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ORIGINAL PAPER

Effect of species composition on ecosystem services in European boreal forest

Timo Pukkala[1]

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Abstract Forest management in several boreal countries is strongly focused on conifers because they are more productive, the technical quality of their stems is better, and their wood fibers are longer as compared to broadleaves. Favoring conifers in forest management leads to simple forest structures with low resilience and diversity. Such forests are risky in the face of climate change and fluctuating timber prices. Climate change increases the vitality of many forest pests and pathogens such as *Heterobasidion* spp. and *Ips typographus* L. which attack mainly spruce. Wind damages are also increasing because of a shorter period of frozen soil to provide a firm anchorage against storms. Wind-thrown trees serve as starting points for bark beetle outbreaks. Increasing the proportion of broadleaved species might alleviate some of these problems. This study predicts the long-term (150 years) consequences of current conifer-oriented forest management in two forest areas, and compared this management with silvicultural strategies that promote mixed forests and broadleaved species. The results show that, in the absence of damages, conifer-oriented forestry would lead to 5–10% higher timber yields and carbon sequestration. The somewhat lower carbon sequestration of broadleaved forests was counteracted by their higher albedo (reflectance). Mixed and broadleaf forests were better providers of recreational amenities. Species diversity was much higher in mixed stand and broadleaf-oriented silviculture at stand and forest levels. The analysis indicates that conifer-oriented forest management produces rather small and uncertain economic benefits at a high cost in resilience and diversity.

Keywords Albedo · Boreal forest · Carbon sequestration · Diversity · Mixed forest · Resilience · Scenario analysis

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✉ Timo Pukkala
timo.pukkala@uef.fi

[1] University of Eastern Finland, P.O. Box 111, 80101 Joensuu, Finland

Introduction

Finland is a typical boreal country with abundant forests of only a few important tree species: Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) H. Karst.) and birch. There are two birch species with economic importance, silver birch (*Betula pendula* Roth) and downy birch (*Betula pubescens* Ehrh.). Other broadleaved species include aspen (*Populus tremula* L.), alder (*Alnus incana* (L.) Moench and *A. glutinosa* (L.) Gaertn.), rowan tree (*Sorbus aucuparia* L.) and several *Salix* species. Other species grow on the southern coast of Finland but this region is in the temperate zone.

Conifers are favoured in Finnish forest management, which decreases species diversity with an accompanying increase in economic and biological risks (see for example Knoke et al. 2005, 2017; Jactel et al. 2017). Diversity correlates with resilience: high diversity of forests is assumed to lead to good resilience (Thompson et al. 2009). The mechanisms behind this relationship have been discussed and explained in recent literature (Knoke et al. 2008; Thompson et al. 2009; Jactel et al. 2017). Species mixtures are related to improving resistance against soil-born fungal diseases, fire, and wind damage.

Table 1 Assortments and their roadside prices used in the calculations

Assortment	Minimum top diameter (cm)	Minimum log length (m)	Roadside price (€/m^3)
Pine saw log	15	4.3	57
Pine small log	13	3.4	32
Pine pulpwood log	8	2.0	30
Spruce saw log	16	4.3	57
Spruce small log	13	3.4	32
Spruce pulpwood log	9	2.0	30
Birch saw/veneer log	17	3.4	45
Birch pulpwood log	8	2.0	30
Aspen saw log	17	4.3	40
Aspen pulpwood log	8	2.0	20
Alder pulpwood log	8	2.0	10

The prices of timber assortments vary and future timber prices are not known with certainty (Leskinen and Kangas 1998). It is easy to show that when the prices of different species vary independently (or correlate negatively), the uncertainty related to incomes from timber sales increases when the number of species and timber assortments decrease (Reeves and Haight 2000; Knoke et al. 2008). Most landowners are risk-avoiders who want to avoid bad outcomes. The probability of such outcomes is higher when the number of tree species is low (Knoke and Wurm 2006). It has been shown that the optimal strategy of a risk-averse forest landowner is to grow several species and produce several different timber assortments (Pukkala and Miina 1997; Reeves and Haight 2000; Knoke et al. 2005; Pukkala and Kellomäki 2012; Griess et al. 2016).

The main reason for past and current conifer-oriented forestry is the better volume increment of conifer stands compared to broadleaf stands. The technical quality of conifer stems is better, resulting in a higher proportion of saw logs. Consequently, the potential carbon balance is better for conifers; the higher growth rate of conifers leads to faster sequestration of carbon dioxide and, due to a higher share of saw logs, more carbon can be stored in buildings and other structures. Timber prices have also been higher for conifers. The fibers of conifers are longer than those of broadleaves, leading to better quality pulp-based products.

The drawbacks of conifer-oriented forestry include decreased diversity accompanied with lower resilience and resistance (Thompson et al. 2009; Jactel et al. 2017). Decreased resilience results in a lower capacity to maintain ecosystem services under disturbances and to recover from disturbances (Knoke et al. 2008). It also leads to decreased capacity to maintain ecosystem services under a changing climate (Thompson et al. 2009). A specific drawback of spruce in Finland is that it is still pulped mechanically, resulting in very high energy consumption (Liski et al. 2001). Other drawbacks of conifer monocultures include losses in recreational values of forests (Silvennoinen et al. 2001). Although a pure coniferous stand has a substantially higher volume increment than a pure broadleaf stand, admixing broadleaves and conifers may improve productivity (Man and Lieffers 1999; Pretzsch and Schütze 2009; Pukkala et al. 2013; Forrester 2014; Pretzsch et al. 2015). Yield gains of mixed stands are possible, especially on medium and good sites where several species grow well. On medium sites, a mixture of Scots pine and Norway spruce may be more productive than either species alone (Pukkala et al. 1994, 1997). It has been shown that broadleaved species often improve the growth of conifers in mixed stands (Pukkala et al. 2013; Pretzsch et al. 2015). Man and Lieffers (1999) and Pretzsch et al. (2015) discussed the mechanisms behind this effect. An obvious reason for the favourable effects of admixtures is that

