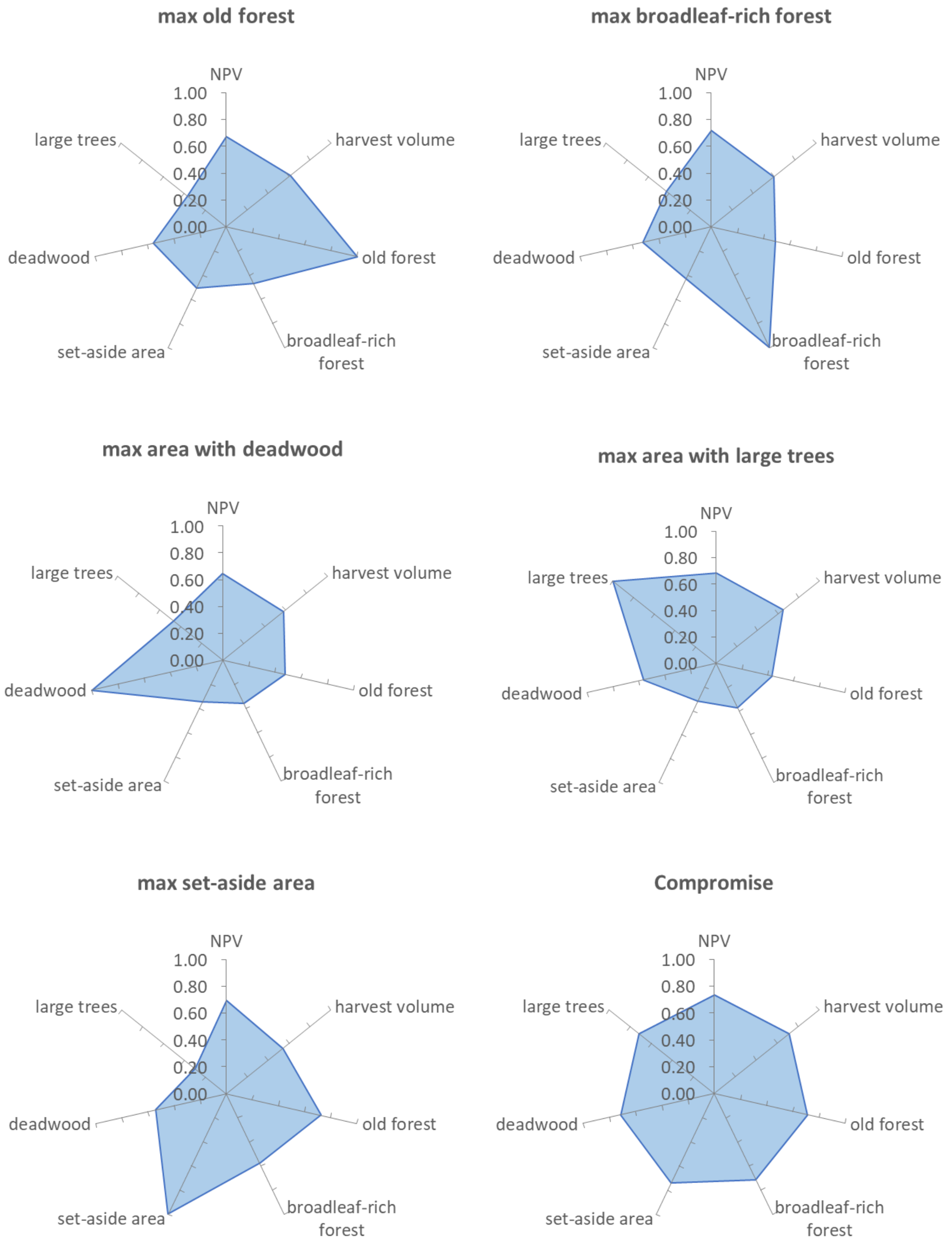


Figure 11. Relative indicator levels (maximum possible = 1) when maximizing each indicator separately, and for the compromise solution.

