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The effect of spatial and temporal planning scale on the trade-off between the financial value and carbon storage in production forests

Tristan R.M. Bakx [a,*], Renats Trubins [b], Jeannette Eggers [c], Cecilia Akselsson [a,d]

[a] Department of Physical Geography and Ecosystem Science, Lund University, SE-223 62 Lund, Sweden
[b] Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, SE-230 53 Alnarp, Sweden
[c] Department of Forest Resource Management, Swedish University of Agricultural Sciences, SE-901 83 Umeå, Sweden
[d] Centre for Environmental and Climate Science, Lund University, S-223 62 Lund, Sweden

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ABSTRACT

Background: Increasing carbon stock in standing forests is one of the proposed ways to mitigate climate change. However, in production forests, this typically would lead to reduced harvesting possibilities and thus reduced financial gain for the forest owners. The size of this reduction should depend on the chosen target level of the carbon stock as well as the required speed of accumulation. Furthermore, due to landscape heterogeneity, the size of the loss can be expected to vary the planning scale, often related to forest property size.
Aim: This study aimed to quantify the effects of spatial and temporal planning scales on the severity of the trade-off between Net Present Value (NPV) of future timber sales and carbon storage in production forests in Southern Sweden.
Methods: We used the Heureka PlanWise forest decision support system with built-in Linear Programming functionality. We created six Production Possibility Frontiers (PPF) that quantified the trade-off for the combinations of two scenarios for timing of carbon accumulation (either by 2100 or by 2100 with an intermediate target by 2045) and three spatial management scales (~3300 ha, ~300 ha, and ~60 ha; 1068 stands).
Results: There was a strong effect of temporal scale, with consistently lower NPV, with the same carbon stock in 2100, when the intermediate target for 2045 was applied. The effect of the spatial scale was only apparent between the smallest (50 ha) scale and the larger scales (300 and 3300 ha), with consistently lower NPV with the same carbon stock at the smallest scale.
Conclusion: We conclude that both the effects of spatial management scale and temporal scale on the cost of carbon storage should be considered in relation to potential climate policies.

1. Introduction

The climate crisis has led to increasing pressure on society to utilize forests to mitigate climate change because of their great capacity to capture and store atmospheric carbon (Canadell and Raupach, 2008). Climate change mitigation can take place through storage in standing forests and forest soils, as well as through substitution of products such as construction materials or fuels by wood-based products (e.g. Lundmark et al., 2014). It is expected that the role of forests in mitigating climate change will increase in the future (Lewis et al., 2019).

There are several ways to increase carbon storage in standing forests and their soils, such as expansion of forest area, restoration of degraded forests, and increased storage of carbon in existing forests (Canadell and Raupach, 2008, Lewis et al., 2019). In Sweden, which is the focus of our study, rotational forestry is the dominant silvicultural system. This is a cyclic system where mostly even-aged forest stands are planted, tended to, and harvested. The system is a way to achieve an even-flow of timber products, which was an important objective for Sweden since until the early 20th century forest was harvested without any widespread regeneration (Lindbladh et al., 2014). The size of a stand is typically about three to five hectares in southern and about 10 ha in northern Sweden. Carbon storage in forests under even-aged management can be increased by, amongst other options, prolonging rotation periods. Prolonging rotation periods beyond the economic optimum will imply a certain financial cost for the forest owner. Furthermore, an additional cost can emerge as a result of the perturbation of the forest age class

* Corresponding author.
E-mail address: Tristan.bakx@nateko.lu.se (T.R.M. Bakx).

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structure of the property if the forest owner decides to seek a renewal of an even age class distribution based on the new extended rotations.

Most production forests have not reached carbon saturation, which means that they have the potential to sequester more carbon. Depending on the initial conditions and management, the carbon stock of such forests can be increased at slower or faster rates. Two common timescales for climate change research are 2100, which is commonly used in scenario predictions, and 2045, which is the current target of the Swedish government for GHG emission neutrality (Swedish Government, 2016). Two studies have demonstrated that the forests in Sweden can make an important contribution to reaching the emission neutrality target. First, Lundmark et al. (2014) showed how a combination of substitution by forest products and intensification of forestry practices could help with achieving the end-of-century target. Then, Cintas et al. (2017) showed that carbon neutrality by 2050 (the previous target year of the Swedish government) could only be reached by increasing the carbon stock in the forests. If carbon stock increase in the forests should be used to reach the emission neutrality targets set by the Swedish government by means of reduced harvests, it is important to estimate the potential economic losses for the forest owners. This temporal aspect of the carbon storage-financial value trade-off has not yet been broadly studied.

