Effects of different management options of Norway spruce on radiative forcing through changes in carbon stocks and albedo

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Norway spruce (Picea abies Karst. (L.)) in the boreal zone can be managed as even-aged or uneven-aged stands, or be grown with no management at all. Here, we investigated how these management options affect carbon dynamics, particularly the carbon stocks in the forest ecosystem (trees and soil), and albedo, and their combined effect on radiative forcing compared to a reference case, clear-cut site before planting seedlings. This allowed us to assess the potential of different management regimes to mitigate global warming. We ran long-term simulations under the current climate on a sub-mesic site in central Finland (62°N) using an eco-physiological forest-ecosystem model. Compared to even-aged management, no management (old-growth forest) increased ecosystem carbon stocks by 47 per cent and decreased albedo by 15 per cent, whereas uneven-aged management reduced ecosystem carbon stocks by 16 per cent and increased albedo by 10 per cent. Only the no management option resulted in a significant net cooling effect whereas for even-aged and uneven-aged management, the opposing effects of changes in albedo and carbon stocks largely cancelled each other with little remaining net effect. On the other hand, the latter one even made a small net warming contribution. Overall, maintaining higher ecosystem carbon stocks implied the larger cooling benefits. This was evident even though lower albedo enhanced radiation absorption, and thus warming. Increasing use of the no management option by forest owners may require proper incentives such as compensation for lost harvest incomes.

Introduction

Boreal forests can contribute substantially to climate-change mitigation by sequestering carbon from the atmosphere and storing it in forest ecosystems and wood-based products (Kellomäki, 2017). Management intensity affects carbon sequestration and carbon stocks in forests through changes to forest structure and function (García-Gonzalo et al., 2007a, b; Kellomäki et al., 2019). Even-aged plantations sequester carbon as stands grow but lose carbon in harvested timber. Old-growth forests can store large amounts of carbon over centuries. In old-growth forests, carbon dynamics is affected by age structure, the mortality of mature trees and natural regeneration and ingrowth of seedlings in canopy gaps (Luyssaert et al., 2008). The net carbon exchange determines the amount of carbon storage in forest over a specified period. The biological carbon sink (i.e. annual growth of trees) is larger in managed than in unmanaged (intact) forests, but the net sink (net biome productivity) is lower due to harvesting (Kellomäki, 2017; Moomaw et al., 2020).

Forest structure affects the reflective properties of the forest and, thus, surface albedo (Betts, 2000; Rautiainen et al., 2011). An increase in the carbon stocks of a forest reduces the atmospheric CO₂ concentration and its associated radiative forcing and, consequently, has a cooling effect (Kirschbaum et al., 2011, 2013; Bright et al., 2015; Thom et al., 2017). At the same time, as forests grow, their albedo is reduced (Rautiainen et al., 2011; Lukeš et al., 2013; Otto et al., 2014). This increases radiative forcing, thus enhancing global warming (Bonan 2008, Kirschbaum et al., 2011, 2013; Thom et al., 2017). The net effect on radiative forcing of changes in the albedo and carbon storage of a forest depends on the relative magnitude of these two opposing processes (Kirschbaum et al., 2011, 2013).

The influence of albedo and carbon storage on radiative forcing are of similar magnitude in young forests, but in older forests, the impact of carbon storage dominates (Schwaiger and Bird, 2010; Kirschbaum et al., 2011, 2013; Thom et al., 2017). For example, in a radiata pine (Pinus radiata) forest in New Zealand, changes in albedo negated the benefits from increased carbon storage by 24 per cent over a whole rotation (Kirschbaum et al., 2011). Compared to no management, the removal of forest biomass by thinning decreases the carbon storage, with little effect on albedo (Kirschbaum et al., 2011; Otto et al., 2014).

