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The effect of different forest management regimes on the ecosystem services and biodiversity of Finnish boreal forests

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Talousmetsien hoito ja tasaikäisrakenteinen metsänkasvatus ovat muuttaneet metsien rakennetta, ja vähentäneet monien metsälajien elinympäristöjen määrää. Tämä yhdessä Suomen kasvaneen hakkuutavoitteen kanssa vaikuttaa negatiivisesti sekä metsien ekosysteemipalveluihin, että monimuotoisuuteen. Tämän tutkimuksen tavoitteena oli tutkia metsänhoitomenetelmien maisematason vaikutusta monimuotoisuuteen ja ekosysteemipalveluihin pitkällä aikajänteellä, sekä käyttäen laajempaa valikoimaa metsänhoitomenetelmiä kuin aiemmissa tutkimuksissa. Metsätiedosto simuloitiin SIMO-metsäsimulaattorilla 150 vuotta eteenpäin erilaisilla metsänhoitomenetelmillä, joihin sisältyi mm. yleisimmin käytettyjä tasaikäisrakenteisia metsänhoitomenetelmiä sekä eri-ikäisrakenteisia menetelmiä. Vaikutuksia arvioitiin ekosysteemipalvelu- ja monimuotoisuusindikaattoreilla, ja käsittelemättömiä metsiä käytettiin verrokkina. Tulosten mukaan metsänhoidon vaikutukset vaihtelevat indikaattoreittain. Puolukka, myytävät sienet, ja puutavara hyötyvät tasaikäisrakenteisesta metsänhoidosta, mutta muiden indikaattoreiden tapauksessa lempeämmät menetelmät, kuten pidennetty kiertoaika, harventamattomuus ja eri-ikäisrakenteisuus johtivat suurempiin indikaattoriarvoihin. Aina metsänhoidon negatiivisia vaikutuksia ei voitu lievittää, mikä korostaa suojelualueiden tärkeyttä, ja osoittaa monimuotoisuuden ja puun tuoton välisen ristiriidan. Metsänkäsittelymenetelmiä tulisi näiden tulosten perusteella monipuolistaa, ja vähemmän intensiivisten hoitomenetelmien käyttöä lisätä entisestään.

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Intensive forest management, including the commonly used even-aged rotation forestry, has changed forest structure and decreased habitat availability for many forest species, negatively affecting ecosystem services and biodiversity of boreal forests. Despite earlier studies on this topic, and the importance of the topic in the face of increasing national harvest targets, combining a wider set of management regimes, and over a long timescale has yet been studied. The purpose of this study was to explore the effects of a wide set of forest management regimes on ecosystem services and biodiversity on a long timescale. A forest data set was simulated 150 years into the future with SIMO forest simulator under different management regimes, including variations of even-aged rotation forestry regimes, and continuous cover forestry, and the effects were compared on a set of ecosystem service and biodiversity indicators. Forests without management were used as a reference. The results revealed that the effects of management regimes differ between indicators. From ecosystem service indicators, timber, mushroom and cowberry benefited from even-aged rotation management, but for others and for all biodiversity indicators the less intense regimes such as continuous cover forestry, extended rotation length or refraining from thinning led to higher indicator values. In many cases the negative effects of management couldn't be fully alleviated with any regime, pointing out the need for conservation areas and a conflict between timber production and biodiversity. The findings of this study highlight the need to diversify forest management and promote the use of less intense forest management practices to prevent damage to biodiversity and ecosystem services.

CONTENTS

1 INTRODUCTION

Loss of suitable habitat has been recognised as one of the main factors causing loss of biodiversity globally (Millenium Ecosystem Assessment 2005). Intensive forest management for timber production is contributing to that loss, creating a threat to biodiversity (Bradshaw et al. 2009). In addition to biodiversity, intensive forest management influences the delivery of ecosystem services (Gamfeldt et al. 2013). Ecosystem services can be defined as benefits humans obtain from ecosystems (Millenium Ecosystem Assessment 2005). Boreal forests are an important provider of ecosystem services since almost one third of world's forests is in the boreal zone (Bradshaw et al. 2009). These services cover a wide variety of benefits, and have been shown be important to human well-being, and to have monetary value (Millenium Ecosystem Assessment 2005).

Ecosystem services, in boreal forests and elsewhere, can be divided into three main categories: provisioning, cultural and regulating services (Millenium Ecosystem Assessment 2005). In addition, services such as primary production or nutrient cycling can be thought of as supporting services, maintaining the services of the other three categories. The most easily recognisable, and measurable, services of boreal forests are the provisioning services, products obtained from the forest since they often have direct monetary value (Millenium Ecosystem Assessment 2005). Boreal forests contain 45% of world's stock of growing timber, making timber production the most economically important provisioning service (Vanhanen et al. 2012). Boreal forests also provide non-timber products of economic and cultural value, such as berries, mushrooms and game (Saastamoinen et al. 2014). Forests provide cultural values as well, such as scenic beauty of a forest landscape, and recreational activities such as hiking or bird watching (Saastamoinen et al. 2014). Climate regulation by carbon sequestration and storage is a globally important regulating service provided by forests, and boreal forests have been estimated to hold one third of the global carbon stock (Pan et al. 2011). In boreal forests, soils hold majority of the carbon (Malhi et al. 1999). In addition, forests regulate water flows and for example filter groundwater and retain nutrients (Saastamoinen et al. 2014).

Both ecosystem functioning and ecosystem structure have been argued to have a crucial role in the delivery of ecosystem services (Haines-Young & Potschin 2010). Ecosystem functioning has further been linked with biodiversity (Mace et al. 2012, Tilman et al. 2014). Studies have shown clear relationships between increasing ecosystem functioning and species richness and the number of functional groups (Tilman et al. 2014). The relationships are complex, partly because biodiversity affects at many levels of ecosystem functioning and therefore ecosystem service delivery (Mace et al. 2012). It has also been shown that the trend is not the same for all ecosystem services, for some such as provisioning services, biodiversity does not have a positive effect (Cimon-Morin et al. 2013). In boreal forests, natural disturbances are a major maintaining force of biodiversity (Kuuluvainen & Aakala 2011). Because of natural disturbances, a forest not influenced by humans is composed of patches of different developmental stages. Another important factor for maintaining biodiversity is deadwood, since 20-25% of species in boreal forests are dependent on it (Siitonen 2001).

Forests in Fennoscandia have been managed for decades for timber production (Vanhanen et al. 2012) and in Finland the forestry sector is the second largest industry by gross value (Metsäteollisuus 2017). The main forest management method over the past decades has been, and still is, even-aged rotation forestry (Äijälä et al. 2014). In this method, the forest stand is even aged and grows from bare ground with seeds or planted saplings until the age of the stand is approximately 60-100 years, depending on the dominant tree species, habitat and latitude. The forest is then clear-cut, and a new rotation starts. During the rotation a set of thinnings can be performed to allow more space for the best quality trees to grow.

Intensive forest management for timber production has altered the structure of forests during many decades, diminishing the kind of structural variation created by natural disturbances (Hansen et al. 1991). In managed forests the human-induced disturbances (i.e. harvests) tend to be uniform in size and intensity. In addition to altered structure, forest habitats have become increasingly fragmented by stands at different developmental stages (Kouki et al. 2001). Fragmentation makes it harder for species to find habitats with suitable characteristics, especially for specialist species (Andren 1994). Managed forests are also often more or less monocultures, since during early development of a stand the unwanted tree individuals are removed (Äijälä et al. 2014). In managed forests the amount of deadwood is considerably lower than in natural conditions (2-10 m^3ha^{-1} in managed vs. 60-90 m^3ha^{-1} in natural forest), decreasing the amount of suitable habitat for deadwood-dependent species and thus creating a threat to biodiversity (Siitonen 2001). Indeed, almost half of Finland's threatened forest species live in old forests and other deadwood-rich environments, and the decrease of these habitats and amount of deadwood has been listed as one of the most important reasons why forest species become endangered (Hyvärinen et al. 2019).

The effects of [even aged] forest management are also reflected on the delivery of ecosystem services from boreal forests, creating conflicts between timber harvesting and various services, such as recreational use, game and bilberry production on a local scale, and carbon storage and sequestration on a larger spatial scale (Gamfeldt et al. 2013, Triviño et al. 2017). Studies have shown that the currently most widely used rotation length is not the optimal for maximising the carbon stock of forests (Triviño et al. 2017). Instead, carbon storage is suggested to be greater with extended rotation length, since older forest stores more carbon than a younger forest (Liski et al. 2001, Kaipainen et al. 2004). Other forest management actions, such as removing harvest residues from the harvest site, can also impact negatively the carbon stock of the forest (Repo et al. 2011).

Options on how to simultaneously harvest timber and preserve as much of the ecosystem services and biodiversity as possible have been studied to provide tools for more sustainable forest management (eg. Hynynen et al. 2005, Miina et al. 2010, Triviño et al. 2017). Conserving forest by setting it aside from management is not effective enough method to conserve biodiversity if no measures are taken outside the protected areas, since only a small fraction of land is conserved (Perhans et al. 2011). Research shows that increasing rotation length is one way to increase the production of collectable goods, in addition to the abovementioned carbon storage, and to benefit biodiversity in some cases (Peura et al. 2016, Roberge et al. 2018). Diversifying the selection of management regimes can also increase habitat availability of specialized species that are suffering from even-aged forest management (Mönkkönen et al. 2014, Roberge et al. 2018). Green tree retention, where living trees are left in patches at final harvest, creates structural diversity at the harvest site and is used in forestry as a method to alleviate the negative effects of clearcutting on deadwood availability and forest biota, especially deadwood-dependent species (Vanha-Majamaa & Jalonen 2001, Kaukonen et al. 2018). Continuous cover forestry (CCF), where the forest has an uneven-aged structure, offers an alternative management option to the recommended even-aged management (Peura et al. 2017). There has been some debate on the usefulness of CCF and its effects on different ecosystem services, but it has been suggested to benefit for example berry production (Pukkala 2016a). CCF has also suggested to increase habitat availability for species preferring later successional forests (Mönkkönen et al. 2014). Research has indicated that the best result benefiting timber harvest, habitat availability and ecosystem service functioning can be achieved when multiple management options are implemented at a landscape scale through careful planning (Mönkkönen et al. 2014).

Current research still contains a gap concerning the effects of different forest management regimes and their effects on biodiversity and ecosystem services, especially the long-term effects. Most studies have used a timescale shorter than 100 years, which often restricts the assessment of regime effects to the first rotation and ignores the effects during subsequent forest rotations. Also, the selection of management regimes has been composed of either rotational forestry regimes with variations (e.g. Mönkkönen et al. 2014) or CCF versus one version of rotational forestry (e.g. Peura et al. 2017). There have not yet been studies combining the effects of different versions of rotational forestry and CCF regimes in one study.