In southern Sweden, forest landscapes are split into many properties with heterogeneously distributed growing conditions. The total variation in growing conditions of stands increases with the extent of the area on which management is planned. That could allow the larger management units to reach the carbon stock targets at a lower financial cost (with fewer and smaller deviations from optimal stand treatment programs). This means that the production possibilities for simultaneous provision of carbon storage and financial value over the whole landscape are potentially lower when the landscape is managed in small properties than when the landscape is managed in large properties or when the landscape is managed as a single unit. It has been shown that the production possibilities for simultaneous provision of carbon storage and financial value in Finnish production forests increase until the scale of several hundred hectares (Pohjanmies et al., 2017). It is important to quantify this relationship between the spatial management scale and the production possibilities in other contexts as well.

This study aimed to quantify the trade-offs between carbon sequestration in forests and the financial value of wood production for different combinations of temporal carbon storage targets and spatial management scales. Specifically, we aimed to determine how the levels of Net Present Value (NPV) and carbon stock that can be simultaneously achieved in production forests depend on the timing of carbon storage targets and the spatial scale at which management is optimized. Additionally, we aimed to investigate how the optimizations at different spatial and temporal scales would affect the mix of selected management programs.

2. Methods

We created Production Possibility Frontiers (PPFs), for the combinations of two different timings of carbon accumulation and three spatial scales (six combinations in total). PPFs, or Pareto frontiers, show how much of two services, in this case, carbon stock and NPV, can be produced simultaneously under set circumstances. We created the six PPFs by optimizing forest management in a forest landscape in southern Sweden from 2010 until 2110 for simultaneous production of NPV and carbon stock at the six spatio-temporal scale combinations. Furthermore, we visualized and quantified the management allocation in the six PPFs to evaluate how the management allocation related to different spatio-temporal management scales.

2.1. Study area

We studied the production forest in a 46 km^2 watershed (SMHI 2017, SVAR2016, Watershed ID 1889) with a high proportion of production forest (71%, 33 km^2), in the southern Swedish municipality of Hässleholm (1306 km^2, 56° 10′ 0″ N, 13° 46′ 0″ E, Fig. 1A), The study area has a hemiboreal climate (Köppen class Dfb, Peel et al., 2007), which is a humid continental climate with warm summers, although there are considerable marine influences on the climate making winters softer than usual in continental climates at this latitude. The soils in the study area are mainly till soils, but fluvioglacial sediment soils and peat soils are also present.

2.2. Input data

The input data were produced from a raster map of forests in Sweden (25×25 m^2) based on satellite and observational data from the national forest inventory (NFI) (SLU, 2005). This map was segmented into stands and the needed complementary attributes were added by matching stands to NFI plots from the region. The input data consisted of the description of environmental conditions like the location, elevation, slope, climate, site index, soil type, soil moisture, and vegetation characteristics like tree species composition, age, height, and understorey vegetation type (see https://www.heurekaslu.se/wiki/Import_of_stand_register for a detailed description of all input data variables). The result of this process was a map of the forest in Hässleholm with a rather low accuracy at the stand scale, but representing what forests in this part of Sweden can look like. For more information about the input data see Eggers et al. (2015).

2.3. Initial state

There was a total of 1068 stands (0.2–31.1 ha, mean size = 3.1 ha) in the forest map. At the start of the planning period, in 2010, the forests in the study area were on average 42 years old (range between 0 and 134 years, Fig. 2). The species proportions in standing volume were: 50.1% Norway Spruce (*Picea abies*), 14.5% Scots Pine (*Pinus sylvestris*), 10.5% Birch (*Betula pendula*), 7.8% Beech (*Fagus sylvatica*), 7.0% Oak (*Quercus robur*), the remaining 10.1% other broadleaved species and mixed broadleaved stands. The site index (SI, local productivity defined as the height of dominant trees in a stand at the age of 100 years) was generally high (range: 18–37, mean SI weighted by area = 31.3).

2.4. Generation of production possibility frontiers

2.4.1. Overview

We used the PlanWise tool of the Heureka forest decision support system (Wikström et al., 2011) to simulate forest growth and to optimize management to create the PPFs. Heureka PlanWise simulates future forest conditions based on the initial state of forest stands, the proposed management actions, and a set of sub-models that represent ecosystem processes and the consequences of management. First, forest growth, the economic value of wood production as well as biomass and soil carbon stocks were simulated for a wide variety of treatment programs. Then, a set of optimization problems was solved using Linear Programming in Heureka PlanWise in combination with Gurobi Optimizer 8.1 (Gurobi Optimization, 2016) with two timings for carbon accumulation goals (carbon stock targets either only in 2100 or both in 2045 & 2100) and at three spatial scales (small owners ~60 ha, large owners ~300 ha, and watershed ~3300 ha). These optimizations resulted in the six production possibility frontiers.

