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Advancing climate-smart forestry with an interactive decision-support tool that incorporates the preferences of private forest owners☆

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ABSTRACT

We explored the potential of interactive multiobjective optimization for climate-smart forest management planning in privately owned forests. Through workshops with two groups of four forest owners each in Eastern Finland, we evaluated the influence of management preferences, information on climate-smart forestry practices, and monetary compensation on their decision-making process in a 20-year planning period. An interactive decision support tool enabled the analysis of trade-offs among different objectives and finding solutions that reflected the preferences of forest owners. In both groups, when informed of climate-smart forestry, the forest owners increased the amount of carbon stored in their forests compared to the initial planning stage, where carbon was not included as an objective. Interestingly, the approach of providing information increased carbon storage more than what could be achieved later by monetary compensation. Although these are preliminary findings, they may provide valuable insights for future research and practical applications in improving the climate-smartness of forestry.

Practical recommendations:

1. Promote research and piloting towards information-based nudging.
2. Understand forest owners' behavioral motivations in strategic planning and policy-making.
3. Distinguish between short-term and long-term effects in carbon compensation.
4. Deploy interactive decision support tools that enable multiobjective optimization.

1. Introduction

Many nations pursue carbon neutrality, aiming to balance greenhouse gas emissions from human activities with natural sinks. The European Commission has set ambitious goals for greenhouse gas removal via forestry as a part of its 2030 Climate and Energy Framework (European Commission, 2013). Forests are a key land-based sink, yet observed declines in forest carbon sequestration (Korosuo et al., 2023) suggest an urgent need for national mechanisms—whether voluntary or enforced—to encourage forest owners to adopt more climate-oriented management. Similarly, Pan et al. (2024) call for climate-smart forestry practices to minimize carbon emissions and maximize carbon uptake and its benefits.

Giffen et al. (2025) argue that modern sustainable forestry must incorporate climate change adaptation and mitigation, balancing the short- and long-term objectives listed in Table 1. Climate-smart forestry is a more specific, climate-focused sustainable forest management paradigm (Nabuurs et al., 2017) with an aim to enhance forest adaptation and climate change mitigation while maintaining the socio-economic benefits (Bowditch et al., 2020; Verkerk et al., 2020). It seeks to store carbon in both forests (i.e., trees and soil) and long-lived wood products. However, its implementation varies across forest ecosystems

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Table 1
Objectives for climate-smart forestry (Giffen et al., 2025).

Objective	Short term (0–30 years)	Long term
Climate adaptation	Maintain resistance and resilience at the face of changing climate.	Transition to ecosystems adapted to expected future conditions.
Climate mitigation	Increase carbon storage in trees and long-lived wood products, and substitute wood for more carbon-intensive materials.	Maintain and increase long-term carbon storage.
Forest products	Improve forest management to increase both the quality and quantity of wood to support increased use in construction and other products.	Manage current forests for trees that will mature in future decades.
Non-timber values	Implement reduced-impact harvesting to maintain or enhance non-timber values while increasing productivity.	Adopt strategies that support non-timber values also in the future.

and management approaches (Shephard and Maggard, 2023). A textbook approach to increase carbon storage through forest planning would be to impose an end-inventory constraint on forest management optimization (Kangas et al., 2015). However, without binding sequestration targets, outcomes ultimately reflect the preferences of individual forest owners.

In Northern Europe, up to 70 percent of the forested area is privately owned, often in small holdings (Weiss et al., 2019), whose owners have substantially varying management preferences (Horne et al., 2020). However, many multiobjective planning studies apply uniform objectives on a large landscape scale (Triviño et al., 2015; Díaz-Yáñez et al., 2021; Eyvindson et al., 2021; Pohjanmies et al., 2021; Shavazipour et al., 2022; Blattert et al., 2023), for instance, more than 2000 ha (Pohjanmies et al., 2021), whereas the average forest holding size in Finland is less than 50 ha (Karppinen et al., 2020). Moreover, analyses that assign a monetary value to carbon sequestration may indicate an "optimal" strategy for selected stands (Kangas and Ollikainen, 2023; Parkatti et al., 2023; Tahvonen et al., 2024). However, the optimality of these strategies should be evaluated at the forest holding level, where actual decisions are often made based on the forest owners' multiple objectives for the forest stands that belong to a certain holding (Kurttila et al., 2006, 2008).

Forest owners' willingness to adopt climate-smart practices has been studied through participation decisions (Miller et al., 2012; Håbesland et al., 2016), program acceptance (Pormon et al., 2026; Tzemi et al., 2025) and management intentions regarding climate change and biodiversity (Husa and Kosenius, 2021) . However, the intention and behavior can sometimes differ, leading to a more positive estimation of willingness (Murphy et al., 2005) . Providing information on climate-smart practices, such as ash fertilization (Maidell et al., 2024), can increase willingness (or nudge) to adopt such measures without altering economic incentives. Looking beyond individual holdings, landscape-level cooperation and nudging through peer communication can shape owner behavior (André et al., 2017). Shared environmental benefits can motivate cooperative actions (Häyrinen et al., 2025), with networks of forest owners often coalescing around a single, proactive owner (Hamunen et al., 2015). However, research comparing the effects of nudging with economic incentives appears insufficient to draw conclusions about the drivers affecting forest owners' behavior.