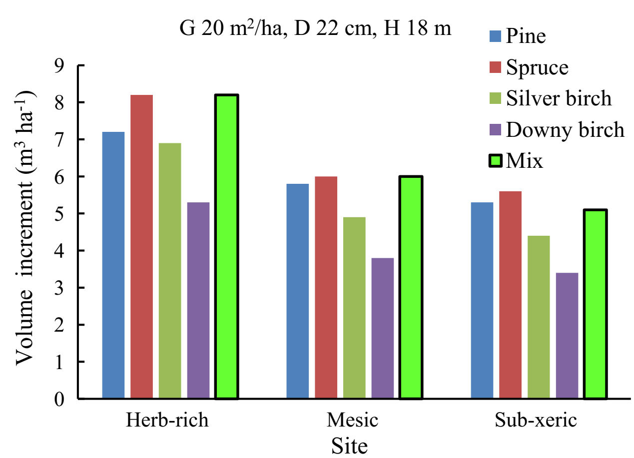

Fig. 1 Predicted annual volume increment of stands of different species on different growing sites (herb-rich, mesic, sub-xeric) when stand basal area (G) is 20 m^2/ha, mean tree diameter (D) is 22 cm and mean tree height (H) is 18 m, according to the models of Pukkala et al. (2013). In a mixed stand (mix), the proportions of different species are: herb-rich site 2/3 spruce and 1/3 silver birch; mesic site 1/3 pine, 1/3 spruce and 1/3 silver birch; sub-xeric site 80% pine, 10% silver birch and 10% downy birch

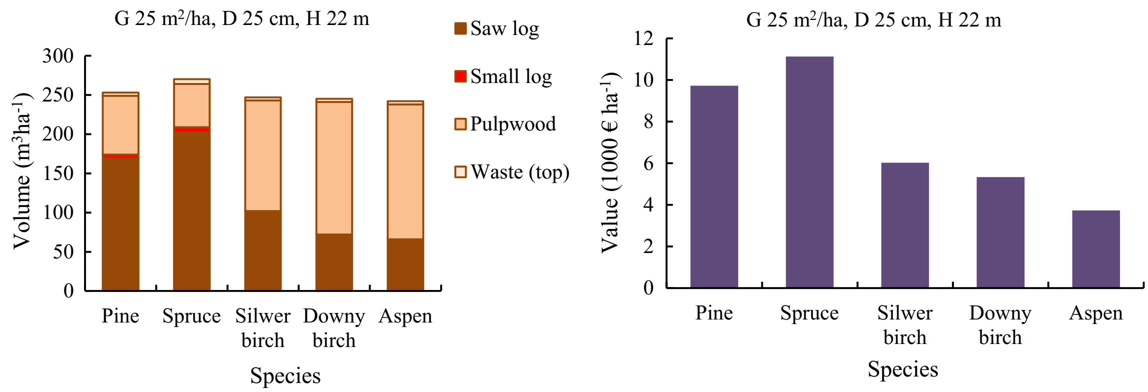

Fig. 2 Volumes of different assortments (left) and stumpage value of the growing stock (right) in stands of different species when stand basal area (G) is 25 m^2/ha, mean tree diameter (D) is 25 cm and mean tree height (H) is 22 m. The volumes and values are based on taper models (Laasasenaho 1982) and the definitions and unit prices of timber assortments are shown in Table 1

different species utilize growth resources in different ways; for example, the root systems are at different depths, and species also differ in shade tolerance and the use of different wavelengths of radiation (Man and Lieffers 1999). As a result, the use of growth resources is more efficient in mixed stands.

The effect of tree species on volume increment in Finnish conditions is shown in Fig. 1 which is based on the growth models of Pukkala et al. (2013). Superior volume production of conifers is evident, but the yield of species mixtures is not necessarily much lower than that of pure conifer stands. Certain species mixtures may even produce slightly more than a pure conifer stand (Pukkala et al. 2013; Pretzsch et al. 2015). The other advantage of conifers, namely a higher share of saw logs resulting in substantially higher income from timber sales, can be seen in Fig. 2 which is based on current price levels and current definitions of different timber assortments in Finland.

Yield losses due to lower volume production of broadleaves can be alleviated, besides growing mixed stands, by utilizing different temporal growth patterns of different species. Birch and aspen, for example, are pioneer species growing rapidly at a young age, while spruce is a climax species growing relatively rapidly at older ages. Therefore, both wood production and economic profitability might be increased by starting with a young birch-dominated mixed stand, and converting it gradually into a spruce-dominated stand by harvesting predominantly birch in the first commercial thinnings (Mielikäinen 1985; Valkonen and Valsta 2001). The same recommendation can be made for pine-spruce mixtures, in which the proportion of spruce could be gradually increased (Pukkala et al. 1994).

Broadleaves improve site fertility (Man and Lieffers 1999; Anyomi et al. 2013, 2014), and species mixtures improve the health of the stand (Piri et al. 1990; Möykkynen and Pukkala 2010), and reduce stand vulnerability to biotic and abiotic risks (Griess et al. 2012; Jactel et al. 2017). Broadleaves also have a better albedo (Kuusinen et al. 2013; Lukeš et al. 2014) and higher wood density (Repola 2006) than coniferous species, which improves their performance in climate change mitigation.

Problems related to coniferous monocultures are aggravated under climate change (Reyer et al. 2017). Climate change may increase wind damage, especially to spruce (Reyer et al. 2017). Another threat is spruce bark beetle (*Ips typographus*), which attacks damaged trees but also non-damaged ones if the density of the beetle population is high. Climate change increases the vigor and population growth rate of spruce bark beetle (Honkaniemi 2017) and it may decrease the resistance of spruce, for instance, to increasing frequency of drought. As a combination of all these phenomena, the likelihood of severe bark beetle outbreaks has increased and will continue to increase in the future.

