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Dead wood creation to compensate for habitat loss from intensive forestry

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Abstract

Negative consequences of human activities for biodiversity may be mitigated by compensation measures. Although the interest in applying compensation measures is generally increasing, such measures have rarely been applied in forestry. Many boreal forests are managed by clear felling and used for timber and pulp production. There is an increasing interest in intensifying forestry by also harvesting slash and stumps for biofuel at felling. We evaluated the efficiency of combining intensified forestry production with compensation measures, by estimating the net revenue from slash and stump harvest, the cost of high stump creation, and simulating habitat amount for 680 bark- and wood-living species (fungi, beetles, lichens, and bryophytes) in Norway spruce forests in Sweden under different scenarios of biofuel harvest and compensation. We show that the harvest of slash and stumps has a clear negative effect on the habitat amount available for many species, especially for many fungi and beetles. Combining slash harvesting with the creation of high stumps results in an economic surplus and at the same time provides significantly more habitat in comparison with no slash harvesting and no high stump creation. When undertaking stump harvesting it is currently impossible to achieve such positive effects. Thus, our analyses show that compensation can sometimes be a useful tool when both economic and biodiversity goals must be achieved in forestry, but in other cases it is a better alternative to avoid the activity that causes the negative effects.

1. Introduction

Projects related to economic development often have negative consequences for biodiversity (Czech, 2008). In several countries, governmental policy states that such negative consequences should be minimised if possible, and residual effects should be mitigated by compensation measures (McKenney and Kiesecker, 2010). Employing compensation measures may be a way to balance the interests of economic development and biodiversity conservation (Fig. 1). A compensation measure mitigates the negative effects of a human activity on biodiversity by generating ecologically equivalent gains, and the measure is something different from just conducting the activity in a different way or to a lower extent. Compensation measures have rarely been applied in forestry.

Recently, there has been an increasing interest in producing energy from forest biomass, because of the lower carbon dioxide emissions from long-term stored carbon in comparison with many other energy sources (Lattimore et al., 2009). This provides new opportunities for income from forestry. However, harvesting more wood for bioenergy production may have severe environmental consequences, including loss of forest biodiversity (Berger et al., 2013) and function (Schulze et al., 2012). Species confined to dead wood are more directly suffering from forest fuel harvest than any other species (Bouget et al., 2012). It has been estimated that in the boreal zone of Europe, species dependent on dead wood constitute 20-25 % of all forest-dwelling species (Siitonen, 2001). In Europe, where many previously forested regions are today strongly affected by habitat loss and degradation, many species dependent on dead wood are threatened (Nieto & Alexander 2010). However, even in areas with much more intact forest ecosystems (such as Tasmania), there are concerns that fuelwood harvesting may have significant negative effects on threatened saproxylic species (Grove & Meggs 2003). In managed forest landscapes, dead wood dependent species are threatened mainly due to the much smaller amounts of dead wood in managed forests compared to natural conditions (Siitonen, 2001). It may be possible to mitigate the negative effects of forest fuel harvest on biodiversity by the creation of dead wood of high quality for species of conservation concern. Such mitigation measures could include the creation of high stumps (i.e. leaving a 3-5 m high stump of some stems at felling), which is a commonly applied method to increase the amount of dead wood habitat (Jonsson et al., 2006).

Environmental management decisions should be based on information about both the costs (e.g. biodiversity loss) and benefits (e.g. economic surplus) of different management regimes. Many studies consider the effect of forest fuel harvesting; however, so far economics (e.g. Kallio et al., 2011) and biodiversity aspects (e.g. Bouget et al., 2012) have usually been treated separately. However, recently Miettinen et al. (2013) have considered the effect of whole-tree harvesting with stump removal on several ecosystem services including biodiversity conservation, but biodiversity was not included in their numerical analysis. Some analyses consider the cost-efficiency of efforts that could be employed as compensation efforts (e.g. Jonsson et al., 2006), however, they do not include analyses of activities that they may be aimed to compensate for. Thus, the effectiveness of combining intensified forestry production with compensation has to our knowledge never been analysed.