Building on the above framing, we take a practical, forest-owner-centered perspective on climate-smart forestry and examine how forest owners' objectives interact with mitigation-relevant outcomes in forest planning. The analysis was conducted at the forest holding and landscape levels within a 20-year planning context, motivated by Finland's 2035 carbon-neutrality target and the importance of management choices that maintain or enhance forest carbon stocks in the near term. The primary aim of this pilot study is to test how an interactive, multiobjective optimization-based workflow characterizes trade-offs between carbon storage in living aboveground biomass and forest owners' economic objectives. The secondary aim is to assess how forest owners' preferences, information, and compensation-based guidance influence the selected management solutions and the resulting economic-carbon trade-offs. Finally, we use the pilot to identify research needs for guiding private forest owners toward climate-smart forestry practices and to specify requirements for an associated decision-support tool.

2. Materials and methods

2.1. Forest owners

For this study, two groups of forest owners were formed around one or two active forest owners. At first, several locally active forest owners were contacted to find interested and suitable forest owners to participate. After finding two active forest owners through earlier projects and contacts, the snowball method (Morgan, 2008) was used to identify other active forest owners in the same area. Sharing a holding border with the initial owners was a selection criterion, and ultimately, two groups of four participants each were formed in two locations in Eastern Finland.

An initial thematic interview (Pykäläinen, 2000) of the forest owners included questions about their socio-demographic information, forest holdings, plans and objectives for forest ownership, decision making processes regarding their forest holdings, and experiences and attitudes toward risks and climate change. The semi-structured interview (Ayres, 2008) was supplemented with more structured questions (Firmin, 2008) about typical forest owners and holdings, following the questions of the Finnish Forest Owner 2020 study (Karppinen et al., 2020; Horne et al., 2020). The forest owners were also asked to indicate any restrictions regarding practical forest management (e.g., avoiding clear-cutting in certain areas). These stand-specific restrictions were obeyed when selecting treatments in the optimization process. General information about the forest owners and their forest holdings is shown in Table 2. English translations of the interview questions can be found in the supplementary material.

2.2. Finding the preferred forestry plans

Forest management plans specific to each holding were prepared in multiple phases structured to workshops as illustrated in Fig. 1. Separate optimization problems were formulated for each phase as integer linear multiobjective optimization problems (detailed in Section 2.3). The decision variables in these problems represented the management actions to be taken at specific stands at specific times.

First, in workshop I, the forest owners applied an interactive multiobjective optimization method NIMBUS (Miettinen and Mäkelä, 2006) to simultaneously optimize harvesting income from the three planning periods (detailed in Section 2.4); timber volume at the end of the 20 years' planning horizon; and the net present value (NPV) of the harvest income plus tree stock and bare land value, discounted from the end of the planning horizon using an interest rate of 3%. Our objective was not to evaluate the intrinsic climate-smartness of management alternatives as such. Instead, we used existing simulator outputs to represent consequences of management and focused on the decision problem of quantifying the trade-offs forest owners may be willing to accept between near-term carbon storage and growing stock volume vs. economic objectives (periodic harvest income and net present value). These objectives were chosen because they reflect relevant trade-offs for forest owners and are feasible to simulate.

The goal was to find management plans for holdings based on their owners' preferences, but without specific attention to climate objectives (labeled hereafter as individual preferred plans - Workshop I). This was done with several goals in mind:

Table 2
Forest owner characteristics and forest holding information reported by forest owners. Both groups had four forest owners with their own forest holdings. The two co-owners mentioned in Group 2 were present but did not actively participate in the workshop.

	Group 1	Group 2
Gender		
Man	2	3
Woman	2	1 (2 co-owners)
Age		
45–54	3	–
55–64	–	2
65–74	1	1
Forest ownership time (years)		
Average	19.5	21.5
Min	10	10
Max	38	41
Residence		
Living on forest holding	3	1
Holiday home on forest holding	1	2
Owner through		
Bought from open market	1	2
Bought from family	3	2
Size of forest holding		
Average	90.5	19.5
Min	20	11
Max	222	32
Forest plan or forest information in use		
Forest plan from Forest Management Association	–	1
Forest plan from forestry company	4	1
Metsään.fi (free forest information e-service)	1	1