Spruce butt rot (*Heterobasidion*) is another threat, especially in spruce stands, causing an annual economic loss of about 800 million EUR in Europe (Woodward et al. 1998; Jactel et al. 2017). Losses are expected to increase with climate change due to prolonged periods of mild weather suitable for spore infection of logging injuries and newly cut stumps. The mycelium of *Heterobasidion* also grows faster in root systems of stumps and living roots. Moreover, more northern regions will become vulnerable to *Heterobasidion* under a warming climate.

A mixture of birch and other broadleaved species might alleviate these threats to spruce monocultures. The spread of *Heterobasidion* is more difficult in mixed spruce stands since the admixture reduces the number of contacts between spruce root systems (Möykkynen and Pukkala 2010). Birch is more resistant against wind throw due to its deeper roots, streamlining of its stems and branches, and a smaller wind load in winter when it is leafless (Heinonen et al. 2009). Surveys in Central Europe show that the probability of wind throw is 5–10 times higher for spruce than for broadleaves (Lüpke and Spellmann 1999; Knoke et al. 2008). Pine also is clearly more sensitive to wind damage than broadleaves. Spruces are probably more resistant to bark beetles in mixed stands because broadleaved trees provide shade for spruce stems and reduce the physical stress of spruce growing near stand edges (Man and Lieffers 1999; Overbeck and Schmidt 2012).

The above shows that current conifer-oriented forest management in Finland and other boreal countries has both advantages and disadvantages. Therefore, choosing the best management strategy is not easy. Proper decision-making requires quantified information on the pros and cons of alternative management systems.

The purpose of the current study was to analyze the consequences of favouring broadleaved species in forest management. The effects of this paradigmatic change were evaluated in terms of the following ecosystem services: timber production and income; climate change mitigation (carbon sequestration and albedo); tree species diversity which correlates with overall biodiversity, resistance and resilience; and amenity values of forests. Analyses were conducted for 150 years in two case study forests representative of southern Finland. Three different forest management strategies were compared: (1) continuing the current conifer-oriented management; (2) promoting species mixtures in pre-commercial and commercial thinning treatments; and, (3) diversifying the range of planted species in addition to promoting species mixtures.

Materials and methods

Two case study forests from southern Finland were selected. The first (Forest 1), consisted of 273 compartments and covered 210 ha. The other forest (Forest 2) was 502 ha and it had 593 stand compartments. Every stand was assessed in the field using an angle gauge to measure stand basal area separately for every tree species and canopy layer. The mean diameter, height and age of each separately assessed stratum were also measured.

In both forests, most growing sites represented mesic (*Myrtillus* type) and herb-rich (*Oxalis-Myrtillus* type) fertility classes. In Forest 1, the proportion of herb-rich and mesic sites was 79% and in Forest 2 it was 89%. The remaining sites were poorer in fertility and more suitable for pine. Mesic sites are suitable for all main tree species of Finland, namely pine, spruce and birch, whereas herb-rich sites are suitable for spruce and birch. Pine also grows on herb-rich sites but its technical quality suffers from excessive fertility, resulting in low production of good-quality saw logs.

The species compositions of the two forests were reasonably balanced in that only 49% (Forest 1) or 30% (Forest 2) of growing stock volume was spruce. In Forest 1, the percentages of other species were: pine 26%, silver birch 17%, downy birch 3% and other species 5%. In Forest 2, the percentages were: pine 33%, silver birch 22%, downy birch 5% and other species 10%. Many stands were to some degree mixtures of more than one species. This was a good starting point for shifting silviculture to different alternative directions.

The basal areas and mean diameters were used to derive the diameter distribution of every stratum (tree species and canopy layer) (Pukkala and Miina 2005). The range of diameters was divided into ten classes of equal width and one representative tree (class midpoint tree) was taken from each class to represent the diameter class in simulations (Pukkala and Miina 2005). The growth, survival and ingrowth models of Pukkala et al. (2013) were used to simulate treatment schedules for all stands for fifteen 10-year periods (150 years). The models were used in two different ways: without calibration and calibration based on the latest national forest inventory (NFI11) as explained in Heinonen et al. (2017). Calibration improved the growth of pine and decreased the growth rate of all broadleaved species as compared to non-calibrated models.

Additional models used in calculations were the tree height models of Pukkala et al. (2009), taper models of Laasasenaho (1982), and biomass models of Repola (2008, 2009). The incomes from cuttings were calculated by multiplying the harvested assortment volumes by their roadside prices (Table 1) and subtracting the felling and forwarding costs from the value of sold timber. The models of Rummukainen et al. (1995) were used to calculate the harvesting costs, and the roadside prices were taken from statistics maintained by the Natural Resources Institute of Finland.

Carbon dynamics was simulated as described in Pukkala (2017). It consisted of three sub-processes which were all simulated: living biomass, wood-based products, and dead organic matter. Simulation of the dynamics of dead organic materials consisted of calculating the biomass of annual litterfall (above- and below-ground litter), tree mortality, and residues of harvested trees, and simulating the decomposition of all these components using the Yasso07 model (Liski et al. 2009; Tuomi et al. 2011). Albedo (reflectance of the canopy) was predicted with a model based on Kuusinen et al. (2013) and describes albedo in August when broadleaf species still have their leaves and there is no snow on the forest floor.

A scenic beauty index was calculated for every simulated schedule at 10-year intervals. The empirical model of Pukkala et al. (1988) was used for this purpose. The model reflects the scenic beauty preferences of Finns. To develop the model, 121 people evaluated 100 different tree stands for scenic beauty using a scale from 0 (very poor) to 10 (very good). A regression model was then fitted to predict the mean rating of the 121 judges from stand characteristics such as species composition, stand density and mean tree size.