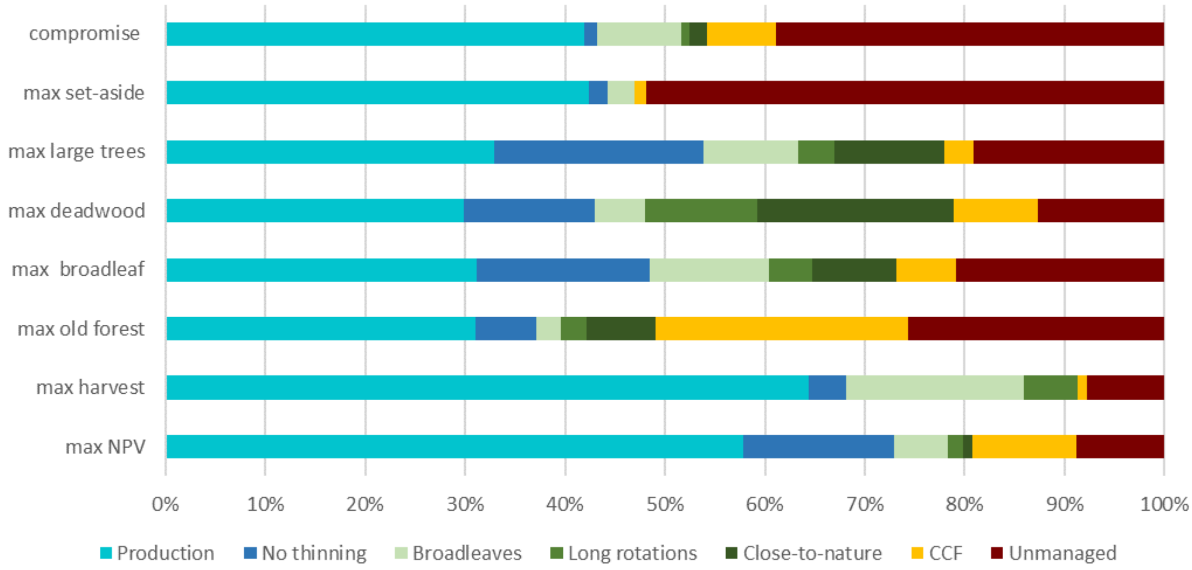


Figure 12: Management strategies when maximizing each indicator separately, and for the compromise solution.

4. Discussion

In this report we have tried to give an overview of the PlanWise application and how PlanWise could be used in different analysis. PlanWise is a powerful tool for projecting the potential development of the forest into the future, analysing the impact of management strategies, and investigating which mixture of management strategies best fulfil user-defined objectives. However, its successful use requires at least a basic understanding of forestry and decision support theory and concepts. The large potential in specifying details in forest management in the system results in a large number of parameters that users can adapt. This, in turn, also means that some degree of familiarity with the system is needed to do more advanced analysis and that the users also are aware of the limitations of the Heureka system.

One important thing to remember is that Heureka only allows the user to investigate the development of a large number of variables coupled to the tree layer. Even if this allows for the analysis of several ecosystem services, including wood and woody biofuel production, carbon storage and sequestration, recreation, and proxies for biodiversity, analysis that requires information about the field layer over time cannot be done only from within Heureka.

Another aspect is that linear optimization approaches like the one used in PlanWise assume perfect foresight, i.e. that the future development of the forest under a given management strategy is deterministic (known with certainty). This is of course quite a strong assumption given all the uncertainties that occur in reality, such as stochastic biotic or abiotic damages, changes in timber prices and in management costs, new or improved management techniques or changing social norms on how forests should be managed. In short, the only thing we can be certain about is that the future is uncertain. Still, PlanWise and linear optimization approaches can give invaluable decision support. The results of an analysis can be interpreted as what is likely to happen for the selected treatment configuration given our current knowledge.

Third, the growth and yield models that form the basis of the projections are empirical regression models, which means that the potential to account for environmental changes is limited. It is possible to include impacts of climate change, but this is currently limited to three scenarios (RCP4.5, RCP8.5 and A1B), and they only affect the impact on wood production, not accounting for the potential increase in extreme weather events and disturbances.

Fourth, even though users have many options to vary management-related parameters, options for projecting management alternatives besides the prevailing even-aged management system are limited to selection fellings, applicable for spruce-dominated forests. Results for management strategies based on selection fellings are more uncertain than conventional management due to limited empirical information.

However, despite the mentioned limitations the PlanWise application and the other applications in the Heureka system, RegWise, StandWise and PlanEval are powerful tools for making long-term analysis about the forest resource. One of the strengths of the system is the possibility to generate several scenarios that can be compared to each other to analyze relative differences caused by variations in management.

We hope that this report could give fruitful insights about possibilities and limitations of the system and how the system can be used in different analysis contributing to a sustainable development of the forest landscape.

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