The purpose of this study is to produce information on the long-term effects of different forest management options on biodiversity and ecosystem services. Research on this topic is important for both the forestry sector of Finland and as basis for further studies and has been listed as a research recommendation (Päivinen & Schneider 2019). Moreover, it has been suggested that forest owners would be interested to use a wider set of management methods than merely the recommended even-aged rotation forestry regime (Asikainen et al. 2014), highlighting the need for research on this topic.

Studying especially the long-term effects of management is important because Finland is investing heavily on bio-economy and planning to increase the amount of annually harvested pulp and log wood from 72 million m^3 (2017 level) to 80 million m^3 by year 2025 (MMM 2019). This increase would exert even more pressure on the biodiversity of Finnish forests and the delivery of ecosystem services, which is why the effects need to be studied carefully. Finland already has 833 endangered forest species, and according to the new red list of Finnish species (Hyvärinen et al. 2019) forest management and the changes to forest habitats caused by it is the single most important cause for endangered species in Finland. And since biodiversity is vital to the well-being and functioning of ecosystems, it is important to study the effects of different management methods and have information on how best achieve conservation goals and simultaneously harvest timber. Previous studies have already demonstrated possibilities to combine commercial and conservation goals by diversifying the set of forest management methods used and applying careful landscape level planning. However, information on the specific and long-term impacts of a wider selection of management options is needed.

This research aimed to analyse the landscape-scale effects of different forest management options on both biodiversity and ecosystem services of boreal forests of southern Finland. A selection of management regimes was applied and simulated 150 years into the future to estimate the effects. The research questions to be answered were: 1) How will forest management affect a set of ecosystem service and biodiversity indicators in Finnish boreal forests over a 150-year timescale in comparison to set aside option? 2) How do the management regimes compare with each other in terms of their effects on the indicators?

2 MATERIALS AND METHODS

This study was conducted using a simulation tool, which predicted the future forest dynamics using forest data as a starting point for the simulation (Hynynen et al. 2002). With this approach it was possible to analyse the effects of many different management regimes over a long timescale, which would not have been possible with field work.

The data used in this study was originally from Metsäkeskus (Finnish forest centre) and consisted of 2220 forest stands. A stand is a forestry unit, meaning an area of forest with uniform structure and clear edges with neighbouring stands. The data was collected with laser scanning and ground inventories, and included forest characteristics such as tree species composition, age, forest type, tree volume, basal area and number of trees etc. The mean stand area was 1,8 ha. The data set was chosen to represent a typical southern Finnish forest structure, by tree age class distribution and distribution of forest types, as described by Metsätieteellinen vuosikirja (2014). Most common forest type in the data set was mesic heath (MT), and the most abundant age class of trees was 40 to 59 years (Table 1).

Table 1: The proportions of stands in the original data set belonging to different habitat types and age classes.

Habitat type and abbreviation					**Age class of stands (years)**					
Herb-rich (OMaT)	Herb-rich heath (OmT)	Mesic heath (MT)	sub-xeric heath (VT)	xeric heath (CT)	<20	20-39	40-59	60-79	80-100	>100
1%	16%	47%	31%	5%	17%	24%	28%	20%	9%	3%

The stands were simulated 150 years into the future with SIMO forest simulator (Rasinmäki et al. 2009), using a set of different forest management regimes (Table 2). This timescale was chosen because it was long enough for all the rotations to complete, irrespective of the initial age of the stands. The entire rotation needed to be covered to get information on the long-term effects of the regimes. Using the existing data set as a starting point, the simulation predicted stand dynamics such as tree regeneration, tree growth, competition and tree mortality (Hynynen et al. 2002, Pukkala et al. 2013). At the end of each simulation period the stand data was updated, and a new simulation started. The simulations produced data at five-year intervals. As a result, data describing how the different management regimes change the indicator values over time was obtained.

2.1. Management regimes

The currently recommended "best practice" management regime in Finland is even aged rotation forestry, where the stands stay even aged, and the final harvest is conducted with clearcutting when the forest stand reaches given age and basal area, with green tree retention of 5 trees/ha (Äijälä et al. 2014). The recommended threshold values for harvest differ between habitat types (e.g. mesic heath and sub-xeric heath) and tree species. Most of the chosen management regimes were based on this recommended regime (BAU, business as usual) with modifications (Table 2). Modifications to the BAU regimes included extended rotation time, where the final harvest by clear-cutting was delayed, and some regimes included shortened rotations. There were two sets of BAU regimes with varying rotation lengths, in one thinnings were performed in every rotation, and in the other no thinnings were done in the first rotation, but the subsequent rotations included thinnings. There were also regimes where thinning was excluded altogether. Two BAU regimes included higher level of green tree retention, where 30 trees/ha were left standing.

Four variations of CCF were included, with CCF2 representing the most commonly used version of CCF. In CCF the forest stays covered and uneven-aged, and the largest trees are selectively harvested on average every 15 years, depending on the forest growth rate (Pukkala 2016b). The timing of the selective harvest was based on stand basal area, and once it exceeded a limit value the stand was harvested, until a fixed basal area was reached (Äijälä et al. 2014). The basal areas before harvesting were determined by habitat fertility and ranged from 16 m^2/ha (ClT) to 22 m^2/ha (OMaT). Variations in CCF included a higher or lower harvesting limit, which was determined by stand basal area (see Table 2). A higher cutting limit meant harvests were delayed. Set aside (SA) represented a conservation option without any management actions or human interventions during the 150-year simulation period.

Table 2: The selection of alternative management regimes with descriptions (Mönkkönen et al. 2014). Recommended rotation time refers to the national "best practice" recommendations for each habitat and tree species specifically, after Äjälä et al. (2014).

Management regime	**Rotation time**	**No. of green retention trees /ha**	**Thinnings**	**Clearcutting (yes/no)**	**Other information**
Set aside (SA)	-	-	No	No	No management actions
BAUwT	Recommended	5	Yes	Yes	Recommended regime
BAUwT_m5	-5 years	5	Yes	Yes	
BAUwT_5	+5 years	5	Yes	Yes	
BAUwT_10	+10 years	5	Yes	Yes	
BAUwT_15	+15 years	5	Yes	Yes	
BAUwT_30	+30 years	5	Yes	Yes	
BAUwT_GTR	Recommended	30	Yes	Yes	
BAU	Recommended	5	Not in first rotation, after that yes	Yes	

BAU_m5	-5 years	5	Not in first rotation, after that yes	Yes	
BAU_5	+5 years	5	Not in first rotation, after that yes	Yes	
BAU_10	+10 years	5	Not in first rotation, after that yes	Yes	
BAU_15	+15 years	5	Not in first rotation, after that yes	Yes	
BAU_30	+30 years	5	Not in first rotation, after that yes	Yes	
BAUwGTR	Recommended	30	Not in first rotation, after that yes	Yes	
BAUwoT	Recommended	5	No	Yes	
BAUwoT_m20	-20 years	5	No	Yes	
BAUwoT_10	+10 years	5	No	Yes	
CCF1	No rotations	-	Yes	No	3 m^3 lower cutting limit than CCF2
CCF2	No rotations	-	Yes	No	Most commonly used version of CCF
CCF3	No rotations	-	Yes	No	3 m^3 higher cutting limit than CCF2
CCF4	No rotations	-	Yes	No	6 m^3 higher cutting limit than CCF2

2.2. Indicators

Ecosystem service indicators included a selection of ecosystem service functions (Table 3). SIMO simulated the development of forest structural features over time, and the indicators linked in through these features. Provisioning and cultural services were represented by harvested timber volume, bilberry, cowberry and marketed mushroom production (meaning *Boletus* and *Lactarius* species) and regulating services by carbon storage. The models describing these indicators have been integrated into SIMO and used in earlier studies (for example Peura et al. 2017, Eyvindson et al. 2018). In addition to providing ecosystem services, bilberry has importance at ecosystem level, since it serves as a food source to many animal species (Hedwall et al. 2013). On mineral soils carbon stored in litter, soil, deadwood and biomass (both aboveground and belowground) was included in the model (after Liski et al. 2005, Tuomi et al. 2009 & Tuomi et al. 2011). Some of the stands were on peat soils, where it wasn't possible to estimate the initial stock of carbon stored in soil. For peat soils, only the flux of carbon was used to estimate storage, using an approach detailed by Ojanen et al. (2014).

Biodiversity indicators included six vertebrate species, of which capercaillie, Siberian flying squirrel, three toed woodpecker, lesser spotted woodpecker and long-tailed tit were indicators of old and late successional forests and mature deciduous forests, which have the most urgent conservation needs (Table 3). Capercaillie was included because it is considered as an umbrella species, with higher species richness of breeding forest birds near lekking sites (Pakkala et al. 2003). These species have been used in previous studies as well, because they represent a range of habitat associations and include umbrella species and game species with cultural and economic value (Mönkkönen et al. 2014, Peura et al. 2017).

Both the amount of deadwood and deadwood-dependent species were included as indicators because deadwood is a critical resource and maintains much of the biodiversity of boreal forests (Siitonen et al. 2001). Deadwood-dependent species were selected from an earlier study conducted by Kouki & Tikkanen (2007) and consist of 98 species, mainly beetles (*Coleoptera*) and fungi from the order *Aphyllophorales*, grouped into species groups by their microclimate and resource preferences. Amount of large deciduous trees was included as an indicator because it is an important structural characteristic for biodiversity, and one that has suffered from intensive management (Nilsson et al. 2002).

The effects of the forest management regimes on the biodiversity indicator species and for the deadwood-dependent species were assessed by the habitat availability for each species under the regimes. The habitat availability was described using a calculated habitat suitability index (HSI), which was based on an equation formed from known species habitat requirements and expert opinion for each of the indicators (Mönkkönen et al. 2014). The equations used to form the HSIs have been developed and described in more detail by Mönkkönen et al. (2014). Each stand was given a habitat suitability index between 0 (unsuitable habitat) and 1 (the most suitable habitat) for each species. For deadwood-dependent species, each species was given an HSI by combining its sub-priority functions (resource and environmental requirements, and continuous availability of required habitat through time) together. The individual HSIs were then combined to form one single HSI for all deadwood-dependent species. For each indicator, the individual stand HSIs were then averaged over the landscape at every five-year interval.

Table 3: The indicators used in this study, and their brief descriptions (Kouki & Tikkanen 2007, Miina et al. 2009, Turtiainen et al. 2013, Mönkkönen et al. 2014).