Tree species diversity was described with the Shannon index:

$$H = -\Sigma p_i \ln(p_i) \quad (1)$$

where H is tree species diversity, p_i is the proportion of species i. The index was computed in three different ways, two of which (denoted as Shannon N and Shannon G) describe within-stand diversity. Shannon N was calculated from the frequencies (number of trees per hectare) of different species present in the stand, and Shannon G was calculated from the basal areas of different species. Large trees have more influence on Shannon G and the index may correspond better to the visual impression about the presence of different species in the stand. The third index, Shannon V, was calculated from the volumes of tree species in the whole forest. It describes the number and uniformity of the proportions of different species.

Commercial thinnings were simulated according to current recommendations (Äijälä et al. 2014). In the past, low thinnings (thinning from below) removing small trees from the stand where predominant. The current trend is increased use of thinnings from above. To account for the variability of thinning types, 1/3 of thinnings were simulated as thinning from below, 1/3 as thinning from above, and 1/3 as uniform thinning. Uniform thinning removed the same percentage of trees from all diameter classes. Final fellings were simulated once the mean tree diameter of the stand reached a certain minimum value, which was 24–30 cm depending on species composition and site fertility (Äijälä et al. 2014).

The timing of thinnings and final fellings were varied in order to have several alternative treatment schedules for every stand. This was done by postponing the operations by one to several 10-year periods. One of the treatment schedules was a no-cutting schedule. Site preparation, planting, and seeding were simulated immediately after clear-felling, and the tending treatments of young stands were simulated when the age of the regeneration was about 10 years, typically 10 years after regeneration.

The regeneration method on herb-rich and mesic sites was clear-felling, site preparation and planting. Almost all planting sites in Finland will also have natural regeneration of various species (Miina and Saksa 2006), mainly broadleaves, and this additional regeneration was also simulated. On sub-xeric sites, the regeneration method was clear-felling, site preparation and sowing of pine. On poorer sites, natural regeneration for pine via seed trees was used. The tending treatments of seedling stands (pre-commercial thinnings) were simulated for all young stands, leaving approximately 2000 seedlings per hectare to continue growing.

The above treatments were simulated in three different ways:

1. Conifer-oriented (currently practised) management.
   - Herb-rich and mesic sites were planted to spruce (poorer sites were regenerated to pine).
   - Precommercial thinning (tending) removed all broadleaved species.
   - All species were thinned with the same intensity in commercial thinnings.
2. Mixed-stand-oriented management.
   - Tending and thinning treatments aimed at leaving a mixed stand. The treatments were simulated so that thinning intensity correlated positively with the proportion of the species of the total number of trees (pre-commercial thinning) or of stand basal area (commercial thinning).
   - Otherwise, the management was similar as in conifer-oriented silviculture.
3. Broadleaf-oriented management.
   - Tending and thinning treatments aimed at leaving a mixed stand and they were simulated in the same way as in mixed-stand-oriented management.
   - On herb-rich sites, 50% of the clear-felled area was planted with birch (*B. pendula*) and 50% with spruce.
   - On mesic sites, 1/3 of clear-felled areas were planted with pine, 1/3 with spruce, and 1/3 with birch (*B. pendula*).

In all cases, optimization was used to find the ideal combination of the simulated treatment schedules. Net present value with a 3% discount rate was maximized with the following constraints:

- The round wood harvest each 10-year period had to be at least 10,000 m^3 in Forest 1 and 21,000 m^3 in Forest 2.
- The growing stock volume at the end of each 10-year period had to be at least 35,000 m^3 in Forest 1 and 45,000 m^3 in Forest 2. These values were close to the initial growing stock volumes of the forests.

If it was impossible to meet both constraints, a higher priority was given to the growing stock constraint. The maximized variables and the two constraints resulted in management where forestry was profitable, and the long-term cutting level was equal to long-term volume increment. Therefore, the combinations of simulated management schedules corresponded to a typical management intensity of commercial forests.

Results

Detailed results are presented only for Forest 1 using calibrated growth models. To find out how sensitive the results are to the selected case study forest, all analyses were also done for Forest 2. In addition, all results were calculated both with and without the calibration of the growth models (Pukkala et al. 2013). A summary of the results for all four cases is presented at the end of this section.

Growing stock volume

Continuing the conifer-oriented forest management led to a gradual increase of spruce volume, mainly at the cost of broadleaved species (Fig. 3). The volume of pine also decreased, but since the poorest sites are "absolute pine sites", the decrease stopped after a few decades.

The proportion of different species remained constant in mixed-stand-oriented management although all mesic and herb-rich sites were planted for spruce. Aiming at mixed stands in pre-commercial and commercial thinnings was sufficient for maintaining the initial volume of broadleaved species. Broadleaf-oriented management led to a gradual decrease of spruce volume while broadleaf volume increased, and pine volume remained near its initial level.

Timber yield and income

The accumulated timber removal and net income from forest management (timber sales minus silvicultural costs) were highest in conifer-oriented management, but the differences started to emerge only after about 60 years (Fig. 4). Mixed-stand-oriented management increased the removal of conifers in the thinning treatments of the first 10-year period which aimed at increasing the share of broadleaves. This increased incomes due to higher share and a better price (Table 1) of conifer saw logs.

Climate change mitigation

Conifer-oriented management led to the highest carbon sequestration because of better volume growth and a higher share of saw log in conifers (Fig. 5). However, in the beginning the carbon balance of mixed-stand- and broadleaf-oriented management was slightly better. This may be related to the higher removal of conifer saw logs in the first thinnings of mixed stands, facilitating better carbon sequestration in wood-based products.