In Northern Europe, even-aged management is widely used for Norway spruce (Picea abies Karst. (L.)), which is one of...
the most ecologically and economically valuable tree species. However, an interest in uneven-aged management has recently been on the increase. In even-aged management, the production cycle extends from artificial forest regeneration (planting) through commercial thinnings (typically from below) to final felling, and regeneration for the next cycle, etc. (Äijälä et al., 2014). Under uneven-aged management, the production cycle extends from one selective cutting to another, with mainly larger (co-dominant and dominant) trees being harvested, allowing natural regeneration and the ingrowth of seedlings in canopy gaps. The economic profitability of timber production is higher under uneven-aged than even-aged management due to avoided regeneration costs (e.g. Lundqvist et al., 2007; Pukkala et al., 2011; Peura et al., 2018).

Forest management objectives often involve trade-offs (Felton et al., 2016; Heinonen et al., 2017; Diaz-Yanez et al., 2020). To promote forest resilience and reduce the harmful impacts of timber production on other ecosystem services such as carbon sequestration of forests, uneven-aged management has been proposed as an alternative to rotation-based forestry (Diaz-Yanez et al., 2020). However, the findings of a few available comparative experimental (e.g. Nilsen and Strand, 2013) and simulation (e.g. Pukkala et al., 2011; Peura et al., 2018, Kellomäki et al., 2019) studies on carbon dynamics in uneven- and even-aged managed boreal Norway spruce forests have been contradictory. This may be explained by differences in forest structure (e.g. stocking volume and density) and harvesting intensity between the studies (e.g. Lundqvist, 2017; Hynynen et al., 2019; Kellomäki et al., 2019).

Most studies on the role of boreal forests and their management in climate-change mitigation have focused on carbon sequestration and forest carbon stocks, whereas other climate-regulating functions have rarely been addressed (Bright et al., 2015; Naudts et al., 2016; Thom and Seidl, 2016). However, it is important for us to understand how different management strategies affect climate-change mitigation overall, including carbon storage and changes in albedo-related radiative forcing (Lutz and Howart, 2014; Lutz et al., 2016; Thom et al., 2017), and the relationship between climate-change mitigation and other ecosystem services (Naudts et al., 2016). This is especially important in boreal forests, where surface albedo-related direct radiative forcing could outweigh the effect of carbon storage (Bonan, 2008)

Most forest owners are interested in diversifying their forest management to consider other forest functions alongside timber production and its economic profitability (Pynnönen, 2020). In order to incorporate climate-change mitigation into management decisions, forest owners need a better understanding of the ways by which forests and their management contribute to climate cooling or warming. In this context, we investigated how three different management options for boreal Norway spruce, ‘even-aged’ and ‘uneven-aged’ management and ‘no management’, affect carbon dynamics and particularly tree and soil carbon stocks, while also impacting albedo with direct effects on radiative forcing.

Long-term simulations were done with the eco-physiological forest model FinnFor (Kellomäki and Väisänen, 1997) that includes the regeneration, growth and mortality of trees. The simulations were done under current climatic conditions representative of the middle boreal zone of central Finland (62°N) on medium fertile (Myrtillus type) sites. The effect of forest management on radiative forcing was assessed as the result of forest cover impacting albedo, and carbon stocks in the forest ecosystem (trees and soil) calculated using the approach of Kirschbaum et al. (2011). Our radiative forcing calculations did not consider indirect radiative effects of management. Our calculations also excluded radiative effects of management on carbon stocks in wood-based products and the use of forest biomass to substitute fossil-based materials and energy, because forest owners cannot affect the industrial use of harvested timber.

Materials and methods

Forest-ecosystem model used in the simulations

The eco-physiological, process-based forest-ecosystem model FinnFor, developed by Kellomäki and Väisänen (1997), was used to simulate forest growth and carbon dynamics, as well as radiative forcing due to changes in carbon dynamics and surface albedo, of Norway spruce stands under three management options: even-aged, uneven-aged and no management. The physiological processes of the model include photosynthesis, respiration, transpiration, and water and nutrient uptake, which are driven directly and indirectly by climatic and edaphic factors, e.g. CO₂, temperature, air humidity, soil temperature and soil moisture. The climatic factors also include cloudiness, precipitation, air humidity and solar radiation. Soil moisture and temperature control the decay of soil organic matter (litter, humus) and affect CO₂ emissions from the soil and the cycling of nitrogen for reuse (Kellomäki and Väisänen, 1997; Kellomäki, 2017). The emergence and ingrowth of seedlings under uneven-aged and no management were simulated using the approaches of Fox et al. (1983) and Pukkala (1987a, b), as recently used in Kellomäki et al. (2019). In this stochastic approach, the properties of the seed crop produced by large and mature trees affect the potential number of emerging seedlings. However, herbivory and the availability of stockable area may also limit the density of emerging seedlings (see Appendix 1 for more details).