Indicator	**Description**
Harvested pulp and log wood	Total volume of harvested timber (m^3ha^{-1}).
Carbon storage	Carbon stored in litter, soil and biomass (t C ha^{-1}).
Bilberry (*Vaccinium myrtillus*)	Bilberry yield (kg ha^{-1} $year^{-1}$).
Cowberry (*Vaccinium vitis-idaea*)	Lingonberry yield (kg ha^{-1} $year^{-1}$).
Marketed mushrooms	Marketed mushroom yield (kg ha^{-1} $year^{-1}$).
Capercaillie (*Tetrao urogallus*)	Game bird with social value, and an umbrella species associated with older mature forests of pine-spruce mixture.
Hazel grouse (*Tetrastes bonasia*)	Game bird with social value, indicator of adequate levels of deciduous trees.
Three-toed woodpecker (*Picoides tridactylus*)	Indicator species for mature forests with deadwood.
Lesser-spotted woodpecker (*Dendrocopos minor*)	Indicator species, old deciduous trees and standing dead trees.
Long-tailed tit (*Aegithalos caudatus)*	Indicator species, indicator of mature forests with deciduous trees.
Siberian flying squirrel (*Pteromys volans*)	Red-listed species, spruce-dominated old forests with deciduous trees.
Deadwood-associated species	A set of red-listed deadwood-associated fungi and beetle species.
Deadwood	Volume of deadwood (m^3 ha^{-1})
Large deciduous trees	Number of trees with diameter of over 40cm (ha^{-1})

2.3. Evaluation of differences among management options

The number of forest stands in some of the management regime data sets was different, because not all stands, depending on their initial development stage, were suitable to be used for all regimes in the simulation. Therefore, to avoid bias, only the stands identical in all data sets were used in the analysis. This limited the number of stands to 1408, which is 63% of the stands in the original data set.

The data from the SIMO forest simulator was analysed using RStudio (version 1.1.456), and the effect of each regime (Table 2) on each of the indicators (Table 3) was recorded. For each of the five-year intervals, the indicator values of the forest stands were averaged over the entire landscape. This allowed the effects of the management regimes to be assessed on a landscape scale rather than on stand scale. The results were presented in most cases as line charts, with the effects of all management regimes on one indicator in one figure. To make the figures easier to read, only the indicator values at three time points (50, 100 and 150) were shown, and used to draw the figures. This allows the progression of the effects of the regimes to be assessed over the entire timescale. For harvested timber, the mean yield and standard deviation under each management regime over the 150-year time period was calculated. This provided more information on the amount and constancy of the yield over time.

The effects of the regimes on the indicators were presented in most cases as relative, with normalized values, to the set aside (SA) regime with no human interventions. The normalized values represent the percentage change of the indicator value from the set aside option. The set aside regime therefore acted as a control, or a conservation option, to which the effects of all the other regimes were compared to. This approach, rather than to show the set aside as one management regime among others in the figures, was chosen to make the effects of the regimes easier to compare, both to each other and to the set aside option.

3 RESULTS

3.1. Ecosystem services

From the five ecosystem service indicators used in this study, mushrooms, cowberry and harvested timber benefited from management actions, and all management regimes resulted in higher yields than the set aside option (Figures 1, 2, 4). For bilberry, CCF regimes produced higher yields than set aside and the rest of the regimes (Figure 3). For carbon storage, the effect of all management regimes was negative compared to the set aside (Figure 5).

For marketed mushrooms, the BAU- style even-aged regimes without thinnings, and CCF1 and CCF2 produced the highest yields by the end of the 150-year timescale (Figure 1). The highest yield, almost twice the yield of set aside, was produced with BAU without thinnings and shortened rotation by 20 years. The smallest yields were produced with CCF3, CCF4, and BAU-regimes with slightly elongated rotation.

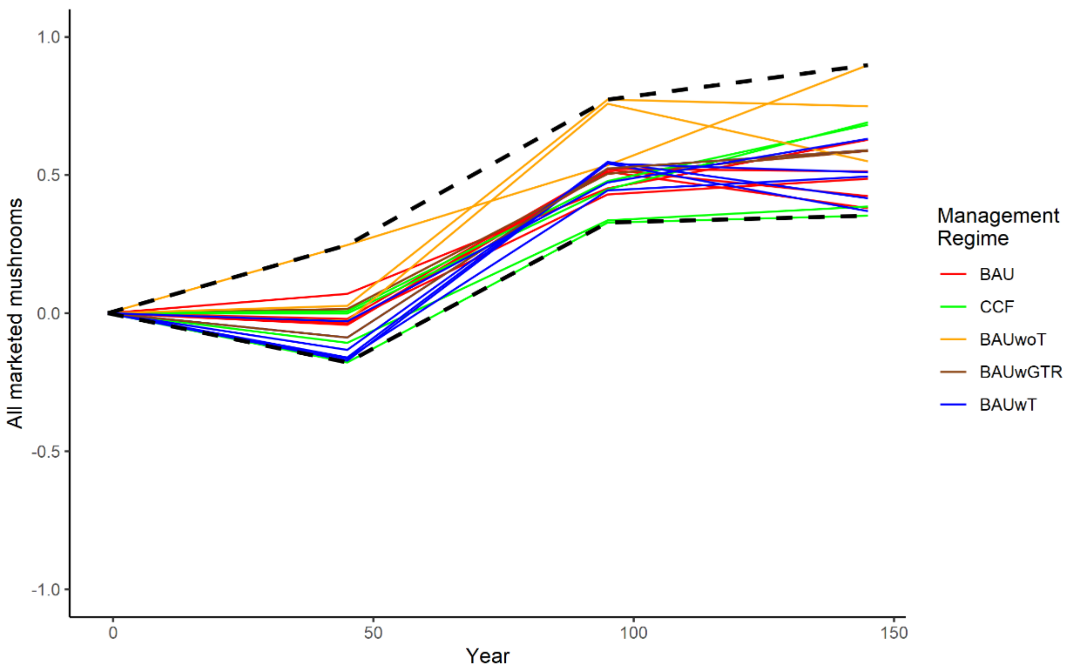

Figure 1: The effect of the management regimes on all marketed mushrooms on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150 year marks.

For cowberry almost all of the more intense management regimes with clearcutting produced the largest yields, the effect being somewhere between 50-100% larger than set aside (Figure 2). The CCF regimes produced consistently smaller cowberry yields during the 150-year timescale than other regimes. However, at the end of the timescale, both BAU-style regimes with elongated rotation by 30 years produced the smallest yields. Bilberry, on the other hand, benefited from CCF and its variations which produced the highest yields (Figure 3). Yields were about 50% higher than with set aside from year 50 onwards. The smallest bilberry yields were produced by regimes without thinning, where the effect was 50% worse than with set aside.

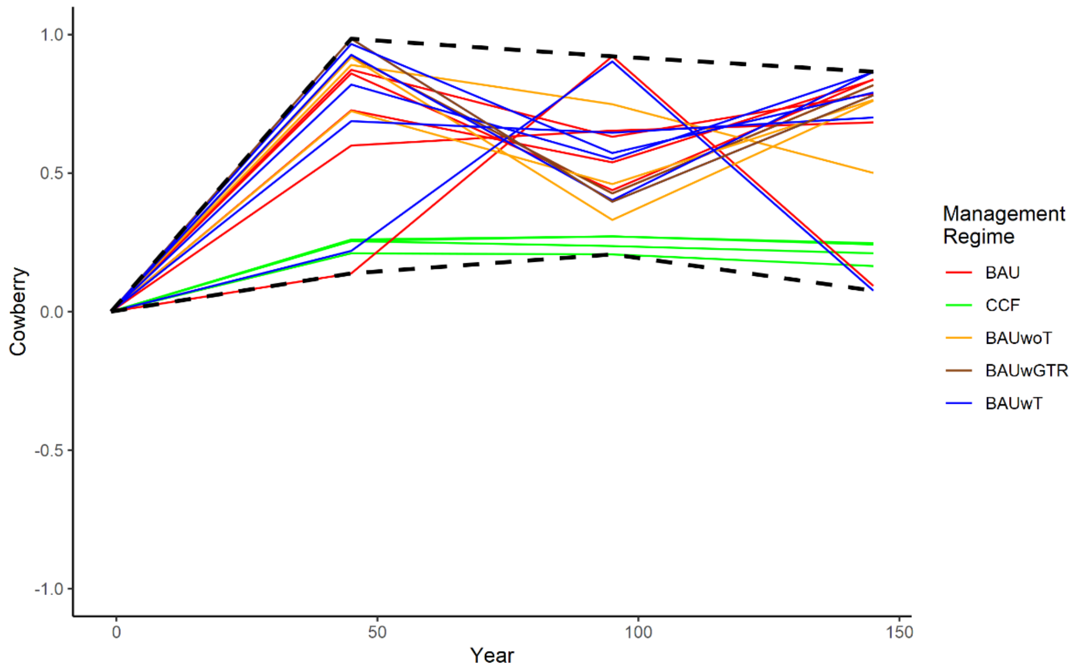

Figure 2: The effect of the management regimes on cowberry on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150 year marks.

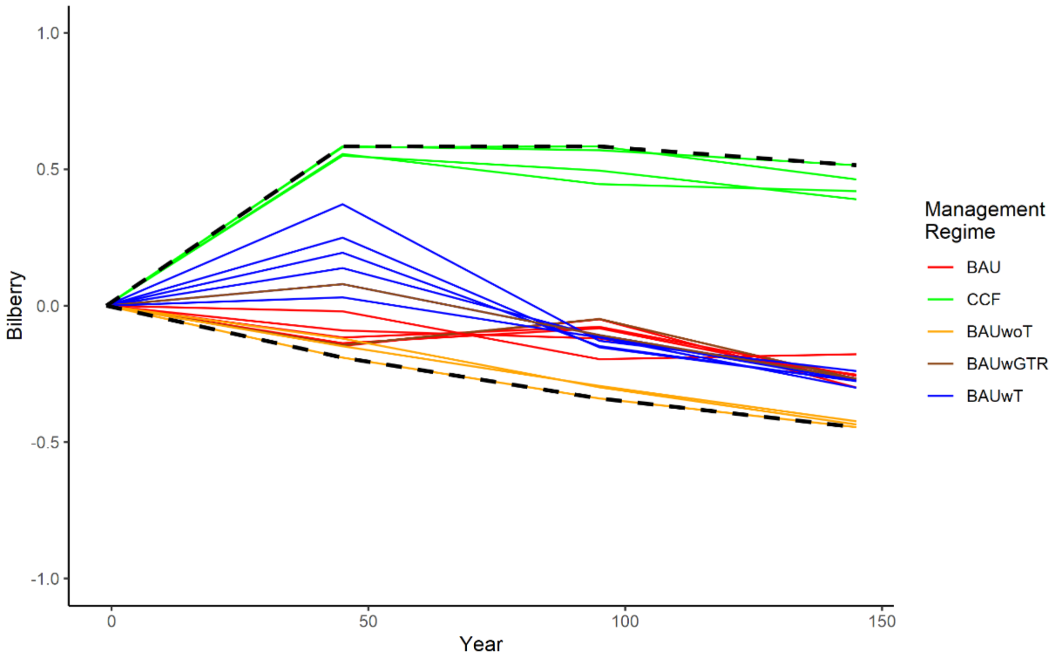

Figure 3: The effect of the management regimes on bilberry on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150 year marks.