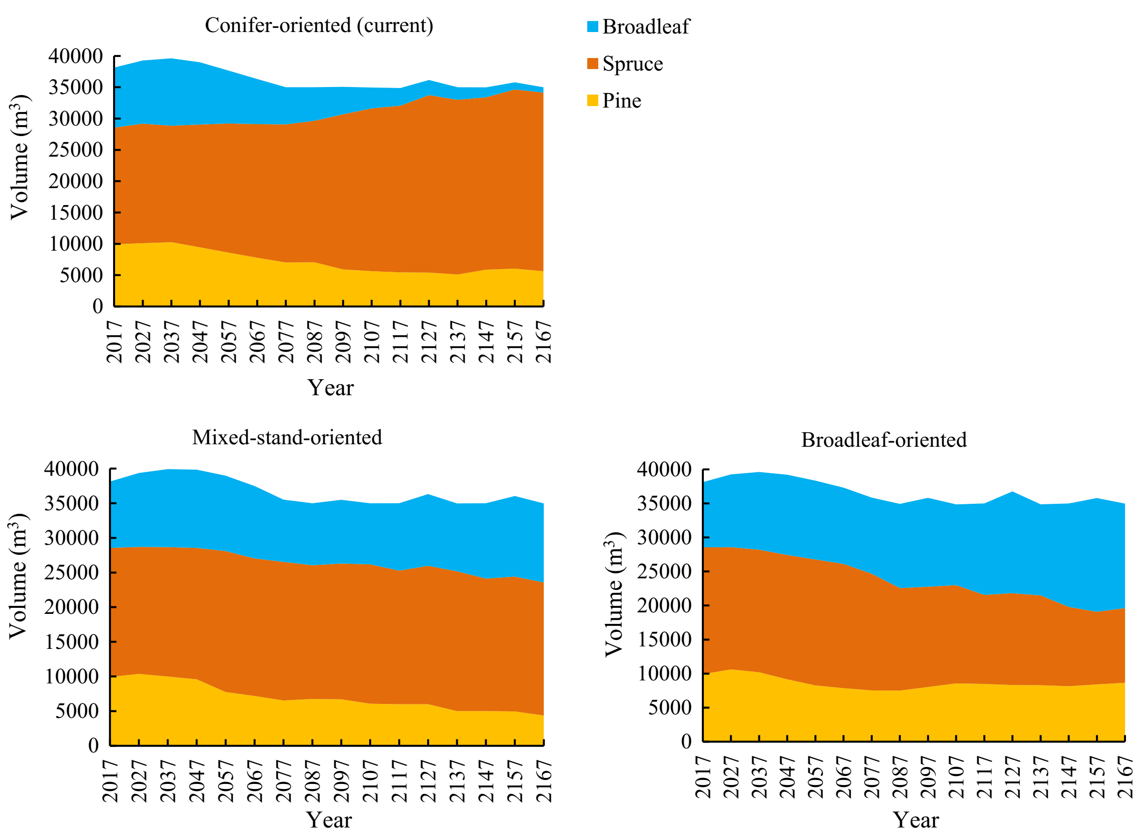

Fig. 3 Development of growing stock volume in the three management scenarios during the 150-year simulation period (Forest 1)

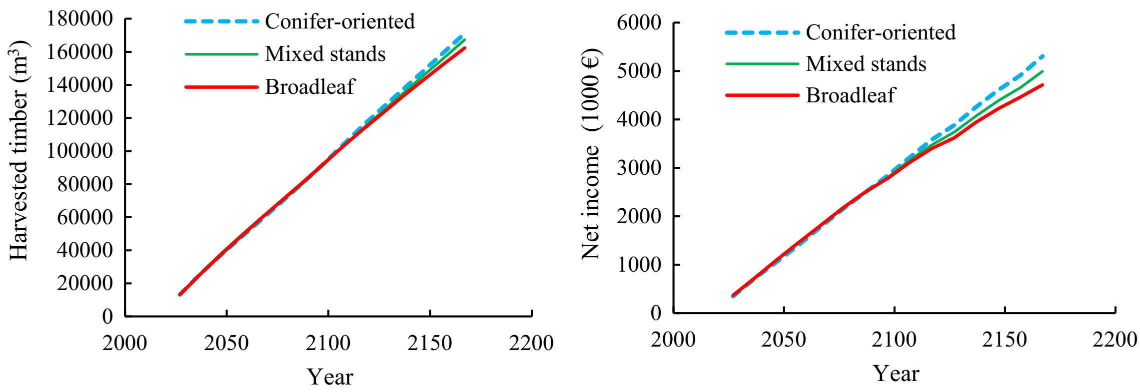

Fig. 4 Accumulated timber harvest and net income in the three management scenarios during the 150-year simulation period (Forest 1)

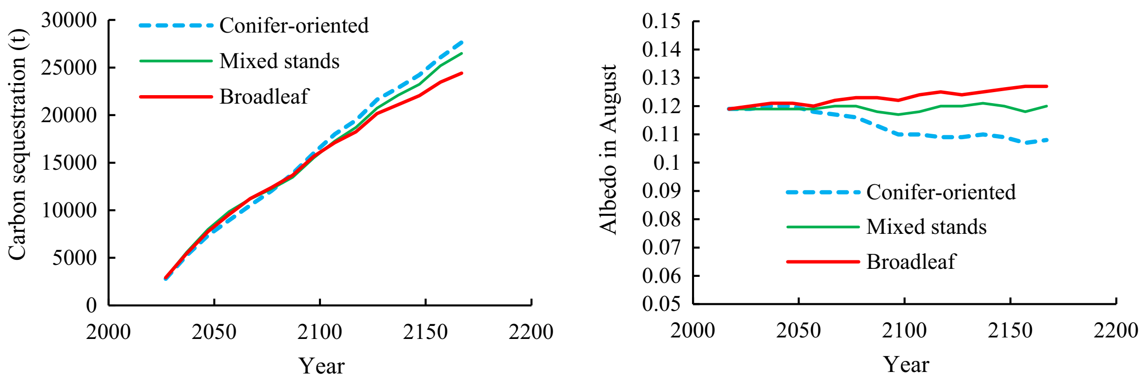

Fig. 5 Accumulated carbon sequestration and average albedo of stands in August in the three management scenarios during the 150-year simulation period (Forest 1)

The results for albedo were opposite to those for carbon sequestration (Fig. 5). Conifer-oriented management led to clearly lower albedo than other management strategies. The models used in this study predict the albedo in August when leaves are fully expanded. Most probably the relative differences in albedo would be higher in winter when broadleaves are leafless and there is snow on the forest floor (Lukeš et al. 2014).