Our objective was to evaluate the effectiveness of combining intensified forestry production with artificial creation of dead wood (high stumps) as a compensation measure to mitigate the negative effects of slash and stump harvest. More specifically, we addressed two questions: (*i*) Is it possible to mitigate biodiversity loss by using some of the revenues from the forest fuel harvest to pay for compensation? This was analysed by predicting to what extent harvested fuel-wood and dead wood created as compensation host the same species. (*ii*) How profitable is forest fuel harvesting if combined with compensation that aims at balancing the negative effects of the harvest? This was analysed by predicting economic surplus and amount of habitat given different management scenarios. The analyses included major groups of wood- and bark-inhabiting species in three Swedish regions with varying forest productivity and species pools. We considered harvesting slash and stumps at felling, since these are the two dominant types of biomass harvest for energy production in Fennoscandian forestry.

2. Methods

2.1 Forestry system

By comparing stands in three Swedish regions – northern (Västerbotten county), central (Gävleborg county) and southern (Kronoberg county) Sweden – we examined the outcome given different productivities (mainly due to the warmer climate in the south), and different species pools (Jonsson et al., 2006). The modelled stands were assigned characteristics similar to the average in each study region (Table 1). Forest management was adapted to optimise the economic outcome in terms of present value, as in Ranius et al. (2005). The stands were monocultures of Norway spruce (*Picea abies* (L.) Karst.) in the dominant management system in

Sweden, including felling followed by plantation, and with between two and four thinnings during a rotation. Norway spruce is one of two dominant species in Fennoscandian boreal forests.

2.2 Simulation scenarios

We ran the simulation under one scenario without forest fuel harvesting, five scenarios with slash harvesting combined with varying levels of compensation (0%, 25%, 50%, 75%, and 100% of the net revenues from slash harvesting spent on compensation), and five scenarios with both slash and stump harvesting also combined with these levels of compensation (Table 2). Slash harvesting involves tops and branches from cut trees being harvested after felling, but other types of dead wood on the ground are also extracted (Rudolphi and Gustafsson, 2005). Based on interpretation of field data (Rudolphi and Gustafsson, 2005), we assumed that 70% of all dead wood with a diameter < 10 cm is harvested at slash harvest, and 35% of dead wood with a larger diameter. Stump harvesting involves low stumps, including larger roots, being harvested after felling. In all our scenarios including stump harvest, 80% of the stumps were removed. We assumed that the stand development and management regime was the same before the simulated rotation period.

2.3 Stand development and dead wood dynamics

The simulation includes models of forest development, tree mortality, dead wood decomposition, and effects of forestry operations. Forest growth was predicted by using a growth model applied in 'The Stand Method', which is a flexible growth model developed by the National Land Survey of Sweden, to use for forest valuation (Anonymous, 1988). We predicted the amount of dead wood by simulating the dynamics of dead wood (including wood in roots, stems, and branches) over a rotation period.

The volume of roots >2 mm in diameter, branches, stumps and tops of trees was calculated using functions for Norway spruce and information on stem volume (Marklund, 1988; Pettersson and Ståhl, 2006). We estimated the surface area of stems and branches using the following equation (all measurements in metres, square or cubic metres):

$$\text{Area} = 6 \times \text{Volume} / \text{Diameter} \qquad \text{Eq. (1)}$$

This was derived from the functions for the surface area and volume of a cone. The stumps were assumed to be approximately cylindrical, i.e.

$$\text{Area} = 4 \times \text{Volume} / \text{Diameter} \qquad \text{Eq. (2)}$$

We assumed that when the wood was crushed during soil scarification after felling, the volume remained constant, while the area was doubled. Trees with dbh < 10 cm were assumed only to have roots with a diameter < 5 cm. For larger trees, we assumed that 85% of the root volume was < 5 cm, 10% was 5–10 cm and 5% was 10–30 cm.

For standing dead wood, we assumed that organisms can use the entire surface area, but only 50% of the surface of downed dead wood is available for use because the remaining 50% is covered by soil and the surrounding vegetation. The entire volume of both standing and downed dead wood could be used.

In the model, dead wood was generated in three ways: (1) trees die naturally, thus creating entire dead trees; (2) branches of living trees die; and (3) branches, tops, stumps and roots are left after thinning operations and felling, and after non-commercial thinnings stems are also left. We assumed the same tree mortality as Ranius et al. (2003), based on field data from the Swedish National Forest Inventory. Like Ågren (1983), we assumed that 2% of the branches die every year.