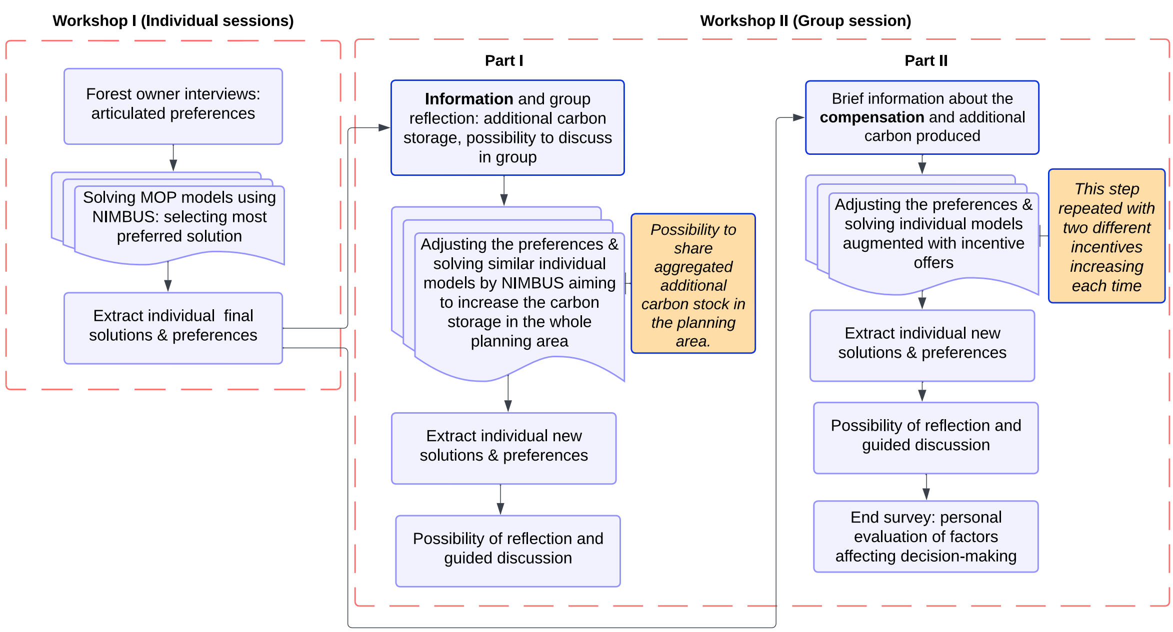

Fig. 1. An overview of the main steps, workflow, and connections of the workshops to prepare the forestry plans. MOP refers to a multiobjective optimization problem and NIMBUS is the multiobjective optimization method applied.

- to introduce the forest owners to interactive multiobjective optimization, and particularly the NIMBUS method,
- to allow them to learn about the trade-offs among the objectives for their forest holding, and
- to establish a baseline, or a reference plan, that would represent their plans for the forest holding without any additional guidance or compensation, steering them towards more climate-smart forestry.

Second, in workshop II, the forest owners with neighboring holdings were brought together to experiment with the effects of (1) information on options to increase carbon storage, (2) group reflections, and (3) carbon price on their forest planning and to learn about the resulting trade-offs.

For Part I of Workshop II, the forest owners received a brief introduction to climate-smart forestry and how to enhance carbon storage in their forest holdings. This was done to inform them about additional carbon storage before starting the forest planning session, which included a new carbon storage objective. They then applied NIMBUS with the intention to *learn what can be done to increase carbon storage in forests, the types of trade-offs involved, and general information about climate-smart forestry and climate targets*.

In Part II of Workshop II, the forest owners were offered a hypothetical monetary incentive in the form of a compensation for producing additional carbon. In this planning task, neither the payer nor the conditions of a compensation program were specified. The optimization task was repeated twice, each with a different, increasing incentive each time, to evaluate the effects of additional compensation compared to the effects of information in Part I.

Throughout both Workshops I and II, the forest owners were guided to focus on planning their forests as they felt natural to them, and to choose options with which they were comfortable.

In summary, the different approaches to support increasing carbon storage were:

1. **Information**:
   - (a) Information about carbon storage in forests and the concept of “additional carbon”.
   - (b) Optimization tool – a carbon related objective was added to the multiobjective optimization problem to help visualize the trade-offs between carbon storage, timber volume, net present value, and harvesting income.
2. **Group reflection possibility**: A possibility to exchange thoughts, share the amount of cumulative additional carbon in the planning area, and discuss.
3. **Incentive**: Two different compensation prices for producing additional carbon were offered, the first one 15€/CO_2 tonne, and the second one 30€/CO_2 tonne.

Finally, the forest owners were asked to individually assess which factor affected their decision to change the initial preference plan, if any changes were made, and to reflect on the forest planning method, its usefulness, and the overall workshop.

2.3. Multiobjective optimization problem

To help the forest owners find their most preferred management plans, the problem was formulated as a multiobjective integer linear optimization problem. In Workshop I, the optimization focused only on the NPV, harvesting income and end-inventory timber volume. The problem formulation was

$$\begin{aligned}
&\text{maximize} && \sum_{j=1}^{n}\sum_{i\in I_j} v_{ij}x_{ij} \\
&\text{maximize} && \sum_{j=1}^{n}\sum_{i\in I_j} s_{ij}x_{ij} \\
&\text{maximize} && \sum_{j=1}^{n}\sum_{i\in I_j}\sum_{t=1}^{T} w_{ijt}x_{ij} \\
&\text{subject to} && \sum_{i\in I_j} x_{ij} = 1, \qquad j=1,\dots,n, \\
& && x_{ij}\in\{0,1\}, \qquad j=1,\dots,n,\ i\in I_j,
\end{aligned} \tag{MOP-1}$$

where n is the number of stands, I_j is the set of feasible management options for the jth stand and the decision variables x_{ij} ($i \in I_j; j = 1,\dots,n$) are defined as

$$x_{ij} = \begin{cases} 1, & \text{if management } i \text{ is chosen for stand } j \\ 0, & \text{otherwise.} \end{cases}$$

The first objective function is the 3% NPV, where v_{ij} represents the NPV of forest in stand $j \in \{1,\dots,n\}$, if management option $i \in I_j$ is chosen in the stand. We considered the NPV at a 3 percent interest rate because this rate itself does not shorten or extend rotations as much as higher or lower rates do. The second objective function is the end-inventory timber volume, where s_{ij} represents the available stock volume in stand $j \in \{1,\dots,n\}$ after 20 years, if management option $i \in I_j$ is chosen in the stand. The third objective function is income from harvesting and selling wood, where w_{ijt} represents the (discounted, 3%) income in time period t from stand $j \in \{1,\dots,n\}$, if management option $i \in I_j$ is chosen in the stand.

As mentioned in 2.2, for Workshop II, a new objective function was added to (MOP-1) to find out how willing the forest owners were to adjust their management schedules. It represents additional stored carbon compared to their most preferred solution from Workshop I and was formulated as

$$\text{maximize} \sum_{j=1}^{n}\sum_{t=1}^{T}\left(\left(\sum_{i\in I_j} c_{ijt}x_{ij}\right) - b_{jt}\right).$$

Here, c_{ijt} (measured in CO_2 tonnes) represents the carbon stored in the trees in stand j in time period t, if management option $i \in I_j$ is chosen in the stand. In addition, b_{jt} represents the baseline that the carbon storage is compared against, that is, the amount of carbon stored in stand j in time period t in the most preferred solution from Workshop I.