We calculated the net effect of changes in total forest-ecosystem carbon stocks and forest albedo on radiative forcing using the approach of Kirschbaum et al. (2011). We calculated albedo values for each management regime based on annual above-ground forest biomass. These albedo values were then used to calculate the annual change in radiative forcing on a hectare basis, compared to the reference scenario (a clear-cut site before planting seedlings (the year 1) at the initialization of simulations). Similarly, we calculated annual changes in radiative forcing due to changes in carbon stocks in trees, soil and the whole ecosystem attributable to the management regime relative to a reference scenario (Kirschbaum et al., 2011). Any increase in radiative forcing, compared to the reference scenario, then contributes to climate warming (see for more details, Supplementary material, Appendix 1) whereas, a decrease in radiative forcing contributes to climate cooling, respectively.

The forest-ecosystem model applies an hourly or daily time step for physiological processes and an annual time step for ecological (e.g. growth) and management processes (Kellomäki and
The performance of the model has been presented and discussed in many previous impact studies in the boreal region. Outlines for the FinnFor model, its calculations and applications are discussed in more detail in the Supplementary material, Appendix 1.

Simulations

Our simulations used the current climate for Norway spruce stands in the middle boreal ($62^\circ$N) region of central Finland. The climate was defined by a mean annual temperature sum of 1100 °C days, precipitation of 540 mm yr$^{-1}$ and an atmospheric CO$_2$ concentration of 390 ppm. For the simulations, mean monthly values of the climate factors were converted into hourly, daily and annual values based on current climate statistics, using the stochastic weather generator developed by Strandman et al. (1993). The simulations used medium fertile sites (Myrtillus type) on moraine soil, with a volumetric water content of 0.25 m$^3$ m$^{-3}$ at field capacity and 0.05 m$^3$ m$^{-3}$ at wilting point. At the initializing of the simulations, the carbon content of soil organic matter (SOM, including litter and humus) was 34 Mg C ha$^{-1}$ (Kellomäki et al., 2008).

The simulations for each management regime were divided in two subperiods. In the first subperiod, even-aged management with thinning from below was used over a 100-year period, with the simulation s being initiated by planting on a clear-cut area, with a spacing of 1800 seedlings ha$^{-1}$. Five cohorts were used in the simulations, with height and diameter ranges of 0.1–0.5 m and 1.0–1.4 cm (0.1 m or 0.1 cm intervals), respectively. In the second subperiod, after 100 years, the simulations used the management-specific regimes described below.

Under even-aged management, the stand was clear cut at the end of the first subperiod, and the site was replanted as described for the initiation of the first simulation period. Natural regeneration was excluded, and several commercial thinnings from below were carried out before the final cut (clear cut) at the end of the rotation. Under even-aged management, a fixed rotation period of 100 years was used, which is within the range of recommended rotation periods for Norway spruce on medium fertile sites (the age range of 70–110 years depending on boreal region, see Äijälä et al., 2014).

Under uneven-aged management, the stand was not clear cut at the end of the first subperiod, but instead, single trees were repeatedly selectively cut from above, using the given production cycle, and allowing natural regeneration and ingrowth of new seedlings to fill the canopy gaps. Under no management, there was no clear cut at the end of the first subperiod and management was totally excluded, relying entirely on natural regeneration and ingrowth of trees to fill the canopy gaps created by natural mortality. In our calculations, we assumed full seed crop potential under uneven-aged management and no management following the study by Kellomäki et al. (2019). Timber (saw logs, pulp wood) was harvested as part of thinning and final cuttings under even-aged management, and in selective cuttings under uneven-aged management, using the recommended thinning/selection thresholds employed in Finnish private forestry (see Äijälä et al., 2014).