2.4.2. Simulation of stand treatment programs

We simulated a wide array of treatment programs for each stand (up to 61 treatment programs) that encompassed several rotation lengths combined with different thinning regimes and a set-aside alternative (Table 1). We simulated rotation times of between 100% and 200% of the minimum allowed rotation time at 20% intervals (Table 1). For each stand and treatment program, we simulated the development of the

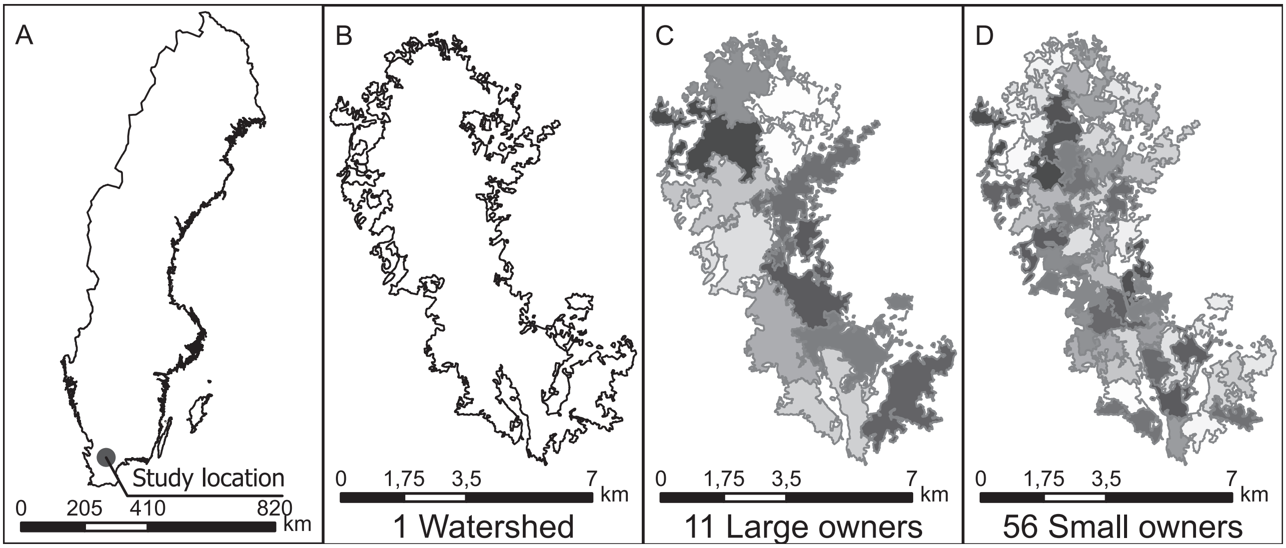

Fig. 1. The location of the study area in Sweden (A) and the three spatial scales at which we optimized management (B-D).

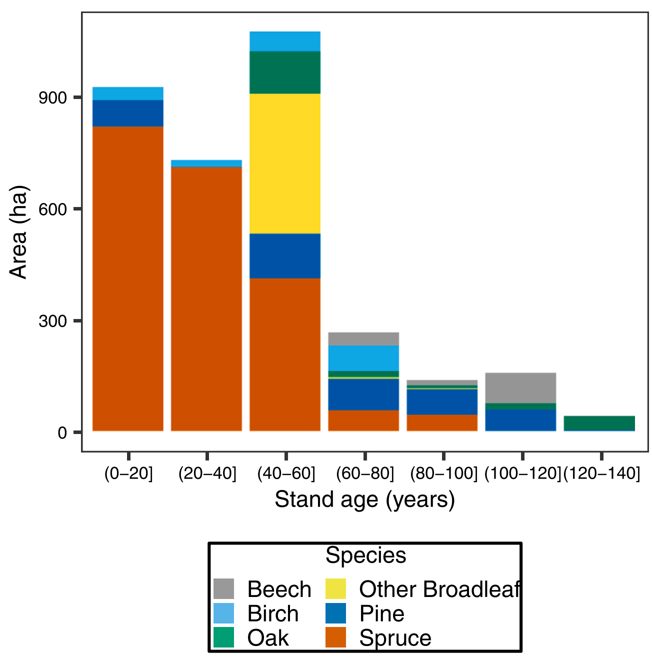

Fig. 2. Area covered by each age class at the start of the planning period separated by dominant tree species. "Other broadleaf" is broadleaved forest that does not include Beech, Oak, or Birch.

forest for 100 years in five-year periods (from 2010 until 2110).