The objective function representing income from harvesting and selling wood was also updated to include added income from potential carbon storage compensation as

$$\text{maximize} \sum_{j=1}^{n}\sum_{i\in I_j}\sum_{t=1}^{T} w_{ijt}x_{ij} + \sum_{j=1}^{n}\sum_{t=1}^{T} p_t\left(\left(\sum_{i\in I_j} c_{ijt}x_{ij}\right) - b_{jt}\right).$$

Here, p_t represents the (discounted) compensation paid for storing 1 tonne of CO_2 for the duration of time period t. Three different variations of this problem were used in Workshop II, each using different compensation prices p_t for the stored carbon. In the Part I, compensation was set equal to 0, effectively keeping the income objective same as it was in Workshop I. For two stages in Part II, the compensation prices were, respectively, set to correspond to 15€ or 30€ per (permanent) CO_2 tonne. These values were chosen, because we could not try many different compensation levels to avoid decision maker fatigue in the workshop, and 15€ and 30€ had also been used in some other recent studies (e.g. Juutinen et al., 2018; Pohjola et al., 2018).

Because the planning period we are looking at is only 20 years, we needed to convert the payments for permanent storage to payments for 1 year of storage (paid at the end of each year). As 100 years is commonly used as the lower limit for a carbon storage to be considered permanent (Brunner et al., 2024), we used that to calculate a yearly payment of equivalent net present value

$$p_{\text{yearly}} = \frac{P \times r}{1-(1+r)^{-100}},$$

so the compensation offered was approximately 0.47€ or 0.95€ per tonne per year for permanent prices P equal to 15€ and 30€ respectively, when the interest rate r was set at 3%.

Moreover, for Workshop II, an extra constraint was also added to the multiobjective optimization problem to ensure that the amount of additional carbon stored was non-negative, that is,

$$\sum_{j=1}^{n}\sum_{t=1}^{T}\left(\left(\sum_{i\in I_j} c_{ijt}x_{ij}\right) - b_{jt}\right) \geq 0.$$

Otherwise, problem (MOP-1) remained the same. The entire multiobjective optimization problem for Workshop II is available in the Supplementary material.

2.4. Forest data

Standard stand-level forest resource data (Valonen et al., 2019; Pynnönen et al., 2021) were downloaded for each holding from the open database of the Finnish Forest Center. The Metsi forestry simulator (LUKE, National Resources Institute Finland, 2023) was used to simulate the outcomes of the management alternatives for each stand. Metsi implements a standard simulation workflow based on stand-level mean tree attributes and a theoretical diameter distribution (Siipilehto and Mehtätalo, 2013), tree height (Siipilehto and Kangas, 2015) and volume models (Kangas et al., 2023). We used Metsi's default parameterization, except we allowed both thinning from above and below and replaced the default growth model with a more up-to-date one (Pukkala et al., 2021).

The resulting management alternatives span 20 years divided into three time periods (two 5-year periods and one 10-year period producing different details for short- and longer-term horizons, respectively). They represent combinations of different thinnings and clear-cuttings based on silvicultural guidelines typical to the area. The amount of feasible management options varied from 1 and 70 between stands, depending on their estimated age, size and species composition of the trees. The soil system boundary was restricted to mineral soils. For each treatment alternative, we used the Metsi simulator to compute the stand-specific harvest income at the time of the operations, the remaining forest value, and growing stock volume at the end of the planning horizon.

Adaptation and disturbance-risk resilience were not assessed explicitly, as the simulations were deterministic (i.e., no stochastic disturbance risk was included) and the analysis focused on how forest owners' choices affect near-term mitigation-relevant carbon storage and economic trade-offs. Carbon was represented as carbon stored in living aboveground biomass, derived from growing stock volume. We did not explicitly model other carbon pools (e.g., harvested wood products or mineral–soil carbon), because these would be driven by the same simulated harvest removals and biomass/litter flows already represented in the model outputs. Under this scope, including such derived pools is unlikely to alter the relative comparison of the studied options within the analyzed horizon.

2.5. NIMBUS method

The forest owners solved the multiobjective optimization problems to find their most preferred forest management plans by applying the NIMBUS method via a web-based graphical user interface implemented as a part of the open-source software framework DESDEO (Misitano et al., 2021). In what follows, we refer to this as a decision support tool. NIMBUS is an interactive multiobjective optimization method using classification types of preferences to direct the search during the iterative solution process (Miettinen and Mäkelä, 1995, 2000, 2006).

In each iteration, NIMBUS requires a decision maker's (here, forest owner's) preferences on how to get from the current Pareto optimal solution to a more preferred one by classifying the objective functions. Each objective function is assigned to one of the five different classes (in a maximization problem) based on the current value:

1. $I^{>}$ value to be improved (i.e., increase in case of maximization),
2. $I^{\geq}$ value to be improved until some desired aspiration level z_i,
3. $I^{=}$ value is satisfactory at the current level,
4. $I^{\leq}$ value may be impaired till a bound u_i, and
5. $I^{\diamond}$ value may temporarily change freely.