Data analysis

The second subperiod of years 101–400 could be considered as a conversion period for no management and uneven-aged management. During that period, all seedlings planted at the beginning of the simulations were replaced by naturally regenerated seedlings. The death of trees made space for the next seedling generation, creating an uneven-aged forest structure. The increase in mortality of trees under no management along with ageing is represented in Figure 1 (also the maximum biological age of trees used in the simulations was 300 years). The uneven-aged structure under no management (old-growth forest) is typical for Norway spruce forest grown for a longer period under natural conditions (Sirén, 1955). The long-term cycling in the basal area of trees under no management stabilized after about 400 years. However, it did not reach true equilibrium conditions even over a simulation period of 1000 years (Figure 1). Further data analyses were done separately for the periods of 101–400 and 401–1000 years. The comparison between different management regimes mainly focused on the period from 401 to 1000 years.

We evaluated the mean growth of stem wood, carbon stocks (in trees and soil) and effects of ecosystem carbon stocks and albedo on direct radiative forcing (alone and together) for different management regimes. Additionally, we compared the amount of stem wood removed in thinnings and the final cut under even-aged management and in selective cuttings under uneven-aged management. Logging residues (foliage, branches, stem wood with diameters ≤6 cm, coarse and fine roots) were left on the site. Also, net present value (NPV, 2 per cent interest rate) for net incomes was calculated. This analysis used a similar interest rate as in previous studies (e.g. Díaz-Yanez et al., 2020) and the same silvicultural costs (€ ha$^{-1}$) and timber prices (€ m$^{-3}$) (see the Supplementary material, Appendix 2, Table A1), as had been used in Kellomäki et al. (2019).
Table 1 Long-term mean values for basal area, growth of stem wood, timber yield (saw logs and pulp wood), net present value (NPV) and carbon stocks (trees, soil and ecosystem) for different management regimes over simulation years 101–400 and 401–1000, respectively.

| Variables                | Simulation years 101–400 | Simulation years 401–1000 |
|--------------------------|--------------------------|---------------------------|
|                          | No manage | Even | Uneven | No manage | Even | Uneven |
| Mean basal area, m² ha⁻¹ |            |      |        |            |      |        |
| Mean growth, m³ ha⁻¹ yr⁻¹|            |      |        |            |      |        |
| Timber yield, m³ ha⁻¹ yr⁻¹|            |      |        |            |      |        |
| Saw logs                 | 47        | 33   | 20     | 45         | 34   | 18     |
| Pulp wood                | 31        | 19   | 26     | 33         | 19   | 26     |
| Ecosystem (trees and soil)| 78      | 52   | 46     | 78         | 53   | 44     |
| Carbon stocks, Mg C ha⁻¹ |            |      |        |            |      |        |
| Trees                    | 60        | 63   | 43     | 58         | 64   | 41     |
| Soil                     | 40        | 37   | 57     | 42         | 36   | 59     |
| % Ecosystem carbon       |            |      |        |            |      |        |
| Trees                    |            |      |        |            |      |        |
| Soil                     |            |      |        |            |      |        |

Results

Growth of stem volume and carbon stocks in the forest ecosystem

The mean annual growth of stem wood over the simulation years 401–1000 ranged from 3.1 to 8.9 m³ ha⁻¹ yr⁻¹ under the three management regimes (Figure 2, Table 1). With no management (old-growth forest), the mean growth was 54 per cent lower than under even-aged management. Although it was 31 per cent higher under no management than under even-aged management, total timber yield was 10 percent higher under uneven-aged than under even-aged management. The NPV (with a 2 percent interest rate) for timber production was 110 per cent greater under uneven-aged than under even-aged management.

Mean carbon stocks in the trees ranged from 18 to 45 Mg C ha⁻¹, in the soil from 19 to 33 Mg C ha⁻¹ and in the whole ecosystem from 44 to 78 Mg C ha⁻¹ for all three management regimes over the years 401–1000. Mean carbon stocks in trees, soil and the ecosystem as a whole were 34, 70 and 47 per cent larger under no management than even-aged management. Under uneven-aged management, mean carbon stocks in trees and the whole ecosystem were 46 and 16 percent lower, but in the soil, they were 37 percent higher under even-aged management. The carbon in trees contributed 41, 58 and 64 per cent to the total ecosystem carbon stocks under uneven-aged, no management and even-aged management, respectively.