The NPV was calculated as the difference between the sum of the discounted revenues and the costs of management for an approximately infinite time horizon. We used the default wood and pulp prices and the default costs of management with the Skogforsk harvest cost calculation model in Heureka 2.16. We converted all financial results from Swedish Kronor (SEK) to Euros (€) with an exchange rate of 9.42 SEK = 1 € (the twenty-year average exchange rate on June 10th, 2020, European Central Bank (ECB) (2021). The carbon stock included both the above and below ground carbon as well as carbon in deadwood. The above-ground carbon is calculated as 0.5 kg C per kg dry weight biomass and the biomass was calculated according to Marklund (1988) for older forests and Claesson and Kenneth Sahlén (2001) for young forests. Soil carbon was simulated based on the biomass of stumps, roots, and litter and their decomposition according to Petersson and Ståhl (2006). The amount of carbon in deadwood depended on the amount of deadwood, the tree mortality, and the decomposition, which was modeled to be exponential and species-specific for pine and spruce (Harmon et al., 2000). The percentage of C per kg deadwood was related to the state of decomposition as in Sandström et al. (2007).

Table 1
Overview of the variables and settings in the treatment schedule simulation.

Variable	Abbreviation	Description	Setting
Minimum rotation time	minRT	The minimum age at which a stand could be felled. We multiplied the minimum rotation time by a percentage to create a diverse variety of rotation times.	For spruce and pine, minRT depends on the site index. For other species, minRT is a fixed length in the law (Swedish Forest Agency, 2020). Levels: 100%, 120%, 140%, 160%, 180%, 200%
Final felling delay	-	The number of five-year periods by which final felling could be delayed compared to minRT.	0 or 1 periods
Number of thinnings	thin.	The number of thinnings applied during a single rotation.	0, 1, 2, or 3 thinnings
Thinning delay	-	The number of five-year periods by which thinning could be delayed compared to the thinning guide.	0, 1, or 2 periods
Climate	-	The climate change scenario that was applied to the forest growth simulations.	ECHAM5 A1B (business as usual emissions, climate change)
Fertilization		If forest stands were fertilized to promote growth.	No
Regeneration	-	How forest stands were regenerated after final felling.	The same species was planted as in the previous generation. No tree breeding effects.

2.4.3. Temporal scales

We set minimum carbon stock as a constraint in the optimization ($C_{constraint}$) for two points in time to represent different policy scenarios (Table 2). In the first scenario, forest carbon stock must reach a specified target level by 2100 while causing as small NPV reduction as possible. In the other scenario carbon stocks should grow fast and reach a specified target level already by 2045, and then continue growing further to the same 2100 target as in the first scenario, also while minimizing the NPV loss.

2.4.4. Spatial scales

The three spatial scales for the optimization of treatment program allocation (Fig. 1B-D, Table 3) were the following: The first spatial scale was the whole watershed together. In the second spatial scale, we created 11 groups of stands representing the scale at which large owners operate. In the third spatial scale, we created 56 groups of stands, representing the scale at which small owners operate. Henceforth, the three spatial scales will be called watershed, large owners, and small owners. The property boundaries were fictional and were created to allow us to study the effect of planning scale on the trade-off, and not to simulate real-world forest ownership. We also ignored real-world protected forests in this area to further simplify the experimental design so that our results could be attributed to the spatial and temporal scale of planning optimization as much as possible.

2.4.5. Optimization of treatment program allocation

We used Linear Programming to optimize the management under different combinations of objectives and constraints concerning forest carbon stock and NPV levels. The discount rate in all the NPV calculations was 3%. The first step was to identify the maximum and minimum levels of carbon stock that could be achieved. The carbon stock levels in 2045 and 2100 ($MinC_{2045}$ and $MinC_{2100}$) obtained in an optimization for maximum NPV ($NPV_{objective}$), with no other constraints than the non-decline of the carbon stock after the specified years, were considered as the minimum levels in the calculation of the intermediate constraint levels of the Pareto frontier optimizations (Fig. 3). The next step was to determine the maximum carbon stock ($MaxC_{2100}$) in 2100 by optimizing for maximum carbon in that year with the non-decline constraint afterwards ($Carbon_{objective\ 2100}$). To identify the final input for the intermediate constraint level calculation, the maximum carbon stock in 2045 ($MaxC_{2045}$), we optimized for maximum carbon stock in 2045 ($Carbon_{objective\ 2045}$) with the constraint that the carbon stock reached $MaxC_{2100}$ level in 2100 and the non-decline constraints after both years.