For harvested timber (Figure 4) regimes with BAU-style even-aged rotations with reduced rotation lengths produced the highest timber yields when averaged over the entire timescale, and the most even flow of timber (Table 4). The regimes with longer rotation lengths than the recommended produced the lowest overall yields and the most uneven flow of timber.

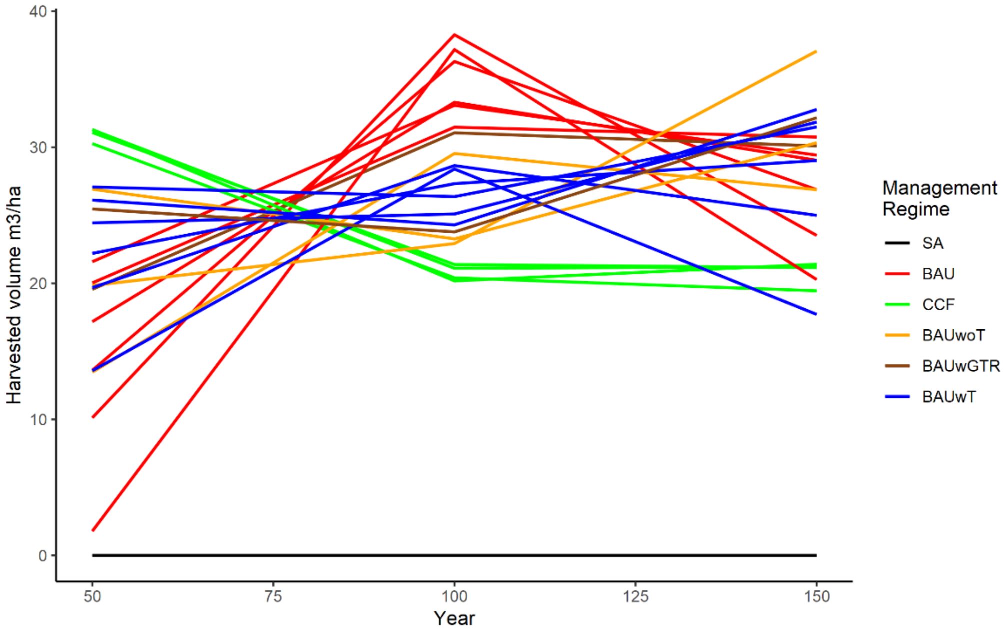

Figure 4: The amount of harvested pulp and log wood produced by the management regimes during the 150-year timescale. The amount produced with set aside (SA) remains at zero since it includes no management actions.

Table 4: Mean and standard deviation for harvested pulp and log wood as averaged over the 150-year timescale (m³/ha). The three regimes with largest and smallest values are shown with addition of continuous cover forestry, in order to highlight which regimes produced the highest and lowest yields overall.

Management regime	**Mean**	**Management regime**	**Standard deviation**
	Largest:		**Largest:**
BAUwT_m5	5.7	BAU_30	3.4
BAU_m5	5.6	BAUwoT_10	3.4
BAUwT	5.5	BAU_15	3.1
	Smallest:		**Smallest:**
BAU_30	3.9	BAUwT_m5	1.1
BAUwT_30	4.0	BAUwT_GTR	1.3
BAUwoT_10	4.7	BAUwT	1.3
CCF2	4.9	CCF2	2.8

For carbon storage (Figure 5) the CCF regimes produced the least negative indicator values, about 50% less than set aside. Other, more intense management regimes affected carbon storage more negatively, although the regimes without thinning produced larger indicator values than other BAU regimes. Carbon storage was most adversely affected by BAU regimes with recommended or slightly shortened rotation lengths, where the indicator values were close to 100% smaller than with set aside.

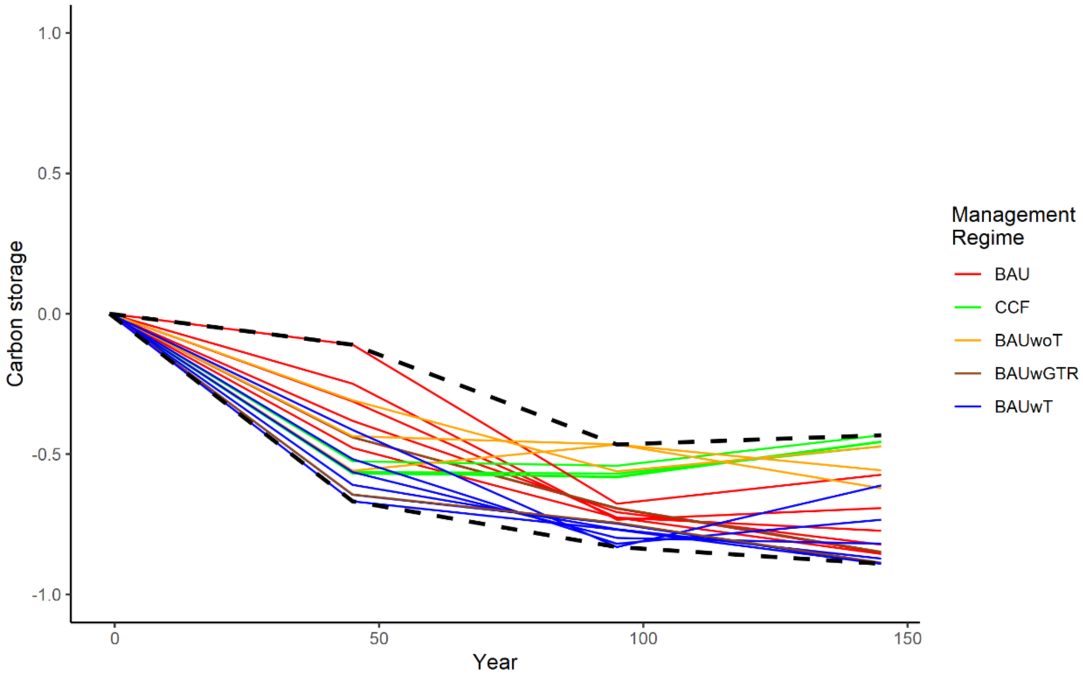

Figure 5: The effect of the management regimes on carbon storage on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150 year marks.

3.2. Biodiversity

For most of the indicators, the effects of all management regimes were negative compared to the effect of the set aside option (Figures 9, 10, 12, 13, 14, 15). The exceptions were hazel grouse, long-tailed tit, and amount of large deciduous trees, where the effect of all regimes at the end of the 150-year timescale was either at the same level with the set aside option, of better (Figures 6, 7 and 8).

For hazel grouse, long-tailed tit and large deciduous trees (Figures 6, 7 and 8) the CCF regimes were the best options, and even led to better outcomes than the set aside option. With lesser spotted woodpecker (Figure 9) and Siberian flying squirrel (Figure 10), CCF regimes produced the best outcome out of all management regimes by the end of the time period. With lesser-spotted woodpecker, the BAU with elongated rotation produced similar results than CCF, but only at the end of the time period. With the flying squirrel, CCF regimes in fact produced the lowest indicator values during the first 100 years of the simulation, and during the final 50 years the values increased. During the first 50 years, BAU regimes with elongated rotation by 30 years produced the highest indicator values out of all management regimes for the flying squirrel. There was also some variation between the four CCF options. With lesser spotted woodpecker, the effects of all four CCF regimes were similar in magnitude (Figure 9), but for long-tailed tit and Siberian flying squirrel, CCF4 with the largest basal area was the best regime (Figure 11). For large deciduous trees, CCF3 which had the second largest basal area produced the best result (Figure 11).

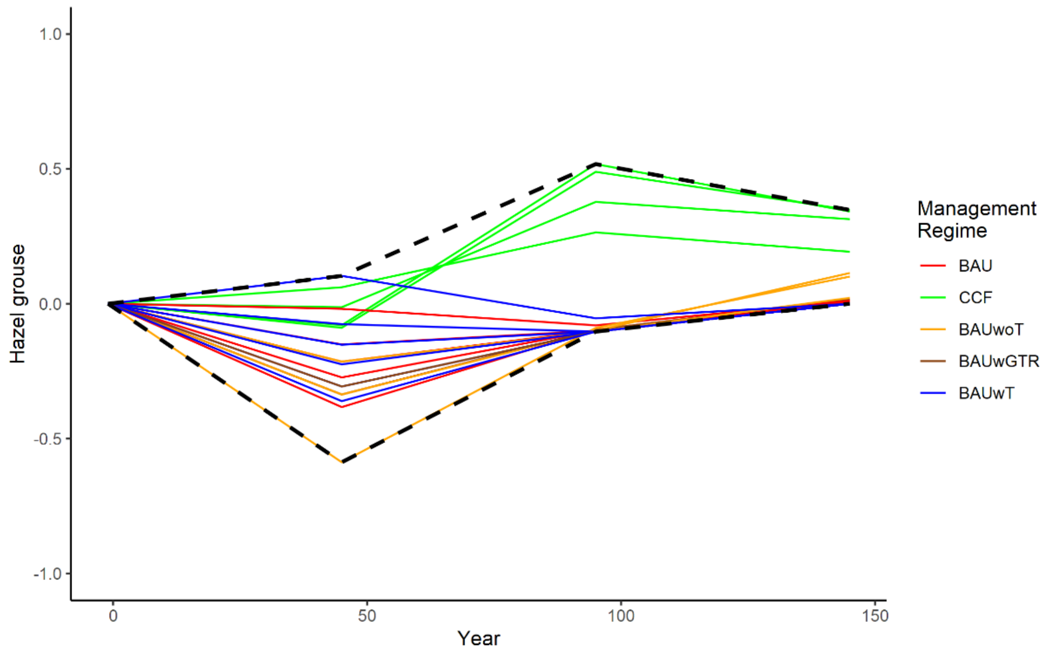

Figure 6: The effect of the management regimes on habitat availability of hazel grouse on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent

percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150 year marks.