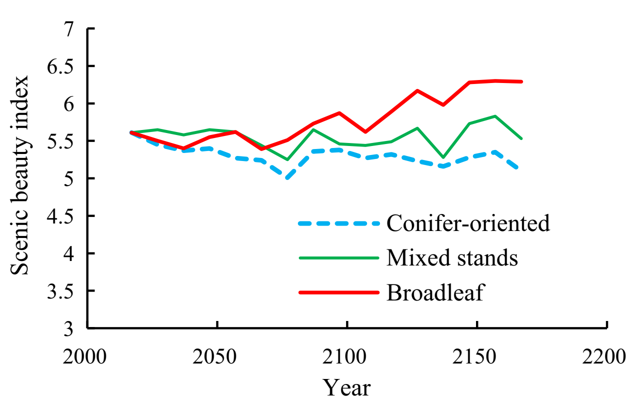

Fig. 6 Average scenic beauty index of stands in the three management scenarios during the 150-year simulation period (Forest 1)

Scenic amenity

The scenic beauty index was the best for broadleaf-oriented management and worst for conifer-oriented management (Fig. 6). The index was based on an empirical model that predicts the landscape preferences of Finnish people (Pukkala et al. 1988). These and other models (Silvennoinen et al. 2001) predict that large pines, birches and aspens improve the scenic beauty of stands. According to the models, a high number of spruce decreases the scenic beauty index, most probably because of the poor visibility in dense spruce stands.

Tree species diversity

Logically, within-stand species diversity was much lower in conifer-oriented management which removed all broadleaves in the tending treatments of young plantations (Shannon G in Fig. 7). Commercial thinnings of mixed-stand- and broadleaf-oriented management specifically aimed at equal shares of different species which increased diversity as compared to conifer-oriented management

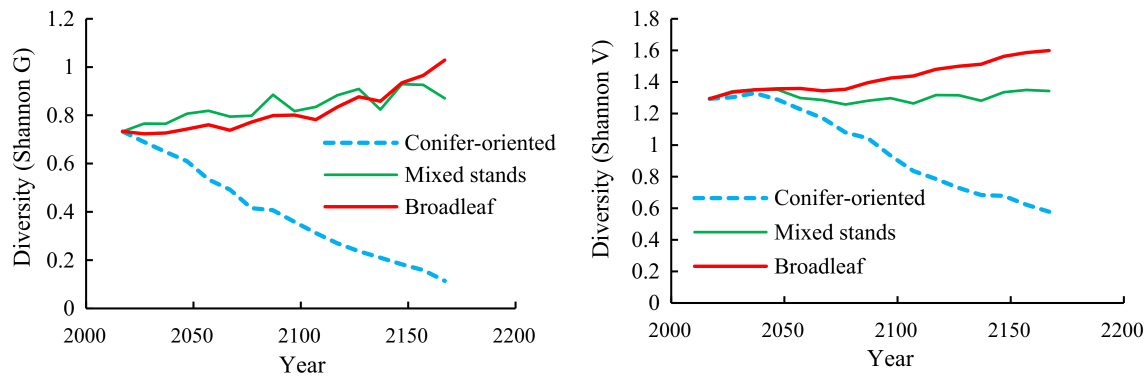

Fig. 7 Average species diversity index of stands (Shannon G) and the diversity of different species in the whole forest (Shannon V) in the three management scenarios during the 150-year simulation period (Forest 1)

which did not regulate the proportions of tree species in commercial thinnings.

The third diversity index, Shannon V, was calculated from the volumes of different species in the whole forest. Therefore, it does not depend only on the diversity of individual stands but it also describes the presence of stands with different species compositions. Mixed-stand- and broadleaf-oriented management did not differ much in within-stand diversity (Shannon N and Shannon G) but they differed clearly in forest level diversity (Shannon V) in which broadleaf-oriented forestry was better (Fig. 7). Considering all scales of diversity, it may be concluded that broadleaf-oriented management was the best, and conifer-oriented forestry was clearly the worst.

Summary of results

The results presented above pertain to Forest 1 and calibrated growth models. The same results were calculated also for Forest 2 and all results were also calculated without calibrating the growth models.

Figure 8 shows a summary of the results for all four cases. Timber production, net income and carbon sequestration were in all cases highest in conifer-oriented management. Mixed-stand-oriented management was the second best when calibrated growth models were used. The difference in favour of conifer-oriented management was 5–20%. When the growth models were used without calibrating them based on NFI data, differences in favour of conifer-oriented management diminished, especially in timber production and carbon sequestration. This is mainly because calibration decreased the growth rate of broadleaved species and increased the growth of pine (and slightly increased the growth rate of spruce).

Albedo and scenic beauty index were 5–10% better in mixed-stand- and broadleaf-oriented management as compared to conifer-oriented silviculture. The greatest differences were found in the three diversity indices in which conifer-oriented management was far behind the other management strategies. The difference was the largest in Shannon G which describes the share of different tree species of stand basal area.

Discussion

The results of this study show that the current conifer-oriented forest management is 5–10% better in timber production, net income and carbon sequestration, as compared to mixed-stand- and broadleaf-oriented management. However, damages other than competition-induced mortality were not simulated and these would most probably reduce the net increment and income most in conifer-oriented forestry (Knoke and Wurm 2006; Knoke et al. 2008; Griess et al. 2012).

Conifer-oriented and the other management strategies started to differ in harvested volume, net income and carbon sequestration after about 60 years. Mixed-stand- and broadleaf-oriented management aimed at increasing the share of broadleaves, which led to a higher removal of conifers in the thinnings of the first decades. This contributed to higher incomes, and better carbon sequestration in wood-based products (Pukkala 2017). Leaving a mixture of broadleaves in the tending treatment of young plantations increased the yield of the early part of the rotation because broadleaves grow fast at a young age (Mielikäinen 1985). This may have resulted in the higher removal or earlier timing of the first commercial thinnings.