Then, we optimized for nine intermediate levels of carbon stock for each of the six combinations of spatial and temporal scale, to quantify the Pareto frontiers. To do this, we optimized management for maximum NPV ($NPV_{objective}$) with constraints for carbon stock. We calculated the carbon constraints as follows:

$$C_{constraint} = MinC + (MaxC - MinC) \bullet p$$

with $C_{constraint}$ as the carbon stock level that has to be reached in the target year (2045 or 2100) and p as the level of the objective. The nine intermediate levels were from 10% to 90% at 10% intervals between the MinC (0%) and MaxC (100%) levels. In all cases, the $C_{constraint}$ was so that after the target year (2045 or 2100), the carbon stock was not allowed to fall below the $C_{constraint}$ of that respective year for the rest of the planning period. The resulting carbon stocks were slightly different between the six PPFs, so to make between scale comparisons completely fair we normalized the NPVs between scales at each level of carbon stock (method and results of normalization in Appendix A).

Table 2
Description of the temporal scales in the management optimization.

Temporal scale	Rule
2100	C is set to reach $C_{constraint,2100}$ by 2100, and not to drop below $C_{constraint,2100}$ after 2100.
2045 & 2100	C is set to reach $C_{constraint,2045}$ and $C_{constraint,2100}$ by 2045 and 2100, respectively, and not to drop below $C_{constraint,2045}$ and $C_{constraint,2100}$ after 2045 and 2100, respectively.

Table 3
Description of the three spatial scales at which management was optimized.

Spatial scale	Number of groups	Number of stands per group (mean ± sd)	Area per group (ha, mean ± sd)
Watershed	1	1068	3333
Large owners	11	98 ± 10	303 ± 17
Small owners	56	19 ± 4	60 ± 8

3. Results

3.1. The carbon storage-NPV trade-off

The general trend was a reduction of NPV from larger to smaller spatial scale and from the single 2100 C target to the double 2045 & 2100 C target. At all scales, the cost of storing more carbon was relatively low at low carbon stock levels (Fig. 4, Table A.1) - at least 50% of the difference between the minimum and the maximum C-stock could be realized for a cost of on average 10% of the maximum NPV. In contrast, the cost was high at higher carbon stock levels shown by the high cost of the 10% increase from 90% to 100% of the maximum carbon (31% of the maximum NPV).

3.2. The effect of temporal and spatial scale on the trade-off

The effect of temporal scale on the trade-off was larger than the effect of spatial scales, and short-term carbon goals were always costlier than long-term goals (Fig. 4, Table A.1).

The potential for carbon storage was lower for the same NPV for the small owners than for the large owners and watershed spatial scale (Fig. 4, Table A.1). The potential for carbon storage was very similar at all NPV levels for the watershed and large owners scales indicating that there are virtually no more efficiency gains to be reaped beyond the large owner scale.

3.3. Development of the carbon stock over time

The development of the carbon stocks differed considerably between temporal scales (Fig. 5). With the added carbon target in 2045, carbon stocks increased fast up to 2045 and fewer stands were harvested in the periods before that than without the 2045 target. In 2045, the carbon stock was 17–18% higher when the 2045 target was included, compared to the 2100 target only. After the 2045 target, carbon stocks levelled off at the 2045 level and increased again towards the 2100 target. The higher the carbon target level, the earlier the carbon stocks rose again after the 2045 target, and at smaller spatial scales, the carbon stocks rose earlier than at large scales. With only the 2100 carbon target, carbon stock did not increase as much towards 2045 (Fig. 5). For the 80% and 90% carbon targets, the increase in carbon stock was more or less constant throughout the entire study period and for the lower carbon targets, there was actually a dip in carbon stock around 2055 (Fig. 5). This dip diminished with decreasing spatial scale. Otherwise, the pattern with two distinct phases of rising carbon stocks and an intermediate phase with a dip in carbon stock was similar to the 2045&2100 temporal scale.