Since we are moving from a Pareto optimal solution to another, a feasible classification is the one that considers impairment in some objective functions when seeking improvements in others. For the second and fourth classes, the decision maker needs to also provide their aspiration levels and lower bounds (in maximization), respectively. To reach a new Pareto optimal solution, NIMBUS utilizes a scalarization function that incorporates the classification information gained from the decision maker. In this study, we use the so-called *synchronous NIMBUS* method (Miettinen and Mäkelä, 2006), which employs up to four different scalarization functions, enabling us to generate up to four different Pareto optimal solutions. The decision maker can set the maximum number of solutions to be generated (between 1 and 4). At each iteration, the decision maker can also select two solutions and ask for generating some more intermediate solutions between them if so desired. Fig. 2 shows an overview of the synchronous NIMBUS method.

The web user interface that the forest owners used to find their most preferred Pareto optimal management plans is shown in Fig. 3. Using the bars on the top left panel, the user expresses the classification, i.e., what kind of changes they want to see to make the current solution more preferred. The top right area contains problem-agnostic visualizations for studying and comparing different solutions and the bottom left area has the same information in a tabular format, highlighting the exact objective values. The bottom right area visualizes the management options (i.e., decision variable values) corresponding to the current solution chosen by the forest owner. It shows the map of their holding, with different colors corresponding to different management options. The buttons below determine the time period shown on the map. No additional context was provided to the forest owners regarding the numeric values, relying on their knowledge of their forest holdings. However, they had the opportunity to ask questions in the workshops whenever needed.

3. Results

3.1. Forest owner feedback

Out of the 8 participating forest owners, most had a positive attitude toward contributing to climate change mitigation (7 persons), but some estimated that they lacked the necessary know-how to store carbon in their own forest (3 persons). Some thought that climate change is not a problem that can be solved by forest owners (4 persons) and many estimated that society puts pressure on forest owners to store more carbon (6 persons).

Regarding the decision support tool and the task, some forest owners found the tool to be useful (3 persons), while others saw its value but did not consider it important personally (3 persons). Few were reluctant to use the tool (2 persons). Those familiar with computers and numerical information preferred to use the tool themselves, while those unfamiliar with computers preferred to have someone else operate the tool for them.

Some forest owners criticized the results that the tool provided. In some cases, the publicly available data did not include the latest management actions that had been done in the forest, which affected the results. Some forest owners managed their forest at the individual tree level and did not find stand-level objectives useful. Further, the aggregated stand measures were not found to convey information related to scenic amenities. This reduced the effectiveness of planning for forest owners of group 2 in particular, as aesthetics strongly motivated their management plans.

3.2. Individual plans in Workshop I

No forest owner committed fully to maximizing only NPV or income. According to the interviews, this was not an articulated preference in most cases.

In Group 1 (4 persons), two forest owners mentioned income as an important goal in their forest planning, and all considered maintaining the forest appearance (tidy, managed, not overgrown) important. Three forest owners preferred to increase the timber volume during the planning period, considering the next forest owner generation. Hunting (2 persons), natural values (2 persons), scenery and recreation (2 persons) were also regarded as important. The forest owners were rather happy with the initial plans, but preferred certain tree species (e.g. *Populus tremula*) and obtaining an even flow of harvesting income over planning periods. The tree growing and harvesting conditions particularly in the poorly productive areas of the plans were not considered realistic.

> *"In that sense, the idea with the property has been that, yeah, it's there for hobbies, but also for the next generations (children)".*
> (Forest owner quote, translated)

All forest owners were linked to their holdings through family history (4 persons) and lived or had a holiday-home there.

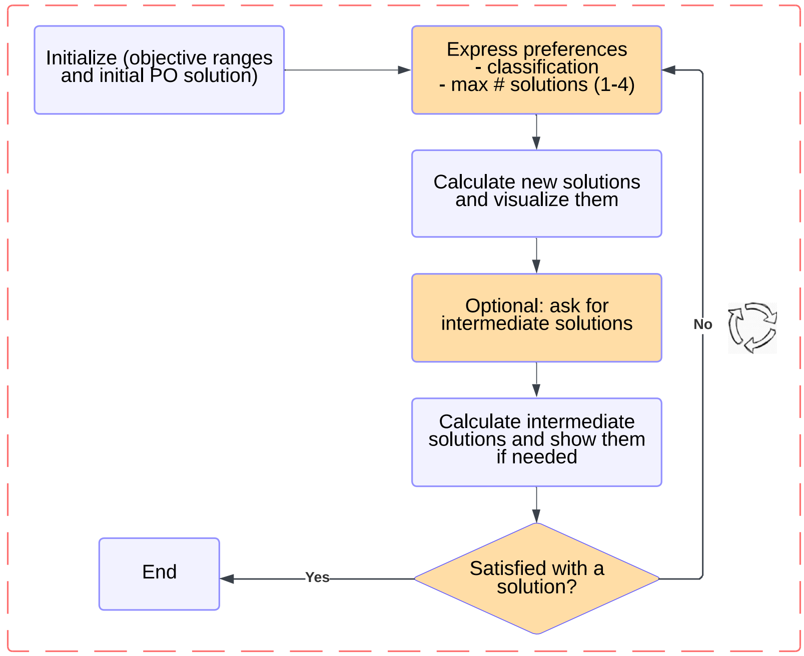

Fig. 2. An overview of the NIMBUS method. Orange boxes (dark) represent the involvement of the forest owner, while the blue–purple (light) boxes denote the involvement of the facilitator and computer. See the online version for the colored picture. Here, PO refers to Pareto optimal.

In Group 2 (4 persons), the scenic amenity was important to all as they lived or had a summer house or some other recreational building on the holding (4 persons). Income was not the main goal, but economic security or additional income was mentioned as being somewhat important (3 persons). Recreation (3 persons) and forest work as a hobby (3 persons) as well as firewood supply for household use were considered important. The holdings in this area were small (approx. 10-30 ha) and forest owners were accustomed to planning in a practical, small-scale manner (3 persons). The forest data was not suitable for such planning, as it was outdated and lacked details (2 persons). In all cases, the initial plan was in the right direction, but needed adjusting many details especially to account for the scenic objectives (4 persons).