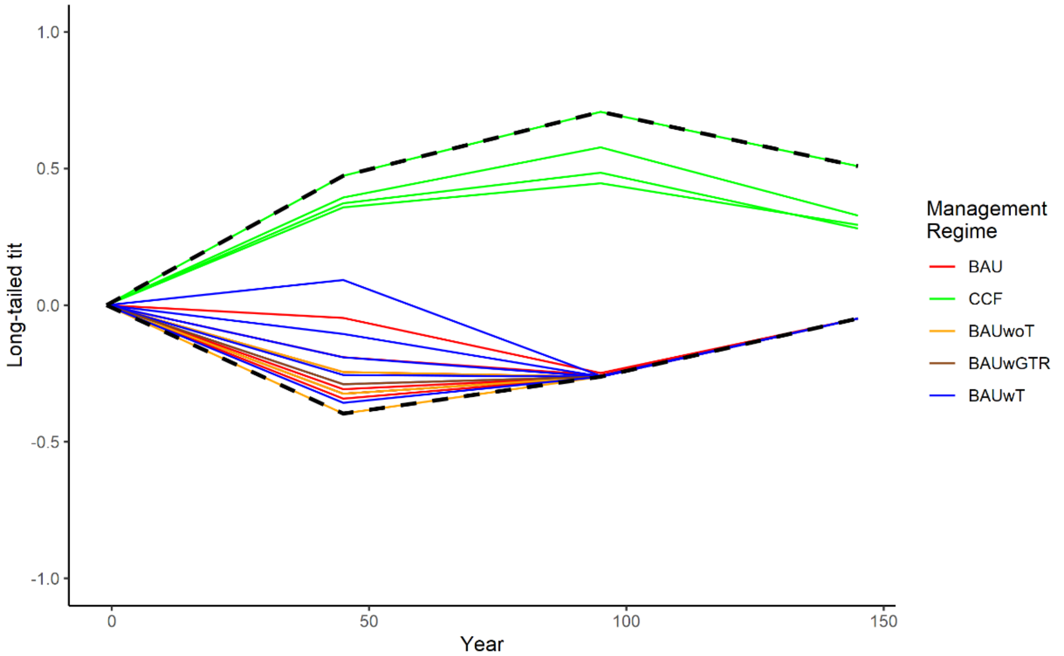

Figure 7: The effect of the management regimes on habitat availability of long-tailed tit on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150 year marks.

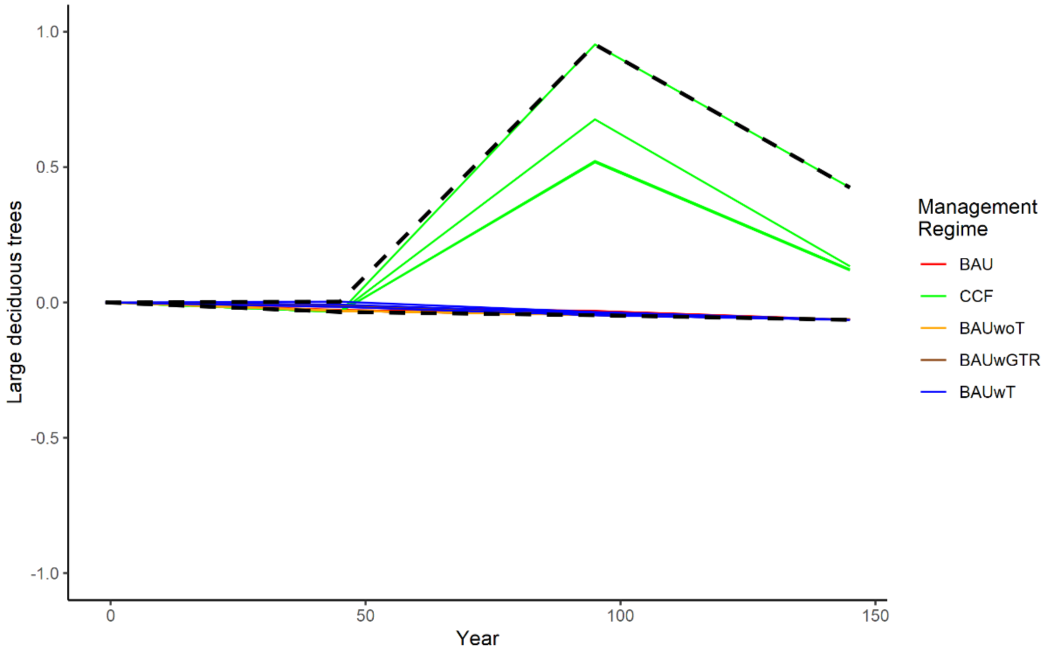

Figure 8: The effect of the management regimes on amount of large deciduous trees on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150-year marks.

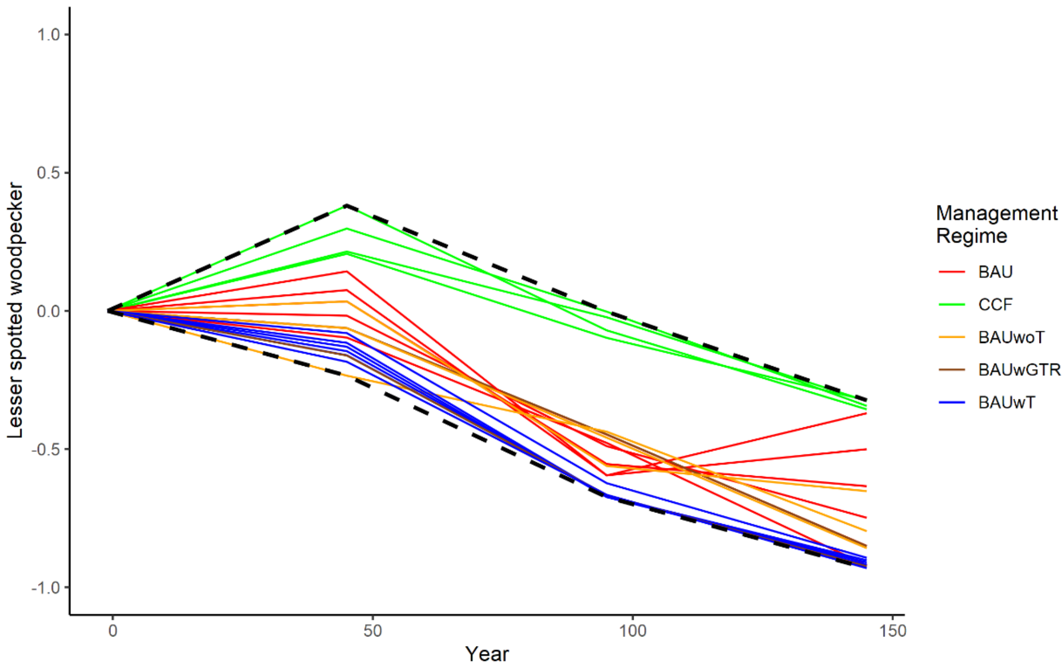

Figure 9: The effect of the management regimes on habitat availability of lesser spotted woodpecker on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150-year marks.

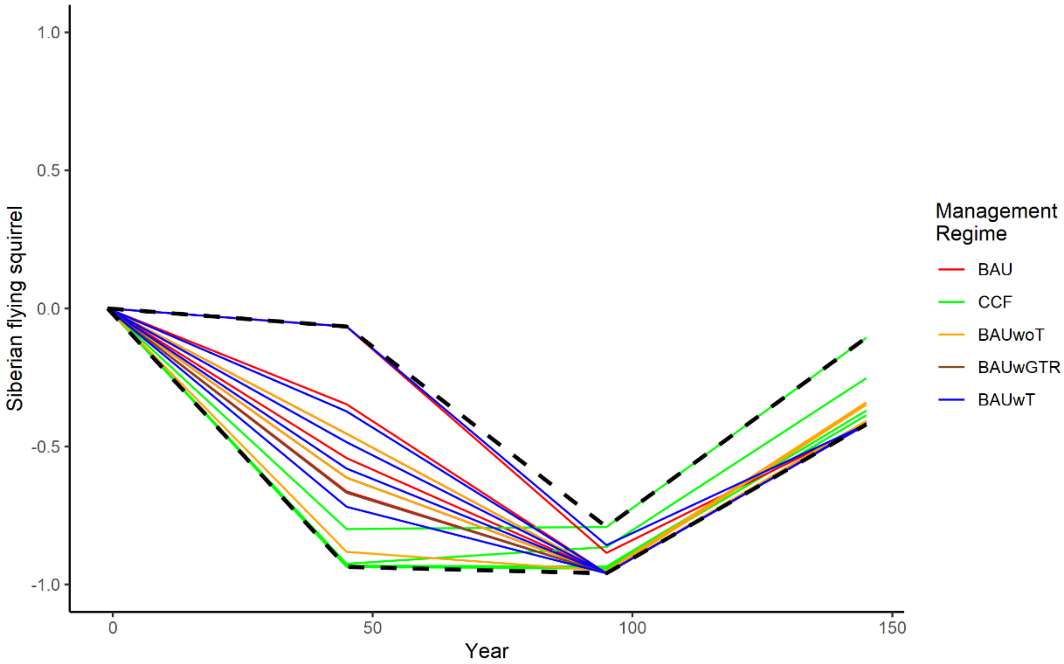

Figure 10: The effect of the management regimes on habitat availability of Siberian flying squirrel on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150-year marks.

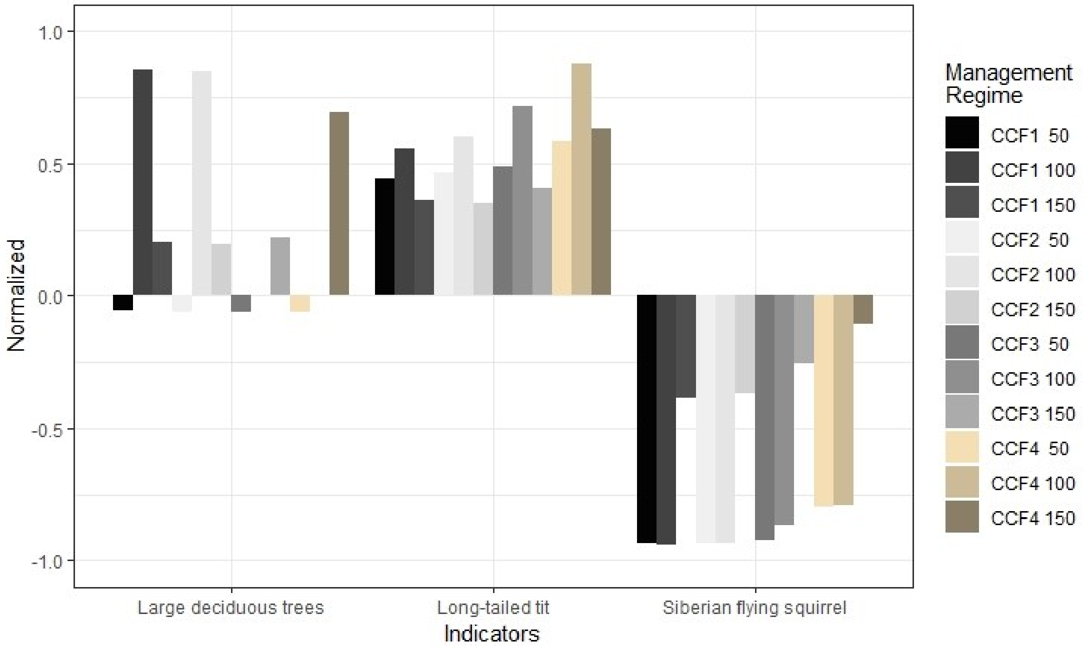

Figure 11: The effect of the four CCF variations on the amount of large deciduous trees, and habitat availabilities of long-tailed tit and Siberian flying squirrel. The values are normalized and presented as percentage change from the set aside option, with negative values indicating the regime has a more negative effect on the indicator than the set aside option would, and positive values vice versa. The values for the indicators are from years 50, 100 and 150, showing the progression of the values.