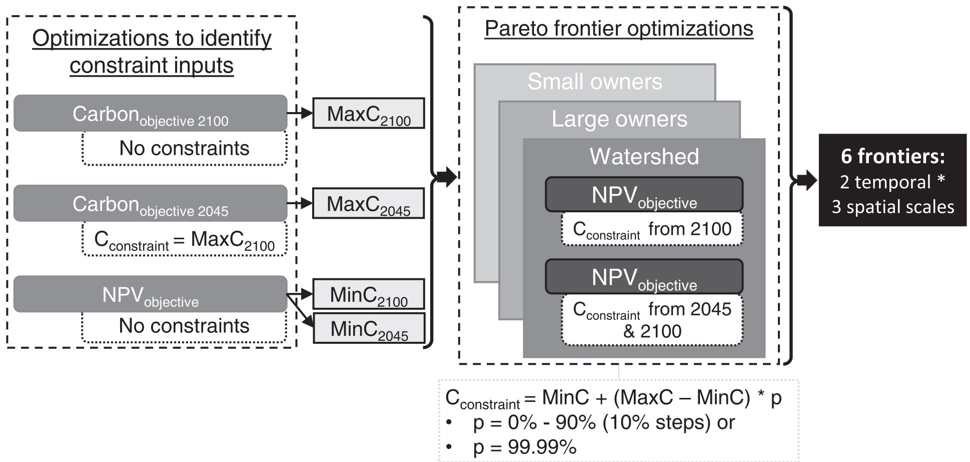

Fig. 3. Flowchart of the optimization procedure with both the optimizations for the identification of the constraint inputs and the actual optimizations for the Pareto frontiers.

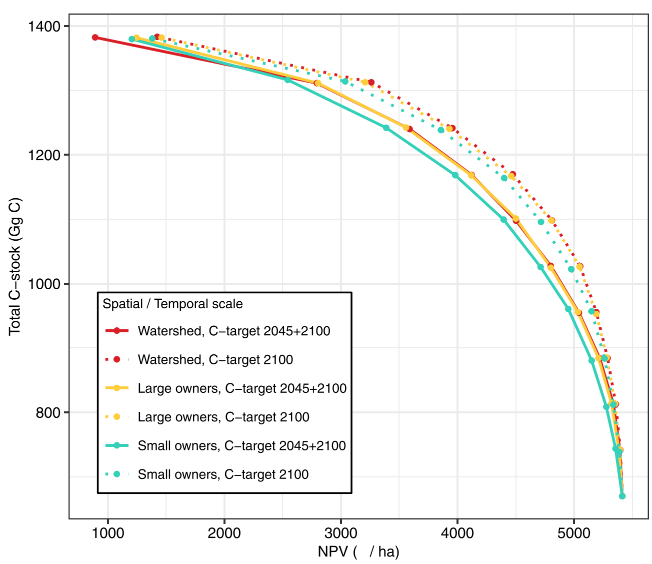

Fig. 4. The Pareto frontiers for each of the combinations of the three spatial and two temporal scales. The figure represents the potential production of C-stock in the year 2100 and NPV, the target year of the optimizations.

3.4. Treatment schedule allocation

The difference in the impact of the scales on the shape of the PPFs can be explained by the differences in the treatment program allocation (Table 4). Between the temporal scales, the differences in treatment programs were clear. Average rotation times were longer in the 2045&2100 scale than in the 2100 scale, more area was set aside in the 2045&2100 scale compared to the 2100 scale, and more thinnings took place in the 2100 scale than in the 2045&2100 scale.

Between the spatial scales, the differences in treatment schedule allocation were small and did not obviously point in any single direction. In both time scales, the average rotation time increased with increasing spatial scale. At both timescales, more stands were set aside at the small owners scale than at the two larger scales. The average number of thinnings per rotation decreased with increasing spatial scale in both time scales.

4. Discussion

We found that earlier timing of carbon storage targets strongly reduced the simultaneous production possibilities of NPV and carbon stock compared to only long-term carbon storage targets. The considerable cost of the additional requirement for carbon storage in 2045 was caused by the limitations the target posed on forest management. Longer rotation lengths, fewer thinnings, and larger set-aside area decreased the NPV of wood production at the chosen interest rate.

The management of the forest for carbon storage and NPV was more efficient at the two larger scales than at the smallest spatial scale. This means that a proportional increase in carbon storage in standing forests would affect the finances of owners with small properties more severely than those of owners with larger properties. On the other hand, savings can be made if forests are managed at larger spatial scales. This result is consistent with Pohjanmies et al. (2017) who also showed a difference between a similar smallest scale and the two bigger scales. This indicates that the effect of spatial management scale on the studied trade-off is typical for the forest conditions in the Nordic countries. This effect of spatial scale is caused by lower spatial heterogeneity and number of stands within the smallest scale management units compared to larger management units as also demonstrated in, for example, Hou et al. (2017) and stressed by De Groot et al. (2012). Accordingly, at the smallest scale, more often than at the larger scales, stands had to be set-aside, because set-aside resulted in the largest increase in carbon stock but also the largest decrease in NPV while other alternatives would not meet the C-stock target.