Radiative forcing related to albedo and carbon stocks in the ecosystem

The calculated mean albedo over the simulation period from years 401 to 1000 was in the range of 0.12–0.15 under all three management regimes (Figure 3, Table 2). Compared to even-aged management, mean albedo was 15 per cent lower under no management and 10 per cent greater under uneven-aged management. These albedo differences related to differences in above-ground biomass over the simulation period. We then calculated mean albedo-based radiative forcing compared to our reference scenario, a clear-cut site with an albedo of 0.23. Calculated albedo-based radiative forcing varied in all three management regimes in the range of 5.0–7.2 GJ ha⁻¹ d⁻¹ over a 600-year period. The albedo-based radiative forcing change was 22 per cent higher under no management and 15 per cent lower under uneven-aged management than under even-aged management.

Compared to the reference scenario, the increased ecosystem carbon stocks (in trees and soil) reduced radiative forcing (cooling effect) for years 401–1000 by an average −4.3, −6.6 and −13.7 GJ ha⁻¹ d⁻¹ under uneven-aged, even-aged and no management, respectively. Compared to the reference scenario, an average cooling effect of carbon in trees was highest under even-aged management (−12.8 GJ ha⁻¹ d⁻¹), followed by even-aged (−9.6 GJ ha⁻¹ d⁻¹) and uneven-aged management (−5.2 GJ ha⁻¹ d⁻¹). Correspondingly, the average warming effect (increase in radiative forcing) of carbon in the soil was higher under even-aged management (2.9 GJ ha⁻¹ d⁻¹) than under no and uneven-aged management (0.9 GJ ha⁻¹ d⁻¹).

The option of no management reduced total direct radiative forcing (−6.5 GJ ha⁻¹ d⁻¹), compared to the reference scenario, through the combined effect of changes in albedo and ecosystem carbon stocks over the years 401–1000. In contrast, even-aged (−0.8 GJ ha⁻¹ d⁻¹) and uneven-aged (0.7 GJ ha⁻¹ d⁻¹) management induced only minor changes in radiative forcing, compared to the reference scenario. The beneficial effect of increasing carbon stocks in trees was largely negated by adverse changes in albedo and soil carbon. Overall, only the no management option resulted in a significant net cooling effect whereas for even-aged and uneven-aged management, the opposing effects of changes in albedo and carbon stocks largely cancelled each other with little remaining net effect. The magnitude of average values for different variables were very similar for the
Figure 2 Key aspects of system performances over time, showing (a) mean growth of stem wood, (b) carbon stocks in trees, (c) carbon stocks in the soil and (d) carbon stocks in the whole ecosystem (in trees and soil) under the three management regimes over a 1000-year period.
Figure 3 Component of the radiative balance over time, showing (a) albedo, and radiative forcing due to (b) changes in albedo (Albedo forcing), (c) ecosystem carbon stocks (trees and soil) alone (Carbon forcing) and (d) together (total forcing) under the three different management regimes over a 1000-year period. The albedo for clear-cut site is shown as the grey line in (a).
incoming radiation is received in boreal regions (hand, in midwinter (December–February), very little (near zero) between bare ground and tree cover (Betts, 2000). On the other boreal region), which can greatly amplify the albedo differences when snow covers the ground (common in midwinter in the influence of both direct and diffusive radiation.

Discussion

We used an eco-physiological forest-ecosystem model to investigate how even-aged, uneven-aged and no management regimes affect albedo and the carbon dynamics in boreal Norway spruce forests. We then used that information to calculate changes in radiative forcing under different management options, compared to the reference scenario (i.e. a clear-cut site that represented the state of the site before any trees had been planted). Based on that, we assessed their consequent potential to mitigate global warming. We calculated radiative forcing using the approach of Kirschbaum et al. (2011), which was recently also used by Thom et al. (2017). The relationship used between black-sky albedo and above-ground forest biomass (excluding ground vegetation) was based on Lukeš et al. (2013). In many other studies it has been indicated that boreal forest albedo decreases as the stands become older and as their standing stock increases (e.g. Rautiainen et al., 2011; Kuusinen et al., 2014; Otto et al., 2014; Hovi et al., 2016). Rautiainen et al. (2011) also showed a good correlation (when ground vegetation was excluded) between black-sky albedo and blue-sky albedo, the latter one combining the influence of both direct and diffusive radiation.