For volume of deadwood, green tree retention (30 trees/ha) produced the least negative effect out of all management regimes, but the indicator value was still over 50% smaller than with set aside (Figure 12). CCF regimes were almost at the same level with the green tree retention regimes and resulted in more deadwood than the rest of the management regimes.

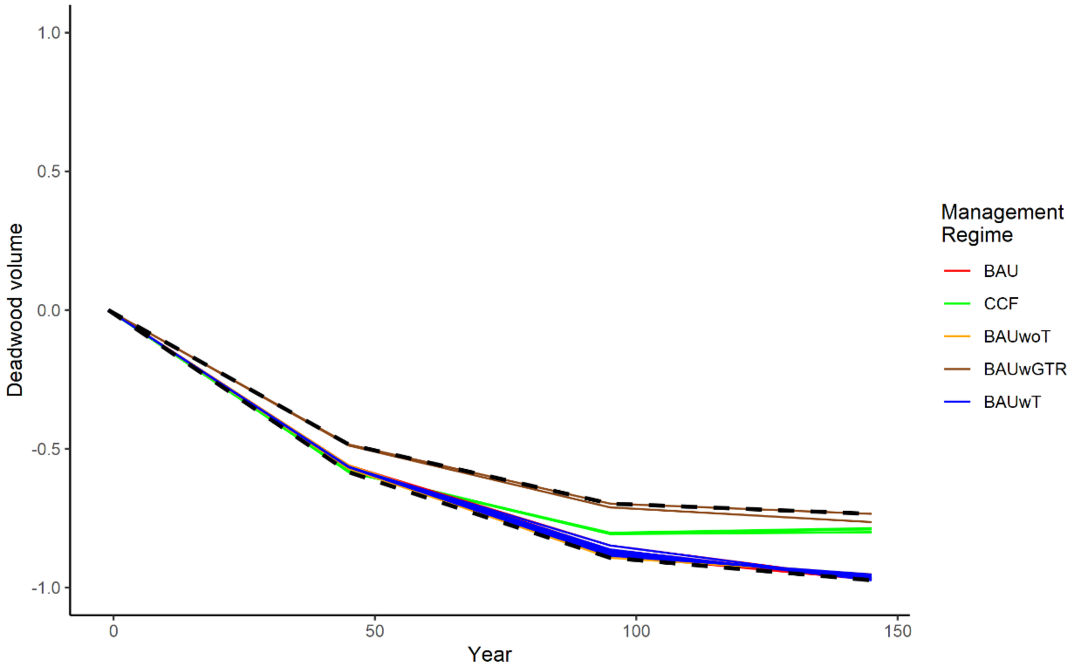

Figure 12: The effect of the management regimes on volume of deadwood on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150-year marks.

For capercaillie, three toed woodpecker, and deadwood-dependent species rotation length led to larger habitat availability than other management options (Figures 13, 14, 15). The magnitude of the effect of elongated rotation compared to the recommended BAU-style management and BAU without thinning can be seen in Figure 16. For capercaillie especially, the differences between the effects of different management regimes are very small, and even with extended rotation the indicator values were over 50% lower than with set aside. With three toed woodpecker and deadwood-dependent species, elongated rotation led to less than 25% reduction in habitat availability by the end of the 150-year time period, compared to set aside. For deadwood-dependent species, regimes without thinnings led to greater habitat availability than the rest of the regimes, and the effect of CCF regimes was also better than the effect most of the even-aged BAU regimes.

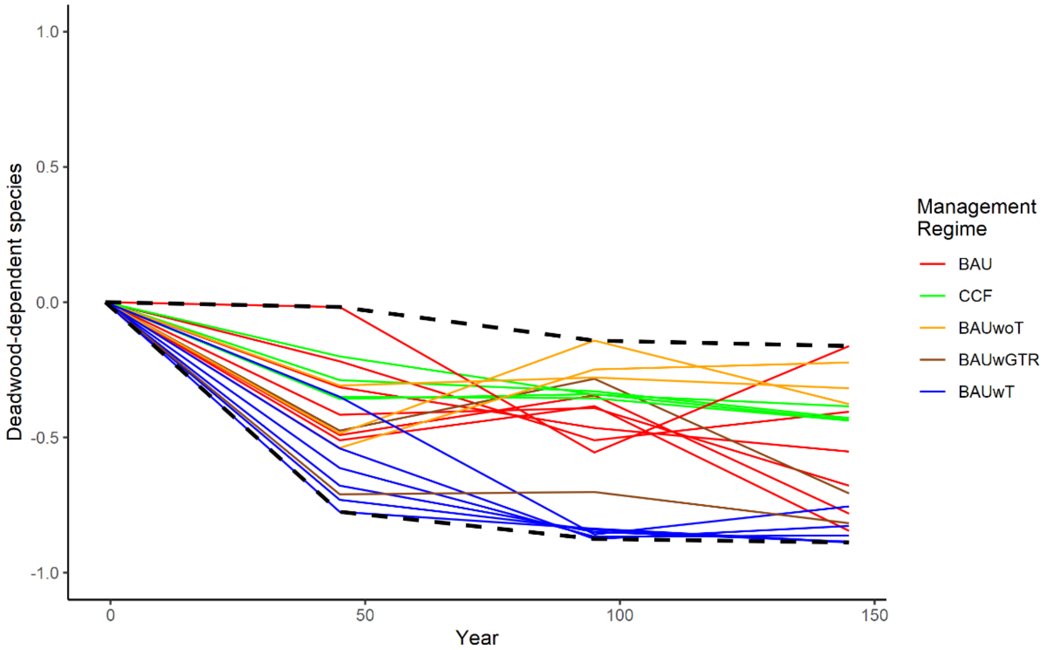

Figure 13: The effect of the management regimes on habitat availability of deadwood-dependent species on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150-year marks.

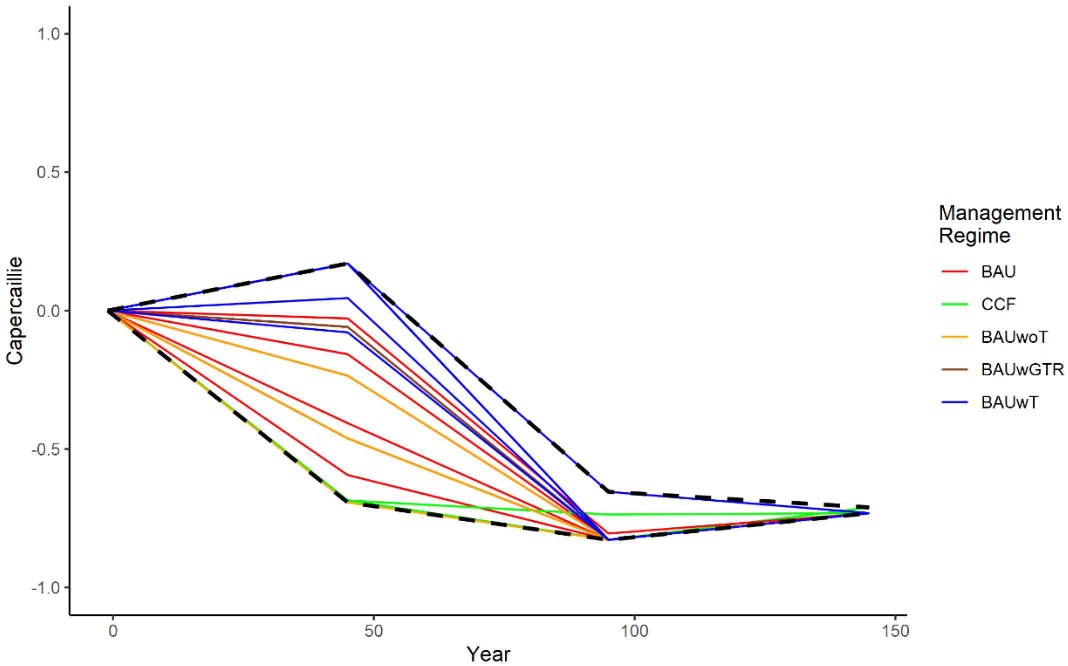

Figure 14: The effect of the management regimes on habitat availability of capercaillie on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150-year marks.

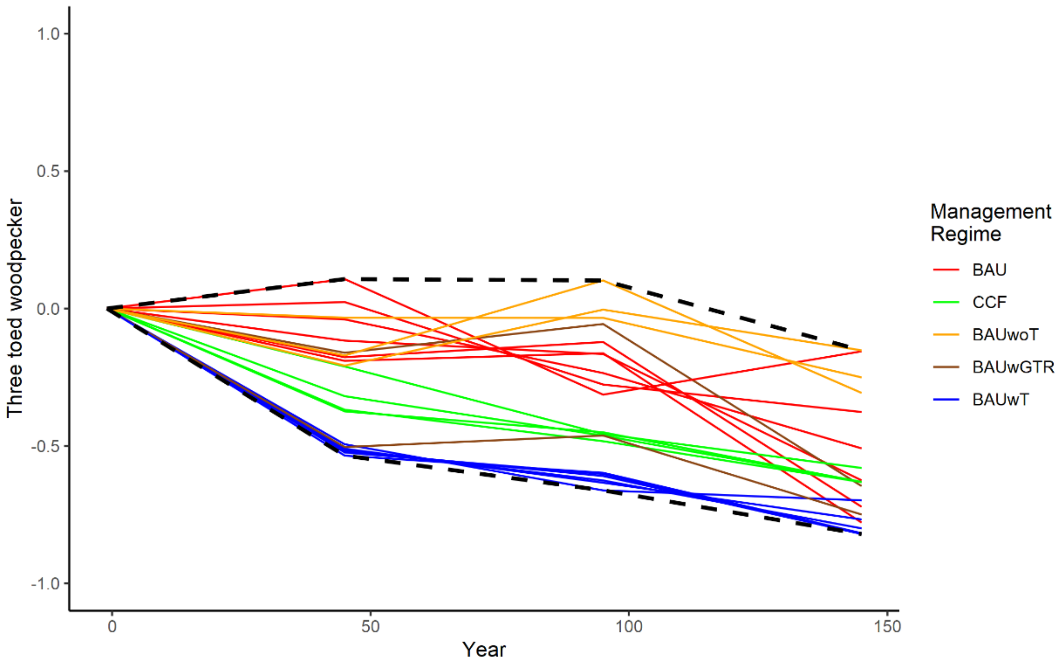

Figure 15: The effect of the management regimes on habitat availability of three toed woodpecker on a 150-year timescale, as relative to the set aside (SA) option. The indicator values represent percentage change from the SA (zero line), and negative values indicate that the regime produces a worse outcome than the SA, positive values indicate that the regime produces a better outcome. Dashed lines mark the most negative and positive values at 50, 100 and 150-year marks.