> *"What would be of great importance is that the environment in which I live would be pleasant".* (Forest owner quote, translated)

3.3. Workshops II with groups

3.3.1. Information effect

When the carbon stock objective and information about it was introduced in Workshop II, along with an opportunity to reflect in a group, most forest owners chose to trade off forest income for carbon. Those who changed their initial plans (7 persons) estimated that the information provided by the decision support tool, information about carbon storage in general, and the group reflections affected their decision slightly or considerably. Some of the forest owners who changed the initial plan were surprised how reasonable it was to increase carbon storage in the short term without greatly affecting the harvesting income (3 persons).

The reasons for not wanting to postpone harvesting or clear-cutting were that it was considered risky due to the aging forests' declining condition (3 persons). Also, distributing wood harvesting throughout the planning period, rather than at the end, was considered better (4 persons) for various reasons (scenic, better income distribution or lower labor intensity). Continuous cover forestry interested forest owners in group 2 (3 persons). One of them chose to apply it in the initial plan and, thus, could not easily increase stored carbon in Workshop II.

3.3.2. Incentive effect

Forest owners found compensations affecting their decision to store additional carbon considerably (4 persons) or slightly (2 persons). The payments for additional carbon were commented to motivate until the forest health (1 persons) or loss of wood value (3 persons) was risked. When discussing possible carbon agreement conditions, the long duration of the contract was considered problematic (3 persons). Also, details related to a forest owner change, and degree of exclusion of forest operations were mentioned. Continuous cover forestry was considered an interesting option (4 persons). Those who did not consider the compensation payment to motivate them also did not consider forests economically important (2 persons).

3.4. Effects on carbon storage

Compared to the individual preferred plans aggregated across the entire landscapes, the final plans generally postponed management alternatives in time, thereby contributing to increased forest carbon storage especially after the first 10 years (Fig. 4). Thereafter, the solutions differed between the two forest owner groups so that the carbon storage kept increasing in group 2, whereas in group 1, the harvests realized in the third planning period reduced the carbon storage from the levels seen after 10 years, nevertheless keeping it higher than the initial carbon storage.

Table 3 shows how the different management plans in Fig. 4 affected the NPV of the forest. The forest owners of group 2 traded-off altogether 91,125€ (1,505€/ha or 11% of the initial) of forest NPV after having received information on climate-smarter practices compared to their individual preferred plans. For plan 3, with the 15€ compensation, the reduction was lower, altogether 63,572€, and for plan 4 with the 30€ compensation, a little higher, 111,509€. For plans 3 and 4, the reduction of the NPV was subsidized by the carbon compensation. Only the effective NPV, which included the compensation, was visible to the forest owners during the decision process. Consequently, forest owners in Group 2 were less willing to accept reductions in NPV when compensation was offered.

Fig. 4 is somewhat different for forest owner group 1. The NPV trade-off for the information-guided plan 2 in Workshop II was 56,091€

Fig. 3. The English version of the graphical web user interface of NIMBUS available in DESDEO. The forest owners used near identical Finnish translation of the user interface to find their most preferred management plans.

(175€/ha; 2% of the NPV of their individual preferred plans). However, as seen in Table 3, the plans 3 and 4 with carbon compensation factored produced an extra effective NPV for the forest owners of the area. This is because even discounted for time, the carbon compensations were higher than the NPV lost from forestry. While the management improved the carbon stocks overall, the different figures highlight the possibility of behaving strategically to obtain extra income from the monetary compensation.

4. Discussion

Despite the limited data from only two groups of forest owners, our study provides interesting insights for designing climate-smart forestry actions and their incentives. First, compared with the initial planning stage, when carbon was not included as an objective, the forest owners in both groups were willing to increase forest carbon storage after carbon was introduced in the later workshops. Interestingly, the information approach increased the carbon storage more than the subsequent monetary compensation. However, it should be acknowledged that the observed effects of information-based guidance cannot be fully isolated from the fact that the information approach preceded the compensation approach. The subsequent decisions may have been influenced by order effects or respondent fatigue. Furthermore, the peer-discussion effect may be difficult to isolate from the information effect, as peer-discussion was allowed throughout the workshop.