We limited our study to some of the currently most common management practices in southern Sweden. It is possible to further enhance climate change mitigation by, for example, harvesting logging residues (de Jong et al., 2017) or fertilizing stands with low nutrient levels (Normark and Fries, 2019). However, these practices likely lead to negative consequences to other ecosystem services (Akselsson et al., 2021; de Jong et al., 2017; de Jong, Dahlberg, 2017; Ranius et al., 2018; Zanchi et al., 2014), which would need to be regarded in trade-off analyses where these practices are included. The addition of less common management alternatives, such as continuous cover forestry, to the conventional methods might also enhance the forest's climate change mitigation potential with possibly less negative consequences to other ecosystem services (Eyvindson et al., 2021; Peura et al., 2018).

Our measure of the forest's financial value, NPV of timber harvests, depends completely on the traditional wood-based forest economy and does not include, for example, hunting and non-wood product values or appreciation of forest land. With this in mind, the estimated NPV losses still give an indication of the amount of financial incentive necessary to promote carbon accumulation in forests. Other assessments of this aspect, in which the financial incentive was introduced in the form of carbon price and which, like our study, disregard non-timber value

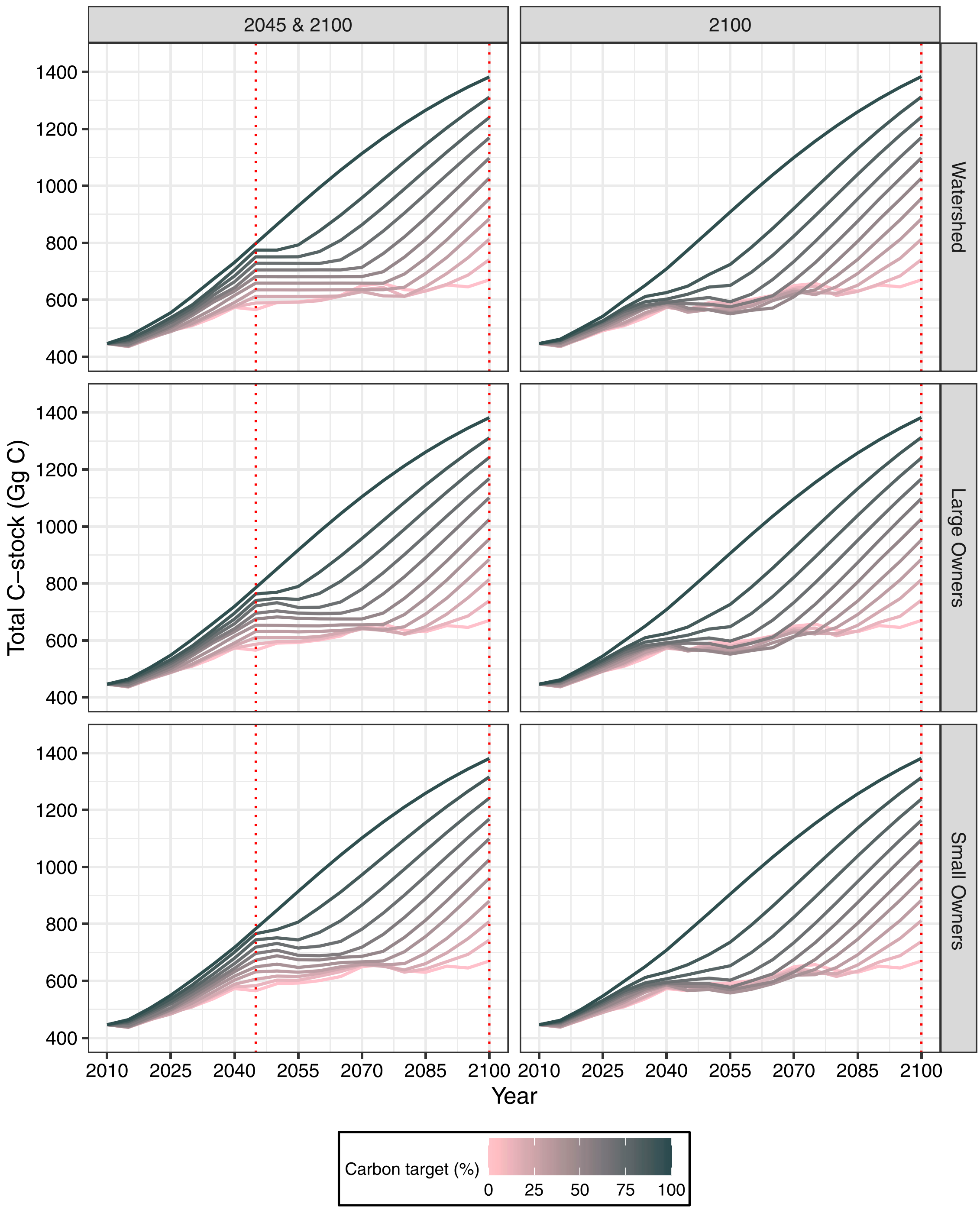

Fig. 5. Development of the carbon stock over time for the three spatial and two temporal scales and under the eleven levels of carbon stock constraint (0–100% of the maximal achievable carbon stock). The constraint forced the carbon stock to reach a minimum level in the respective year (either 2045 & 2100 or only 2100) and not to drop below that level after the target year. The red dotted lines show the year where a constraint level for the C-stock was present in the optimizations.

sources, are, for example, Boyland (2006), Huang and Gary (2006), Pohjola and Valsta (2007) and Pukkala (2020).

A steep increase in forest carbon stock comes at the costs of drastically reduced harvests during the accumulation period, regardless of when it happens. This would have severe impacts on the forest industry, and thus on the potential for substitution of emission intensive products and fossil fuels, which is thought to be needed besides storage in forests (Cintas et al., 2017; Lundmark et al., 2014), as well as secondary societal impacts such as loss of employment in rural areas. In real-world settings, however, the carbon increase trajectories towards target levels would be different than in our optimizations due to the balancing effects of markets (price adjustments) and other reasons such as different preferences and practical considerations of forest owners. On the other hand, increased carbon storage in forests may lead to increased habitat for forest species and recreation potential through increases in beneficial forest structures and spatio-temporal patterns in forests for biodiversity (Felton et al., 2016, 2017).