Forest albedo varies depending on canopy cover, particularly, when snow covers the ground (common in midwinter in the boreal region), which can greatly amplify the albedo differences between bare ground and tree cover (Betts, 2000). On the other hand, in midwinter (December–February), very little (near zero) incoming radiation is received in boreal regions (~60°N) (see e.g. Kuusinen et al., 2012). Whereas during the summer solstice, average incoming radiation is high, in the magnitude of 18.6 MJ m⁻² d⁻¹. Based on this, we excluded the effect of snow cover from our calculations. Over the growing season, albedo is quite stable with little seasonal variability (e.g. Kuusinen et al., 2012, 2013; Hovi et al., 2019; Kalliokoski et al., 2020) which obviated the need to recalculate forest albedo repeatedly. Our radiative forcing included only the direct radiation effect but excluded the indirect impacts of evaporation and secondary organic aerosols and other factors that can further modify overall radiative forcing in boreal forests (e.g. Betts, 2000; Bright et al., 2014, 2015; Naudts et al., 2016; Kalliokoski et al., 2020). We used the same calculations of radiative forcing based on changes in albedo and forest carbon stocks, compared to the reference scenario, for all management regimes. We expect that this should allow sound comparisons between them.

Our findings indicated that only the no management regime (old-growth forest) resulted in a significant net cooling effect (decreased radiative forcing). For even-aged and uneven-aged management, the opposing effects of changes in albedo and carbon stocks largely cancelled each other with little remaining net effect. On the other hand, the uneven-aged management made a small net warming contribution. For comparison, in a radiata pine forest in New Zealand, the changes in albedo negated the benefits of increased carbon storage by only 24 per cent over the whole rotation (Kirschbaum et al., 2011). This difference was largely attributable to the much larger carbon stocks in the pine forest in a very productive region in New Zealand.

In our study, the large differences in the cooling impacts of the different management regimes were mainly due to the differences in their carbon stocks. Mean carbon stocks in the ecosystem (in trees and soil) were largest under no management and lowest under uneven-aged management with lowest thinning thresholds. Our simulations suggested that there would be greater amounts of soil carbon under no and uneven-aged management than under even-aged management. This might be partially explained by the natural regeneration and ingrowth of seedlings and their subsequent higher mortality. Furthermore, the greater frequency of selective cuttings from above (with logging residuals left on site) may partly explain the higher soil carbon stocks relative to the situation under even-aged management, with less frequent thinnings from below.

We also observed trade-offs between timber yield and the economic profitability of timber production for forest owners and the climate cooling effect. No management had the greatest cooling potential but provided no timber or income. Compared to even-aged management, uneven-aged management provided a 10 per cent higher timber yield and 110 per cent higher economic profitability of timber production, but it had the poorest cooling potential. On the other hand, in the future, forest owners could

| Variables                      | Simulation years 101–400 | Simulation years 401–1000 |
|-------------------------------|--------------------------|---------------------------|
|                               | No mana | Even | Uneven | No mana | Even | Uneven |
| Albedo                        | 0.13    | 0.14 | 0.15    | 0.12    | 0.14 | 0.15    |
| Δ Albedo                      | 0.10    | 0.09 | 0.08    | 0.11    | 0.09 | 0.08    |
| Δ Forcing (due to Δ albedo), GJ ha⁻¹ d⁻¹ | 6.3     | 5.8  | 5.2     | 7.2     | 5.9  | 5.0     |
| Δ Forcing, GJ ha⁻¹ d⁻¹       |         |      |         |         |      |         |
| ● Carbon stocks in trees      | -13.4   | -9.3 | -5.7    | -12.8   | -9.6 | -5.2    |
| ● Carbon stocks in the soil   | -0.4    | 3.0  | 0.8     | -0.9    | 2.9  | 0.9     |
| ● Total ecosystem carbon stocks | -13.8  | -6.3 | -4.9    | -13.7   | -6.6 | -4.3    |
| Δ Total direct forcing, GJ ha⁻¹ d⁻¹ | -7.5    | -0.5 | 0.32    | -6.5    | -0.8 | 0.7     |
be payed compensation for climate-change mitigation, e.g. for avoiding or delaying cuttings (Pukkala 2020). Favero et al. (2018) stated recently that albedo effects on radiative forcing, negating carbon stock benefits, should be accounted in cost estimates of climate-change mitigation. This is supported by our findings.