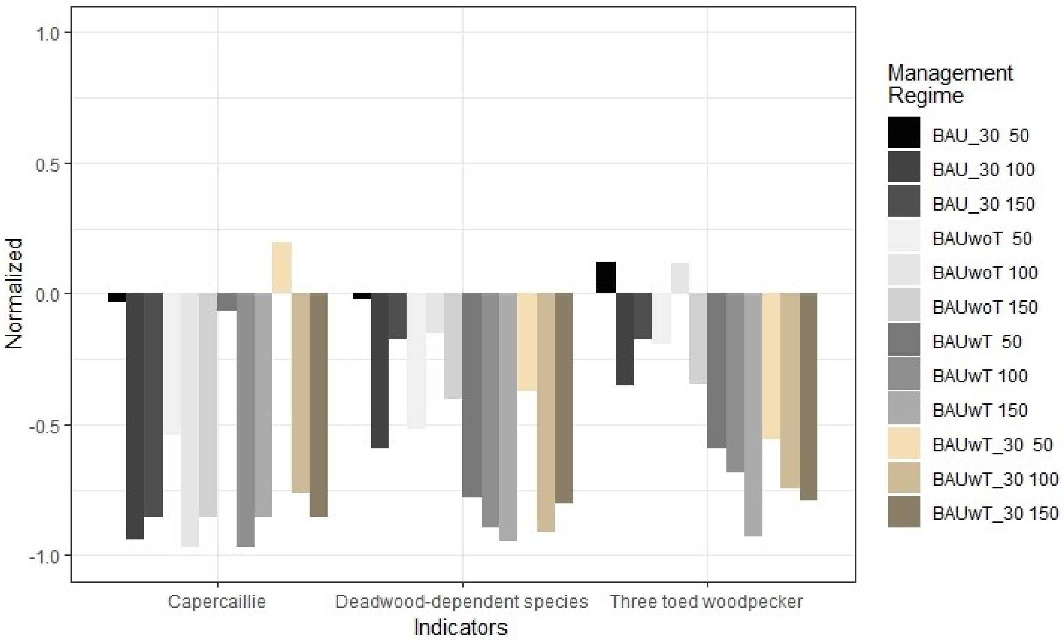

Figure 16: The effects of business as usual with thinning, business as usual with elongated rotation by 30 years and no thinning during first rotation, business as usual without thinning at any point, and business as usual with thinning and elongated rotation on habitat availabilities of capercaillie, deadwood-dependent species and three toed woodpecker. The values are normalized and presented as percentage change from the set aside option, with negative values indicating the regime has a worse effect on the indicator than the set aside option would, and positive values vice versa. The values for the indicators are from years 50, 100 and 150, showing the progression of the values.

4 DISCUSSION

This study aimed to explore the effects different management regimes have on a set of ecosystem and biodiversity indicators over a long timescale and on forested landscapes. The results revealed that the effects of different management regimes vary greatly between indicators, and it is therefore impossible to pick just one or few regimes that would suit all indicators best. Some indicators benefited from management actions when compared to a state of no human interventions, some benefited from a few of the management regimes, and for some the effect of all management actions was strongly negative.

4.1. Ecosystem services

From the ecosystem service indicators used in this study, marketed mushrooms, harvested timber and cowberry produced higher yields when the forest was subjected to management actions than with no management at all. The magnitude of the effect varied among management regimes and depending on the indicator, and at the end of the timescale the indicator values ranged from the set aside level to 100% increase compared to set aside. Bilberry yield was approximately 25 to 50% lower with the BAU-style management regimes than with the set aside option, and carbon storage was negatively affected by all management actions, with indicator values being 50 to 100% lower when compared to the set aside.

According to the results, marketed mushrooms benefited most from even-aged forestry without thinnings. This is partly supported by other studies (Tahvanainen et al. 2016), stating that the effect of thinning depends on the mushroom species, with *Boletus* species benefiting slightly and *Lactarius* species suffering from thinning, and that both species groups produced higher yields in forests younger than 35 years, just before the first thinning is recommended to occur. It has been suggested that the productivity of chanterelle also suffers from thinning (Pilz et al. 2006). From the results it is hard to tell which species groups benefit from which management the most, all marketed mushrooms were grouped together since they are all collectable.

For carbon storage, BAU-style forestry without thinning was also the best option out of the even aged rotation forestry regimes, but by the end of the 150-year timescale CCF regimes produced the best outcome out of all regimes except the set aside. In earlier studies extending the rotation length has been suggested to be an effective way to increase carbon storage (Liski et al. 2001, Triviño et al. 2015). This effect shows also in the results of this study, with even-aged forestry with elongated rotation by 30 years leading to higher carbon storage than similar regimes with shorter rotations. Thinning, on the other hand, has been showed to decrease the amount of carbon stored in vegetation but increase carbon flux from the soil (Liski et al. 2001), and growing forest stands denser has been suggested to decrease carbon emissions from the stand (Routa et al. 2011). The effect of CCF on carbon storage has been studied (e.g. Peura et al. 2017), but not on a timescale as long as 150 years. In these earlier studies the effect of CCF on carbon storage has not differed much from the effect of even-aged forestry, although carbon sequestration has been showed to be slightly higher in forests managed with CCF than with even aged rotation forestry (Peura et al. 2018). One possible explanation for the better performance of CCF on carbon storage is that in forests managed with CCF, carbon storage fluctuates less with time than in forest managed with rotation forestry (Peura et al. 2018). The superiority of the set aside option to store carbon is due to the absence of timber harvesting altogether, and the fact that old forests are considered to store more carbon than younger forests, both in soil and vegetation (Liski et al. 2001, Pregitzer & Euskirchen 2004). It should be noted that the carbon stored in soil was only estimated for stands on mineral soil. The initial carbon stored in peat soil was not estimated due to lack of precise data, and therefore carbon storage in this study could be an understatement.

Bilberry production was highest with CCF regimes, even better than with set aside, while cowberry production was higher than set aside with all management regimes, BAU-style regimes producing the highest yields. The difference between these effects arises from the differing habitat requirements of bilberry and cowberry. Cowberry requires light and isn’t very sensitive to management actions such as clearcutting and is able to recover well after disturbances (Turtiainen et al. 2013). These factors, and the fact that cowberry suffers from dense vegetation cover and the resulting diminished light at field layer help explain why the set aside option had consistently the lowest cowberry yield during the 150-year timescale. It also explains why elongated rotation by 30 years created strong fluctuations in the cowberry yield, with cowberry suffering from the dense vegetation at the end of the rotation. Bilberry, on the other hand, has been showed to suffer from BAU-style forestry, since it is sensitive to and has long recovery time from disturbances such as clearcutting (Hedwall et al. 2012). Without thinning the forest becomes too dense, decreasing bilberry yield (Peura et al. 2018), and this effect is visible in the results of this study as well. Instead, bilberry benefits from mature forest, and it has been argued that extended rotation would benefit bilberry (Miina et al. 2009). The effect of rotation length was not as strong in this study as the positive effect of CCF, which produced the highest bilberry yields, but extended rotation did produce higher yields during the first 50 years compared to similar regimes with shorter rotations. After 50 years the beneficial effect of longer rotation time diminished, and bilberry yield fell to the level of other BAU-style regimes. CCF has been showed to benefit bilberry more than BAU-style management in earlier studies as well (Pukkala et al. 2011, Pukkala et al. 2012, Peura et al. 2018), and the effect is probably due to CCF creating less severe disturbances, but keeping the forest open enough to allow sufficient light to pass to field layer.

Mean harvested volume of timber, with pulp and log wood combined, was highest over the 150-year timescale with BAU-style regimes with slightly shortened rotation times, and lowest with regimes with longer rotation times. Earlier studies have also demonstrated the same negative effect of longer rotations on harvested timber volume (Liski et al. 2001). CCF fell behind most of the rotation forestry regimes in both mean volume and evenness of timber flow, but the difference in mean volume of harvested timber between CCF2 and BAU with shortened rotation was less than 1 m^3 /ha/year. This result contradicts earlier studies claiming CCF to be better for timber harvest than business as usual-style regimes (Pukkala et al. 2012, Pukkala 2016). On the other hand, there are also studies claiming rotation forestry to be more profitable than CCF (Andreassen & Oyen 2002). However, since the prices of regeneration and thinnings were not considered in this study, and timber volume rather than net present value was used as a unit, the results of this study are not directly comparable to earlies studies such as Andreassen & Oyen (2002). These results also do not consider the fact that CCF produces more logwood than pulpwood (Peura et al. 2018), which could affect the profitability of CCF.

The results of this study indicate a conflict between timber harvesting and carbon storage and bilberry yield, since the regimes producing the highest volume of timber were among those having the most negative effect on bilberry and carbon storage. Similar results have been found in other studies (Gamfeld et al. 2013, Triviño et al. 2017), and it has been showed that maximising the simultaneous production of timber and ecosystem services would mean using other management regimes than those aimed to maximise timber production, leading to slightly lower volumes of harvested timber (Peura et al. 2016). Since cowberry and marketed mushrooms benefit from business as usual-style management, there is no significant conflict between them and timber production.

4.2. Biodiversity

Even though management regimes affected the biodiversity indicators in most cases negatively when compared to set aside, CCF regimes were the best out of all management regimes for four out of the six biodiversity indicator species, and five out of the nine biodiversity indicators. CCF produced an even better outcome than set aside for hazel grouse, long-tailed tit and large deciduous trees. In the case of lesser spotted woodpecker and Siberian flying squirrel, CCF regimes can create more habitat availability than other management regimes by better matching their habitat requirements, mainly older forest with large deciduous trees and cavity trees (Hokkanen et al. 1982, Mönkkönen et al. 2014). However, the effect is still negative compared to set aside, and CCF can only alleviate some of the negative effects of management. Hazel grouse and long-tailed tit on the other hand benefited more from CCF than set aside, probably because their habitat requirements call for a slightly younger mixed forest than flying squirrel and lesser spotted woodpecker (Mönkkönen et al. 2014). In CCF, the forest does not mature as with set aside, because the largest trees are harvested at regular intervals. Earlier findings by Peura et al. (2017), where CCF has been shown to benefit indicator species used in this study more than BAU- style management, are therefore supported by the results of this study. Out of the four CCF regimes in this study, CCF4 offered the most mature forest because the thinning limit was highest and resulted in longer period between harvests. This option was the best for flying squirrel and long-tailed tit by the end of the timescale and is an example of how different variations of the same regime can affect biodiversity.

According to the results, the amount of large deciduous trees is larger with CCF regimes than set aside, but this might be because in this study CCF regimes were applied to stands with BAU- style management history, so the stands were transitioning from BAU to CCF during the 150-year timescale. CCF usually favours mixed coniferous and deciduous forest structure (Macdonald et al. 2010), and transition from BAU to CCF often involves a change in both forest age structure and species structure (Vitková & Dhubháin 2013). Transition also requires tree removal to allow space and light for natural tree regeneration in order to achieve more heterogenous age structure. It is possible that these actions would increase the number of deciduous trees in a stand above the expected level if the forest was allowed to mature freely and uninterrupted, as with the set aside option. After the transition period, some of the large deciduous trees would be subjected to harvesting, which shows probably in the results as a decline starting 100 years after the start of the simulation.