This study took into account the beneficial effect of broadleaves on the growth and survival of conifers, as well as the beneficial effect of pine on the growth of spruce. This was possible because the mixture effects were incorporated into the growth models (Pukkala et al. 2013). The favourable effects of broadleaves and pines on ingrowth (advance regeneration) of spruce were also accounted for. However, the various biotic and abiotic damages, other

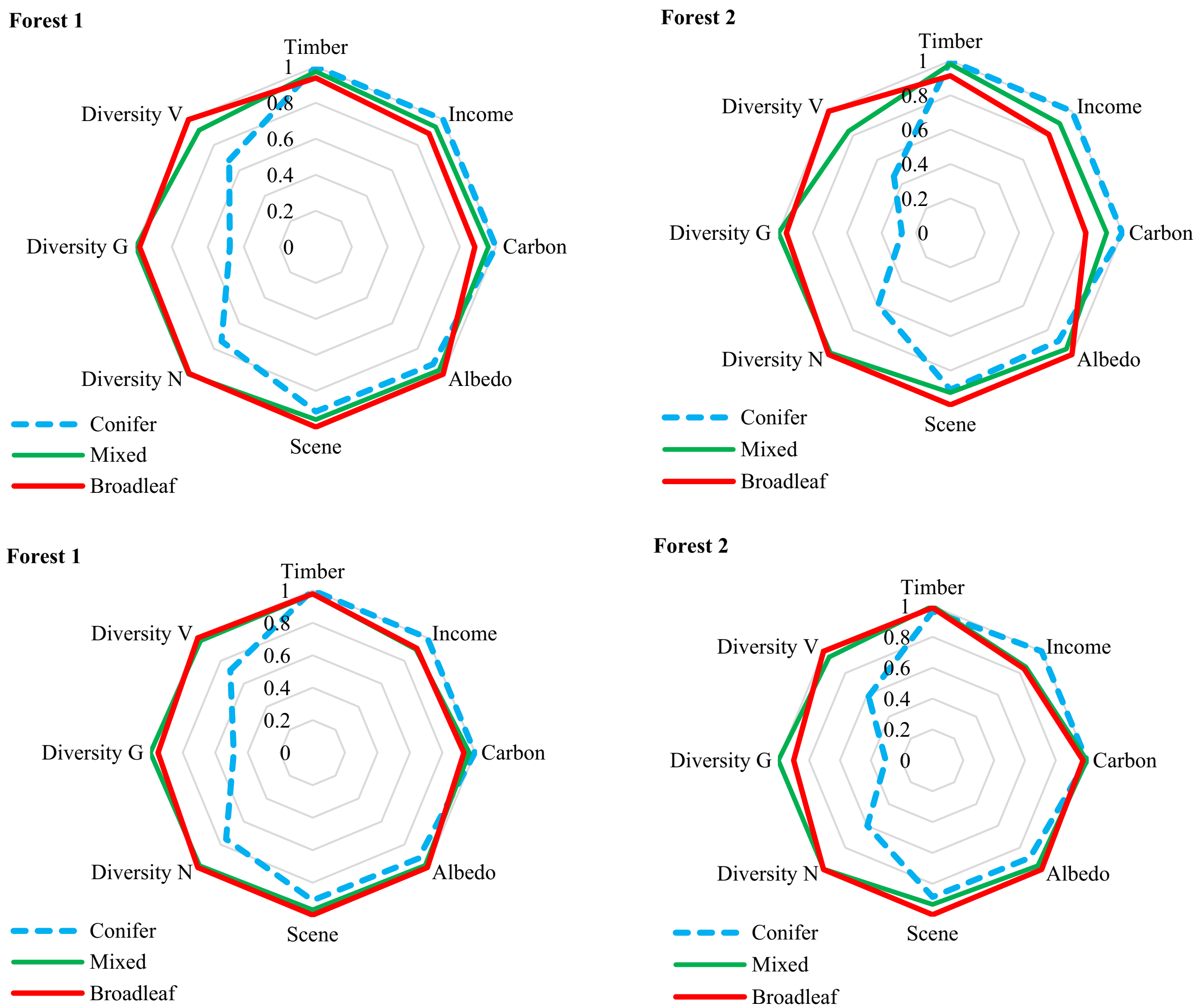

Fig. 8 Relative values of different ecosystem services in conifer-oriented, mixed-stand-oriented and broadleaf-oriented management in two different forests during the 150-year simulation period. The upper pair of diagrams is based on calibrated growth models and the lower pair on non-calibrated models. The management strategy having the highest value of certain output receives a value of 1 and the outputs in the other strategies are expressed relative to the best strategy. Timber production, net income and carbon sequestration are the total accumulated amounts during the 150-year period, while the other outputs are the mean values during the 150-year simulation period

than competition-induced mortality, were not simulated due to the lack of appropriate models and data. If they had been simulated, the yield differences between management scenarios would have been smaller. For example, wind storms annually destroy 3–8 million m^3 of wood in Finland (Zubizarreta-Gerendiain et al. 2017) which is 3–8% of the volume increment of Finnish forests. Spruce are wind-thrown at a higher probability than broadleaves (Knoke et al. 2008; Heinonen et al. 2009). The decreased amount of wind damage via increased broadleaf volumes may already compensate for the yield loss due to the increased share of broadleaves. Other factors which were not simulated include economic and yield losses caused by root rot and bark beetles (Möykkynen and Pukkala 2010; Honkaniemi 2017). These factors further decrease the yield differences between conifer-oriented management and the other strategies and may even alter their ranking.