The current paper only studies two aspects of forestry (i.e. carbon storage and wood production) in a limited manner. Other aspects of forest ecosystems, such as surface water quality, bioenergy production, and biodiversity conservation, have also been shown to depend on spatial scale (e.g. Cintas et al., 2016; Cowie et al., 2021; Oni et al., 2015;

Table 4
Treatment schedule allocation at the 50% carbon target with for the spatial (WS = watershed, LO = large owners, (SO = small owners) and temporal scales.

Scale	Rotation length (yrs) – area weighted mean ±sd	Thinnings per rotation – area weighted mean ±sd	Set-aside (% of study area)
2045 + 2100 – SO	85.5 ± 21.2	0.51 ± 0.92	12.4
2045 + 2100 – LO	86.3 ± 20.1	0.40 ± 0.77	9.6
2045 + 2100 – WS	86.7 ± 19.6	0.42 ± 0.81	8.9
2100 – SO	81.2 ± 18.0	0.97 ± 1.14	7.8
2100 – LO	82.2 ± 17.5	1.02 ± 1.17	5.2
2100 – WS	82.6 ± 17.5	1.06 ± 1.18	5.3

Pohjanmies et al., 2019). Furthermore, trade-offs and synergies exist between carbon storage and other ecosystem services as well (Biber et al., 2015), and therefore, the timing of carbon accumulation can be expected to affect those interactions as well.

4.1. Land-use policy implications

Carbon storage in forests is important for achieving the goal of net zero emissions by 2045 in Sweden. The results of this study highlight the need for policy instruments that give the forest owners economic incentives to manage their forests for near-time stock increases as these, in most cases, would demand a reduction of the forest owners' usual harvest level. At the same time, the incentives should maintain the forest owner's interest in managing the forest (especially, regeneration and tending operations) to keep the growth, and thus the carbon sequestration rates high, avoiding the abandonment of management that would lead to slower growing forest and, consequently, lower carbon sequestration rates. The gains in carbon storage that can be made by increasing the planning scale are small according to this study, but point in the same direction as previous findings (Pohjanmies et al., 2017). However, since larger planning scale may benefit also other regulative ecosystem services besides carbon storage (Hoen and Tron Eid, 2006), policy instruments that promote planning across property boundaries by, for example, stimulating collaboration between neighbouring forest owners, could contribute to not only climate targets but also other environmental targets (Angelstam et al., 2011; Bostedt et al., 2021; Michanek et al., 2018).

5. Conclusion

We conclude that economic implications of the timing of carbon accumulation goals in forests are substantial and therefore, should be considered in climate change mitigation policies. Our results indicate that the positive effect on NPV – carbon accumulation trade-off is likely to increase with temporally nearer carbon accumulation targets while not excluding the possibility of substantial positive effects on the provision of other ecosystem services not covered in this study. Therefore, the issue of spatial planning scale should be investigated further despite the modest benefits found in our study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2023.106583.

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