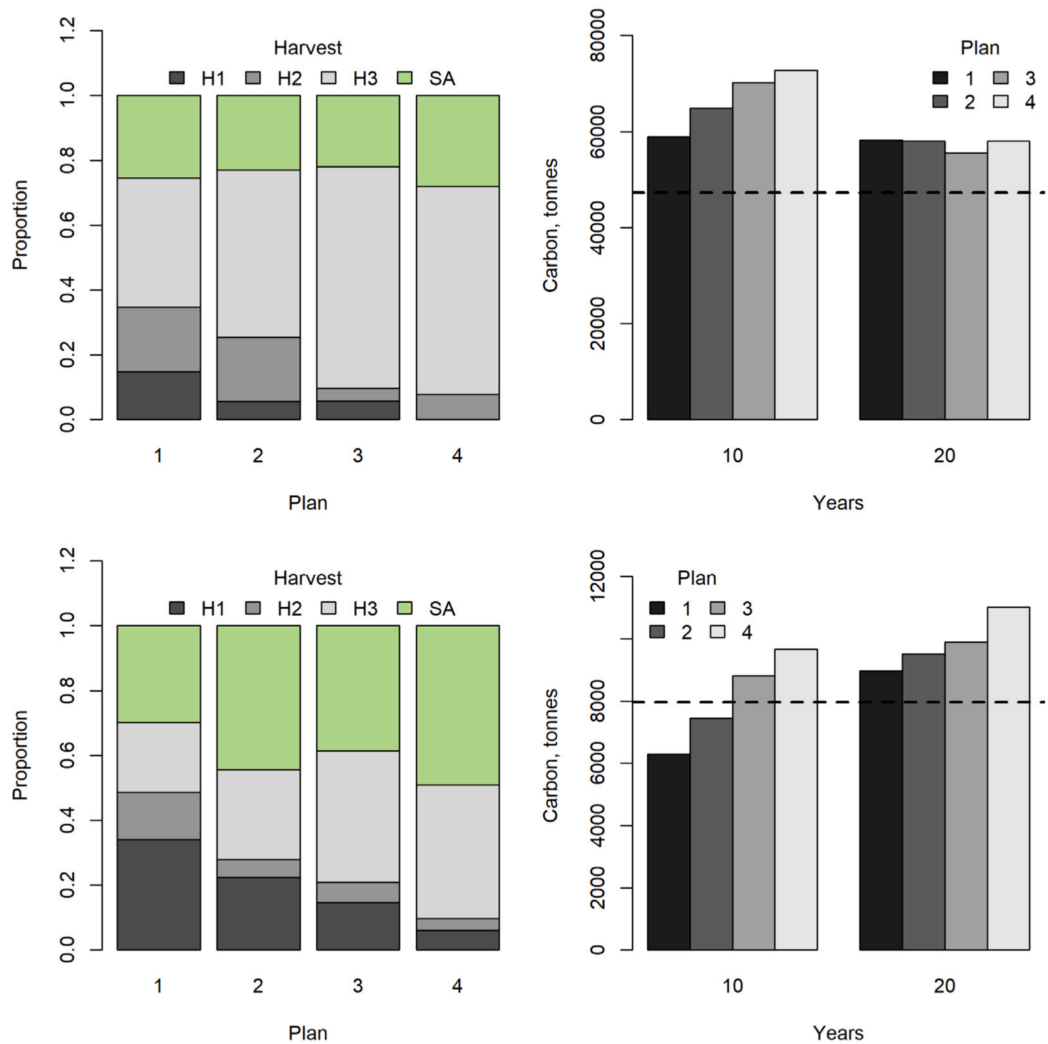

Fig. 4. Left column: temporal distribution of harvests between different plans (H1 = harvested in first 5 years, H2 = harvested in 5–10 years, H3 = harvested in 10–20 years, SA = set aside), where the proportion is expressed relative to the initial growing stock volume. Right column: the size of carbon storage after 10 and 20 years depending on the plan. A dashed horizontal line is shown to relate to the carbon storage in the beginning of the planning period. Top and bottom rows show forest owner groups 1 and 2, respectively. Plan 1 is the individual preferred plan and plans 2, 3, and 4 correspond to plans with the added carbon storage incentives.

Table 3
The effects of the different management plans on the NPV of the forest. The first column shows the NPV of the forest itself, the NPV-change column shows how the NPV changed compared to Plan 1, the Compensation column details the total amount of compensation to be paid, and the Effective NPV column shows the value of the forest with the compensations factored in.

	NPV	NPV-change	Compensation	Effective NPV
Forest owner group 1				
Plan 1	3, 461, 109€			3, 461, 109€
Plan 2	3, 405, 018€	−56, 091€		3, 405, 018€
Plan 3	3, 526, 799€	−5457€	62, 422€	3, 508, 200€
Plan 4	3, 559, 761€	−91, 617€	178, 472€	3, 516, 903€
Forest owner group 2				
Plan 1	820, 613€			820, 614€
Plan 2	729, 488€	−91, 125€		729, 488€
Plan 3	756, 780€	−63, 833€	24, 207€	777, 165€
Plan 4	707, 833€	−112, 780€	66, 415€	762, 408€

Nevertheless, follow-up studies on the information approach are warranted, because investing in it rather than in direct compensation may help avoid the risk of strategic decision-making, in which owners adjust their choices to maximize payments rather than genuinely aligning with climate-smart practices. Furthermore, despite a high general interest, details regarding the implementation of compensation mechanisms may reduce their acceptability (D'Alberto et al., 2024; Pormon et al., 2026).

Although the forest owners and holdings included in this study exhibited a variety of ownership profiles, they may not capture the full diversity of forest owners across Finland. Notably, almost all forest owners either resided on their holding or owned a holiday home there, which may have increased the role of scenic and amenity considerations in planning. This could have contributed to increased preferences for no-treatment or milder harvesting and, consequently, higher carbon storage. This interpretation is consistent with Thompson and Hansen (2012), who observed that absentee forest owners were less favorable toward managing forests for carbon sequestration and trading. Most holdings in our study were smaller than the average Finnish forest holding (Karppinen et al., 2020). Previous evidence on how holding size relates to participation in carbon-oriented programs is mixed (Tzemi et al., 2025; Håbesland et al., 2016; Khanal et al., 2017) . For example, Khanal et al. (2017) found that forest owners with larger holdings were more willing to delay harvesting, whereas Thompson and Hansen (2012) observed a negative association between acreage and attitudes toward carbon sequestration and trading.