Previous experimental and simulation studies that compared even-aged and uneven-aged management regimes reported contradictory results for stem volume growth, carbon stocks in trees and the soil and timber yield (e.g. Lundqvist, 2017, Pukkala et al., 2011, Nilsen and Strand, 2013, Peura et al., 2018, Hynynen et al., 2019, Kellomäki et al., 2019). However, differences in forest structure, volumes of growing stocks and harvesting intensities between these studies may explain differences in their results. The reduction in yearly seeding potential of that under the full seed crop, which we used in our calculations, may also concurrently reduce the stem volume growth and timber yield under uneven-aged management (Kellomäki et al., 2019). On the other hand, carbon flows and stocks (in trees and soil) may be less sensitive to the seed crop reduction (Kellomäki et al., 2019). Instead, lower economic profitability of timber production for forest owners has been reported for even-aged management due to the higher costs for forest regeneration and tending of young seedling stands, especially when economic calculations have started from bare land conditions (e.g. Pukkala et al., 2011; Peura et al., 2018; Kellomäki et al., 2019).

We focused in our stand level radiative forcing calculations on the direct effects of forest management options on radiative forcing and their potential for climate-change mitigation. Thus, our radiative forcing calculations excluded indirect radiative forcing effects of management, such as changes in evapotranspiration and secondary organic aerosols, which contribute to cooling. This would also require regional-scale climate modelling, and was beyond the scope of our work. We also excluded radiative forcing effects through carbon storage in wood-based products and the use of forest biomass to substitute fossil-based materials and energy. This was done, because forest owners cannot affect the industrial use of harvested timber. On the other hand, forest owners (e.g. about 620,000 private forest owners in Finland who manage about 60 per cent of the total forest area) can significantly contribute to climate-change mitigation through proper management decisions. Natural disturbances, such as storms or forest fires, are also expected to increase along with climate change and could reduce forest-ecosystem carbon stocks and potential climate benefits. On the other hand, warmer temperatures and increasing CO₂ concentrations could in general increase forest productivity (e.g. Kellomäki et al., 2018; Kirschbaum et al., 2012). Our calculations ignored both the effects of CO₂ and climate change on natural disturbances of forest stands, which affect provisioning of ecosystem services (e.g. Thom and Seidl, 2016; Reyer et al., 2017; Gutsch et al., 2018; Kellomäki et al., 2008, 2018).

Conclusions

Forest owners need a better understanding of the ways that forests and their management may contribute to climate cooling or warming, in order to incorporate climate-change mitigation into management decisions. Our study showed that only the no management option resulted in a significant net cooling effect. Although for even-aged and uneven-aged management, the opposing effects of changes in albedo and carbon stocks largely cancelled each other with little remaining net effect. Our results for no management may be interpreted as representing old-growth forests (over the years 401–1000). The no management option did undergo significant ups and downs in carbon stocks over the first 400 years during the transition period from even-aged to old-growth forest (years 101–400). If one considers only the first 100 years during the transition period (years 101–200), no management option provided even higher cooling effect than that calculated over a longer period. For the two managed options, the climate effects remained quite stable regardless of the period considered in the simulations. There were also trade-offs between the benefits of carbon- and albedo-related radiative forcing and economic profitability of timber production under the studied management options. We found that increasing use of the no management option may increase the net climate cooling effects of forests. However, this may require compensation payments for forest owners due to large trade-offs between economic profitability for timber production and climate cooling effects. Multiple forest management strategies are also needed simultaneously at the landscape level to reduce warming whilst sustaining timber production and other ecosystem services.
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