Green tree retention is used in forestry as a conservation method, to increase the amount of deadwood and alleviate the negative effects of management for endangered or deadwood-dependent species (Kaukonen et al. 2018), and the results of this study partly support this. Green tree retention was the least negative management option for deadwood volume, but not for deadwood-dependent species. It is widely recognised that deadwood volume is lower in managed forests than in unmanaged (Siitonen 2001), hence it is not surprising that all management regimes had a negative effect on deadwood volume compared to set aside. The effect of green tree retention has been discussed in earlier studies, with no clear consensus on how well green retention trees benefit forest biota, especially red-listed species (Gustafsson et al. 2010). Some studies claim even high levels of green tree retention are not enough to conserve deadwood-dependent species communities, but wood decomposition rates could be maintained (Jacobs & Work 2012). This leads to question the effectiveness of green tree retention as a conservation measure. It should also be noted that the amount of retention trees in the green tree retention-themed regimes of this study was 30 trees/ha, and only 5 trees/ha in the rest of the even-aged forestry regimes. Five trees/ha is also the commonly used amount in forestry and recommended by Metsähallitus (Kaukonen et al. 2018), who is responsible for the management of state-own production forests and sale of timber.

For deadwood dependent species, the best management options were BAU without thinning during first rotation and with extended rotation, and all management options without any thinning. The effect at the end of the timescale was close to that of the set aside option. Refraining from thinning has been showed to be an effective way to increase habitat availability for deadwood-dependent species in earlier studies (Mönkkönen et al. 2014), and the effect is probably due to self-thinning, which generates more deadwood and therefore habitats for deadwood-dependent species than would be generated with thinning (Hynynen et al. 2005). Extended rotation in itself has also been argued to benefit some deadwood-dependent species (Ranius et al. 2016), and mature managed forests have been shown to support deadwood-dependent species assemblages similar to old-growth forests (Stenbacka et al. 2010).

In earlier research there has not been a clear consensus on how deadwood-dependent species are affected by CCF. A recent study by Hjältén et al. (2017) argues CCF to benefit some deadwood-dependent beetle species and to maintain similar species assemblages than in old-growth forests. Some studies, however, suggest harvesting intensity and frequency to affect amount of deadwood and habitat suitability for deadwood-dependent species more than the harvesting method itself (Altegrim & Sjöberg 2004). Therefore, the higher frequency of harvests in CCF compared to BAU without thinning, but lower intensity of harvesting compared to traditional BAU management might help explain why in this study CCF is better for deadwood-dependent species than most BAU regimes, but not as good as BAU regimes without thinning.

Rotation length had a positive effect for habitat availability of capercaillie, three toed woodpecker, the abovementioned deadwood-dependent species, the lesser spotted woodpecker, and to some extent Siberian flying squirrel, compared to the other management regimes. With the flying squirrel, BAU with extended rotation produced higher indicator values than other regimes for the first 50 years of the timescale, but by 100 years the positive effect had disappeared. In addition, three toed woodpecker benefited from regimes without thinning almost as much as from extended rotation and set aside. As with deadwood-dependent species, extending rotation length has been argued to benefit species dependent on mature forest and availability of deadwood (Mönkkönen et al. 2014, Roberge et al. 2018). This factor can be used to explain why three toed woodpecker, a hole nester using insects in decaying trees as a food source (Pakkala et al. 2002), would benefit from both extended rotation and refraining from thinning. Longer rotation length allows the forest to mature further, which is why species preferring mature forest, such as lesser spotted woodpecker would benefit more from management with extended rotation when compared to other BAU – style management regimes.

For capercaillie, the differences between management regimes are large at first, but at the end of the 150-year timescale the differences have become very small and the indicator values are approximately 75% lower than with set aside. Extended rotation has only a marginal benefit compared to other management regimes, except during the first 50 years of the timescale when the even-aged rotation forestry with elongated rotations increased habitat availability for capercaillie. The positive effect disappears however, when final harvests are carried out. These results indicate that none of the studied management regimes alone can alleviate the negative effect of management on habitat availability of capercaillie on a long timescale. It should be noted though that the habitat availability was calculated using characteristics of capercaillie lekking sites only, since they have been shown to have a higher overall species richness of breeding forest birds (Pakkala et al. 2003). Capercaillie can inhabit both younger and older forest (Miettinen 2009), meaning only the lekking sites are considered in these results, not the overall habitat availability.

The results of this study show that management regimes benefiting biodiversity best differ between indicators, but the regimes aren't those providing the largest amount of harvested wood. This indicates a similar conflict between timber harvest and biodiversity conservation as with between timber production and some ecosystem services discussed earlier. The more conservation-minded regimes such as business as usual with extended rotation in fact produce the lowest and most uneven amount of timber over the 150-year timescale, while the BAU regimes with recommended or shortened rotation produce the largest timber yields. This study does not look further into these conflicts, but they have been recognised and studied earlier, with the general result that maximising timber harvesting has a negative effect for biodiversity, and vice versa (Mönkkönen et al. 2014, Triviño et al. 2017). However, with moderate reduction of timber yields, it is possible to achieve high levels of both biodiversity and timber, and also ecosystem services. This would call for careful landscape-level planning and a method called optimization, which aims to form an optimal combination of different management regimes to be used (Mönkkönen et al. 2014). However, these studies have used a much shorter timescale, which could affect the results. There is also a need for an optimization study where CCF is included as one of the management regimes.

4.3. Implications for forest management and uncertainties

The main message these results have for forest management would be that there is a need for a more diverse set of management regimes than merely BAU, in order to maintain both ecosystem services and biodiversity, and simultaneously harvest timber. It has also become clear that the most common forest management, BAU – style forestry, is only optimal if maximising timber harvesting is the goal. Instead, most ecosystem services and all the biodiversity indicators used in this study benefited more from other, less intensive, management regimes, most often some variation of CCF, or BAU without thinning, or extended rotation. Especially the increase in the use of CCF would be recommended, since it had beneficial effects on larger proportion of indicators than any other management regime, apart from set aside. But often even these less intensive regimes were not enough to fully alleviate the negative effects management has on various indicators, which highlights that conservation areas are also needed to preserve and maintain habitats for the more demanding species. If the goal is to preserve ecosystem services and biodiversity in managed forests there are multiple management options for doing this, but it would require careful planning since the indicators differ in their responses to different management regimes. For some indicators, for example Siberian flying squirrel, there are even multiple options along the timescale for providing habitat availability. This highlights the importance of the timescale used to assess the effects. If forestry actions were planned only for the next 50 years, even-aged rotation forestry with extended rotation would be recommended, but from years 50 to 100 management-free areas would be required to provide habitats for flying squirrel, and by the end of the timescale CCF4 with the most delayed harvests would be recommended. Lastly, it is worth noting that in this study the entire landscape was managed with one regime at a time. In reality this might not be the case.

The results also raise a question regarding the effectiveness of green tree retention. Even with the higher amount of retention trees used in this study did not benefit deadwood-dependent species and had only a minor effect on deadwood volume. Since the amount of retention trees in forestry is much often lower than what was suggested in this study, it might not be a sufficient method to produce deadwood or preserve habitats for deadwood-dependent species. However, the simulation used in this study did not assume retention trees to be the same tree individuals in subsequent harvests, which could affect the results and underestimate the effect of green tree retention. If retention trees would be kept as retention trees during multiple rotations, they could potentially have greater positive effect on both deadwood volume and habitat availability for deadwood-dependent species, since living retention trees may take longer than one rotation to die naturally and become deadwood.

The simulation approach used in this study has some sources of uncertainties and limitations. For one, the simulations didn't consider the possibility of natural disturbances and chance events such as storms, diseases and pests, and the effect they would have on growth and mortality of trees. Natural disturbances add heterogeneity to forest landscape, and are important for biodiversity (Kuuluvainen 2002), which is why the results might underestimate some biodiversity values, especially deadwood-related. The effect of climate change has also been excluded from the simulations since it is difficult to predict exactly and incorporate to the simulation. Climate change would probably increase forest growth and affect tree species composition in Finland due to changing temperature and precipitation when estimated 150 years into the future (Kellomäki et al. 2008). Climate change would also increase the frequency and intensity of storms (Dale et al. 2001), and would enhance the decomposition rate, and thus affect the carbon balance of boreal forests (Allison & Treseder 2011). The exclusion of the effects of natural disturbances and climate change might have affected the comparability of the results, because for example CCF has been argued to increase resistance against storm damage and even insect pests (Klapwijk et al. 2016, Pukkala et al. 2016). This might even increase the harvested timber volume when compared to BAU, and therefore make CCF more profitable.

It should also be noted that in the simulations the CCF regimes were applied to forest stands previously managed with BAU-style forestry, and were therefore transitioning from BAU to CCF, which can possibly have some consequences on the results, such as large deciduous trees discussed earlier. Also, the set aside, to which all management regimes were compared to, represented an option where managed forest is turned into a conservation area, rather than an already existing conservation area because all set aside stands had been managed as production forests before. This means that the management regimes were not compared against a natural-state forest, but against an option where managed forest is left unmanaged.

4.4. Conclusions

This study demonstrated that there is a great deal of variation in the effects of different management regimes on different indicators at landscape scale. It also demonstrated that conserving ecosystem services and biodiversity cannot be achieved by applying only one regime but requires careful planning and the use of many management regimes. This study also supports earlier results and suggests that BAU–style forestry, although producing a high timber yield compared to other management regimes, is not the optimal regime for biodiversity, or ecosystem services apart from cowberry and marketed mushrooms. Instead, less intensive regimes and actions such as CCF, refraining from thinning and extended rotation length are often better for biodiversity on a long timescale, since they offer more habitats for deadwood-dependent species and species requiring mature forest structure and continuous forest cover. Quite often, however, the negative effects of management cannot be fully alleviated with any regime, highlighting the need for conservation areas to maintain habitats for the most demanding species. These results therefore indicate that maximising timber production has a negative effect for biodiversity and for some ecosystem services, and the use of more conservation-minded regimes results in slightly lower timber yield, which is in line with earlier studies. These results also question the effectiveness of green tree retention as an adequate method to increase the amount of deadwood and provide habitats for deadwood-dependent species.

In the light of Finland's increased harvest targets, these results provide important information on how to simultaneously harvest timber and minimize harm to biodiversity and ecosystem services on a long timescale, as well as point out the conflict between timber harvest and biodiversity. These results could be applied to forest management to promote the use of less intensive management methods. There are also opportunities for further studies, for example on how to optimize biodiversity and ecosystem services values and the production of timber, in the light of these results. Including climate change and natural disturbances in the simulation model would also provide important information on how the effects of climate change affect the results.

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