Our observations of forest owners' preferences basically align with and may further contextualize the recent findings of Tzemi et al. (2025), who examined attitudes toward alternative forestry carbon offset schemes using an online survey and choice experiment. In their study of 1482 Finnish forest owners, the majority declined payments of 2€ to 30€ per cubic meter every ten years for carbon storage. However, participation increased when schemes were initiated by a familiar forestry professional (rather than by the landowner or public authority), when compensation was higher, and—less decisively—depending on whether the funding source was public or private, and whether the schemes accounted for potential forest damage. While Tzemi et al. draw from a broad sample across a wider population, their approach focused on hypothetical scenarios and generalized schemes. In contrast, our study engaged directly with forest owners using real data from their holdings. This interactive and focused approach allowed us to observe how forest owners grounded their decisions in actual circumstances. The information, group reflection, and carbon incentives tangibly influencing their preferences over different objective function values. Thus, although more resource-intensive, our methodology may offer deeper insight into forest owners' decisions. The findings from information and group reflection, not studied by Tzemi et al., should at least be validated with larger and more diverse forest owner groups.

Additionally, the reasoning behind the choices of the forest owners in our experiment indicates that many preferences, such as landscape, accessibility, and variability, are simply not captured by forest planning software. These preferences were considered more important than what was reflected in the model. Some of these preferences are synergetic with increasing carbon storage. These observations can formally be explained by the idea that neoclassical rational decision making, which maximizes utility, is not the same as the actual behavior of a decision maker, as emphasized by behavioral economics. Rather, decision making is driven by other things such as social preferences, community and knowledge.

The forest owners took time to explore options, learn, and analyze before choosing to change their initial plans. This indicates that behavioral interventions targeting the analytical and slow deliberative cognition, which takes time to understand Thaler and Sunstein (2008), and interventions that empower decision makers by expanding their competencies to help them reach their objectives (Hertwig and Grüne-Yanoff, 2017) could support climate-smart forestry. Additionally, continuous cover forestry was considered an interesting option by the forest owners in this study, and is also growing in popularity among forest owners (Juutinen et al., 2020). Therefore, it could support climate-smartness, as it has a lower impact on the recreational value of forests (Peura et al., 2018), a point that some forest owners in this study also highlighted.

If generalizable, our results suggest that policy guidance to help steer individual choices, combined with planning tools that enable the forest owners to see the impacts of their management decisions, could be implemented cost-effectively by leveraging behavioral influences, such as peer-learning. Various nudging mechanisms that steer the decision maker toward a desired outcome through soft methods without restricting their choices (Thaler and Sunstein, 2008) have gained attention in the last decades, including the context of supporting climate-smart forestry practices (e.g. Maidell et al., 2024; Valatin et al., 2016). These mechanisms should also be studied alongside research that emphasizes monetary incentives.

Despite the threshold of using a computer-assisted tool, the forest owners benefited from the ability to study trade-offs among objective functions. The interactive method and graphical user interface provided insight and allowed them to search for preferred solutions by updating their preferences. Some of the forest owners lacked the knowledge necessary to increase carbon storage in their forests, although they may have been interested in doing so. Knowledge on carbon sequestration may increase willingness to adopt extended rotations (Khanal et al., 2017). Laakkonen et al. (2018) similarly noted that many forest owners were unsure and depended on professional guidance regarding climate-related issues. Incorporating the aforementioned nudging mechanisms into computer-assisted tools could facilitate group decision making and encourage forest owners to take more climate-oriented actions. This is a future research direction to explore.

5. Practical recommendations

Although our analyses rely on limited data and a small number of forest owners, the observed patterns on the responses to information, peer discussion, and compensation are informative and warrant further testing in larger samples and diverse ownership contexts. We can summarize practical recommendations as follows.

1. *Promote research and piloting towards information-based nudging*:
   In our pilot, information guidance and peer discussions increased carbon storage outcomes more effectively than monetary incentives. Further, group workshops enabled climate-positive shifts. These results indicate that educational and peer-based mechanisms deserve further investigation alongside the conventional financial instruments.
2. *Understand forest owners' behavioral motivations*:
   Forest owners often base their decisions on personal values, aesthetics, recreation, and intergenerational stewardship, rather than solely on economic or other measurable values. Strategic planning and policy should account for these behavioral drivers by incorporating behavioral science insights and diverse ownership contexts into utilitarian maximum sustained yield types of analyses.
3. *Distinguish between short-term and long-term effects in carbon compensation*:
   Most forest owners participating in our experiments increased carbon storage in the short term (e.g., by delaying harvests for 10 years), but were hesitant to commit to long-term set-asides due to the assumed risks associated with forest aging. Given that many climate targets are near-term, compensation schemes should recognize the value of short-term carbon gains and remain flexible, transparent, and adaptive to forest owners' concerns.

4. *Deploy interactive decision support tools*:
   Tools based on multiobjective optimization methods, such as the NIMBUS-based tool utilized in this study, with user-friendly interfaces, helped forest owners understand trade-offs and adjust their preferences effectively. Such tools should be adopted in practice to enhance the knowledge of forest owners, provide a decision-making platform, boost their confidence, and broaden and accelerate personalized forest management toward climate-smart and more sustainable goals.

CRediT authorship contribution statement

Veera Tahvanainen: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Juho Roponen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bhupinder Singh Saini:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Juuso Pajasmaa:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Babooshka Shavazipour:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Francisco Ruiz:** Writing – review & editing, Writing – original draft, Conceptualization. **Mikko T. Niemi:** Writing – review & editing, Data curation, Conceptualization. **Tuomo Takala:** Writing – review & editing, Conceptualization. **Jari Vauhkonen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation, Funding acquisition, Conceptualization. **Kaisa Miettinen:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

We have no conflicts of interest to disclose.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.forpol.2026.103764.

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