The analyses of this study were conducted for two forests where the majority of stands represented herb-rich and mesic growing sites which are suitable for growing broadleaves and mixed stands. In Finland, the share of these growing sites is 70% of upland forests and 65% of all forests (mineral soil sites and peatlands). The remaining 30–35% of forests has low site fertility, and is suitable mainly for Scots pine. Improving the resilience of these poor sites by growing mixed stands and broadleaves is not a realistic option. On the other hand, it is generally agreed that pine forests are so well adapted to low fertility sites and their disturbance regimes that pure pine forests on these sites are both resistant and resilient even though their species diversity is minimal (Thompson et al. 2009).

Conifer-oriented management was 5–10% worse in albedo and scenic amenities and much worse (25–50%) in species diversity compared to mixed-stand- and broadleaf-oriented management. Decreased species diversity automatically leads to decreasing overall biodiversity since different tree species provide habitats and resources for different forest-dwelling species (Tikkanen et al. 2007). Diversity also correlates positively with forest resilience (Thompson et al. 2009; Griess et al. 2012; Jactel et al. 2017). Resilience is related to the certainty of the production of various ecosystem services, the resistance of forests against biotic and abiotic risks, and the capacity to recover from disturbances (Thompson et al. 2009). The results show that the current conifer-oriented management of Finnish boreal forests leads to decreased tree species diversity, and therefore probably to decreased resilience and a higher risk of yield and other losses. The trends seen in the simulated conifer-oriented management have already taken place in Finland. The share of birches and other broadleaves has slowly but steadily decreased after the 1920s while the proportion of spruce has gradually increased.

The mixed-stand- and broadleaf-oriented management strategies simulated in this study would be fully feasible in forestry practice. They do not require any drastic changes or adopting new methods in forest management. For example, in mixed-stand-oriented management, only spruce and pine were used in artificial regeneration, and the way of performing commercial thinnings changed only slightly (see Fig. 4). The biggest difference was in pre-commercial thinning where conifer-oriented management removed all broadleaved trees, whereas mixed-stand-oriented management always left mixed post-treatment stands. The simulation of pre-commercial thinning may exaggerate real-life differences between the management strategies because of large variation between individual regeneration areas. Failures in artificial regeneration sometimes force the manager to leave broadleaves in the gaps of conifer plantations while in other cases, natural regeneration of suitable broadleaved species may be insufficient for a mixed stand. Therefore, differences in real-life post-tending plantations would be smaller than the differences between the simulated management strategies of this study. Planting birch on herb-rich sites, and pine and birch on mesic sites, as done in broadleaf-oriented management, are also fully feasible options which have been followed in the past. One of the reasons for the current dominating role of spruce in plantations is moose browsing which has reduced the planting areas of pine and birch.

Growing mixed stands and planting different species are examples of diversified management (Knoke et al. 2017). In broadleaf-oriented forestry, management was diversified at two levels—within stands by growing different species in the stands and between stands by establishing stands with different species compositions. The broadleaf-oriented management strategy may be regarded as a portfolio of different forest management options at two levels. In addition, a portfolio of low, high and uniform thinning was used in all three management strategies. As discussed by Knoke et al. (2005, 2008) and shown in previous research, management diversification and portfolios are means to decrease economic and other risks (Reeves and Haight 2000; Knoke and Wurm 2006; Griess et al. 2016). Portfolios have been shown to maximize the utility of risk-avoiding forest landowners compared to management in which the most productive tree species are grown in every stand. In Finnish conditions, additional ways to diversify management would consist of using different thinning types and management systems for instance, both even- and uneven-aged management.

It has also been shown that the portfolio approach to forest management produces more ecosystem services and improves the biological quality of the forest (Knoke et al. 2008). Risk-averse forest landowners benefit from portfolios and use management that produces a high level of biological diversity. The benefits of portfolios, from a risk management point of view, are recognized in the latest silvicultural guides of Finland (Äijälä et al. 2014). The biggest hindrance for more diversified management may be the foresters and automated forest planning systems which prescribe treatments in a mechanical way, leading to similar prescriptions for all stands on a certain type of growing site.

Previous research shows that optimal management under risk often leads to mixed stands and to growing different species in different stands (Griess and Knoke 2013). For example, assuming moderate risk aversion, Thomson (1991) derived the following optimal species composition for the southern and Midwest USA: 56% southern pine, 27% southern ash and 16% white pine. For Germany, Knoke et al. (2005) calculated that the optimal mixture would have 50–90% Norway spruce and 10–50% European beech for moderate growing conditions in Bavaria, depending on the degree of risk aversion of the forest landowner. When risk and risk-aversion increased, maintaining a more diverse stand structure was profitable.

Pukkala (2015) did not find a strong increase in the proportion of broadleaves under increasing risk and risk aversion. Increasing risk aversion led to leaving a more balanced mixture of pine, spruce and birch in the first thinning but towards the end of the rotation, differences between the optimum for risk-tolerant and risk-averse landowners disappeared. Pukkala and Kellomäki (2012) found that increasing risk and risk aversion led to more diverse optimal stand structures but the effects of both risk and risk attitude were small. In Pukkala and Miina (1997), increasing growth and price uncertainty led to leaving a slightly more diverse size structure in the thinning treatment of a pine and spruce mixture. Increasing risk aversion accentuated this effect. The possible reason for the small influence of risk and risk aversion in Finnish studies is the positive correlation between the prices of different timber assortments (Leskinen and Kangas 1998). Lacking or having a negative correlation would have resulted in higher benefits from species mixtures. In addition, the higher risk of damage in monocultures and especially in spruce (Möykkynen and Pukkala 2010) was not simulated in the above-mentioned Finnish studies.

To conclude, this study showed that the currently practised conifer-oriented Finnish forest management produces modest and uncertain economic gains at a high cost in diversity and amenity values. Since diversity is related to resilience, it can be indirectly concluded that the current management may not be the best possible for the certainty of the production of different ecosystem services. This conclusion does not only concern biological diversity and amenities, but also timber production, carbon sequestration and many other forest functions.

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