Based on several field studies, the average time period for which a stem with dbh > 5 cm remains as dead wood in central Sweden was assumed to be 70 years (Ranius et al., 2005). Over the residence time, the dead wood item moves from one decay class to another (definitions of decay classes: Appendix A) as in Dahlberg et al. (2011). We assumed that dead wood with a diameter < 5 cm, on average, has a residence time 50% shorter than that of larger dead wood. This implies a decomposition rate in between the higher rate observed by Caruso et al. (2008) and the lower rate observed by Hyvönen et al. (2000). The residence time of roots and low stumps was assumed to be 50% shorter than that of other types of dead wood (Dahlberg et al., 2011), because decomposition is faster when dead wood is in contact with the ground. Like Ranius et al. (2005), we assumed a longer residence time in the north and a shorter in the south, due to the different temperatures. Similar regional differences have also been observed by Shorohova et al. (2012). Based on field experience, we assumed that the volume of a dead stem is equal to that of the living stem (i.e. 100%) when the wood is in the first two decay stages, that it is 80% when the wood belongs to class 3, and 60% in decay class 4. The assumed proportions of the wood surface covered with bark were average values from an inventory of dead wood produced for central Sweden, as in Dahlberg et al. (2011).

Dead wood may disappear, for instance because it is removed to minimise the risk of bark beetle outbreaks or during small-scale forest fuel harvest. However, this was not assumed in our simulations, which implies that the outcome reflects the potential amount of dead wood, but the real amount may be lower.

Of the dying trees, we assumed that 60% died standing, while 40% were wind-thrown (Dahlberg et al., 2011). Based on Storaunet and Rolstad (2002), we assumed that the average period a snag remains standing is 22 years. Artificially created high stumps have a longer durability than full-sized snags, and we assumed that they fall after 32 years.

We assumed that dead branches remain on living trees for four years, and then fall to the ground. The predicted volume of dead branches on living trees in our model corresponds to 8% of the volume of living branches, which is consistent with Marklund (unpubl.). The proportion of logs in different light regime classes differs between standing and downed wood, and between stand age classes, according to Dahlberg et al. (2011).

Based on a field study (Hautala et al., 2004), we assumed that 58% of the younger dead wood and 88% of the older dead wood left after felling is broken into smaller pieces during soil scarification. For younger low stumps and their roots, we assumed that 29% were broken into pieces, and for older stumps 88%. We assumed that 50% of the fragmented dead wood has a diameter < 5 cm and the other 50% a diameter of 5–10 cm, and that all bark is lost.

2.4 Prediction of the amount of habitat

The amount of habitat was estimated individually for all 680 Swedish wood- and bark-inhabiting species of beetles, fungi, lichens, liverworts, and mosses that use Norway spruce as their primary substrate. The substrate associations of each species were described using 3–5 categories of each of the following substrate variables: microhabitat type, position, diameter, decay stage and degree of sun exposure (Appendix A). Each category was assigned one of three classes: (0) not or very rarely used by the species; (1) secondary substrate, i.e., used up to 1/5 as often as the primary substrate; (2) primary substrate, i.e., hosting a population density at least five times larger than any of the secondary substrates. These values were used as weightings when we estimated the total amount of substrate available to the individual species, so that a score of “2” for a particular category implies that the amount of dead wood was worth 5 times more than a score of "1". Thus, a substrate type where all five variables were allocated a score of "2" obtained a 5^5 times greater weighting than a substrate type where all variables were classified as "1". We used volume as the measure of the amount of habitat for species that use the inner parts of the wood (beetles mainly living in the wood and fungi) and surface area for species living or the surface or under the bark (beetles mainly living under bark, lichens and mosses).

The habitat associations of species were described based on field experience of species experts (beetles: Mats Jonsell, fungi: Johan Allmér, lichens: Göran Thor, mosses and liverworts: Tomas Hallingbäck) and literature (beetles: Palm, 1959; Hansen 1964; Koch, 1989–1992; Ehnström and Axelsson, 2002; Jonsell, 2008; Jonsell and Hansson, 2011, fungi: Eriksson et al., 1973–1984; Ryvarden and Gilbertson, 1993–94; Olofsson, 1996; fact-sheets of red-listed species at www.artdata.se, lichens: Foucard, 2001; Santesson et al., 2004). We estimated the mean amount of habitat over the entire rotation, which corresponds to the amount of habitat in a normal forest, i.e. a hypothetical landscape where all stands have the same characteristics and are subjected to the same management regime, and the age distribution among stands is even. We modelled the characteristics and fates of individual trees following Ranius et al. (2005), as described in 2.3. In an earlier study, the outcome from this simulation model has been validated; when assuming that recently dead trees are removed after storm fellings, this model predicts an amount of coarse dead wood (diameter > 10 cm) close to that observed in managed forests in Sweden (Ranius et al., 2003). To compare the overall outcome of each scenario, we calculated a substrate index, *B*, by summarising the effect on every species. The substrate index was calculated using the following equation:

$$B = \sum_{i=1}^{n} log\left(\frac{S_i}{C_i}\right) \qquad \text{Eq (3)}$$

where *n* is the total number of species, S is the amount of substrate given a scenario, and C is the amount of substrate given the null scenario (i.e., with no harvest of fuel-wood and no compensation). This index reflects the change in substrate availability for all species, and a certain percentage of decrease or increase is given the same weight independent on how much substrate that originally was available for the species. The index *B* becomes positive if the amount of dead wood increases, and given an increase of a certain dead wood volume, *B* becomes higher if the dead wood added are of types used by many species, if the dead wood are of many types rather than just a few, and if they are of rare types rather than common. Field studies in boreal forests support that species richness of saproxylic species increases with the amount and diversity of dead wood (Martikainen et al., 2000; Penttilä et al., 2004), and that the probability of occurrence per stand of individual species increases with the amount of dead wood of the specific type that is used by the species (Sahlin and Schroeder, 2010).

2.5 Economic calculations

We calculated the economic surplus for each scenario by subtracting the costs of compensation (estimated by multiplying the volume of lost wood by the timber price per volume) from net revenues of forest fuel harvest (estimated from energy gained multiplied by the price of wood chips delivered to power plants per energy unit minus production costs).

We calculated the production costs of slash and stump harvesting using freely available models developed by the Finnish Forest Research Institute (Ranta, 2002; Laitila et al., 2008). The slash and stump models include several possible production chains and we selected the production chain with the highest net revenue as the practice applied in our study. The unit production costs of stump harvesting are about 3 €/MWh higher than of slash harvesting (Appendix B). The higher costs of stump harvest are due, in particular, to extra costs associated with stump extraction and handling compared with slash harvest. The unit costs of stump extraction and handling varied in this study between 2.4 and 3.0 €/MWh. Slash harvesting results in only marginal extra costs at the time of logging due to piling (Laitila et al., 2010). The forest stands had characteristics listed in Table 1. Other parameter values used in the models were based on Laitila et al. (2010), which are close to the averages for managed forests.

In Finland, the average price for forest chips delivered to power plants has been 17.20 €/MWh (Min.: 14.00; Max.: 19.70 €/MWh) in recent years (from January 2008 to June 2011; Anonymous 2011a). In Sweden, the price for delivered wood chips (from slash harvest) has varied between 14.60 and 21.60 €/MWh in the years 2008-2011 (Anonymous, 2012). An alternative to using price lists is to estimate the marginal price for forest chips compared to using peat. This is because in many Finnish power plants, peat is a substitute for forest chips. Accordingly, the marginal price for forest chips varies between 12 and 26 €/MWh, given that the price of emission quotas in recent years has varied from 0 to 30 €/t CO_2 and prices of delivered sod peat from 12 to 15 €/MWh (Anonymous, 2011b). In the analyses, we used 17 €/MWh as the wood chip price level.

The cost of creating high stumps was calculated by multiplying the volumes of lost wood by the timber price per volume. The height of high stumps was always 4 m, but the diameter varied between regions (Table 1), resulting in volumes between 0.15 and 0.32 m^3. We assumed that about 60% of the high stump volume would have been used for timber, while the rest would be used as pulp wood. This resulted in high stump prices of 5.04 €, 7.06 €, and 10.58 € in northern, central and southern Sweden, respectively. Calculations of the net gain from slash and stump harvest and the cost of creating stumps were combined, to estimate how many high stumps were obtained, when various percentages of the net gain were used for compensation (Table 2).

All monetary figures in the results of this paper are presented as 2010 fixed prices in euros. We converted current prices into fixed prices using a producer price index (Anonymous, 2011c). Prices in Swedish kronor (SEK) were converted to euros using the average exchange rate in the years 2008-2010 (9.92 SEK/€; Anonymous 2011d).

3. Results

Slash harvesting reduced the volume of dead wood above ground by 35–37% (mean for a forest stand over a rotation), while slash and stump harvesting combined reduced the volume by 44–51% (corresponding values also including underground dead wood were 22–25% and 42–46%, respectively; Fig. 2). When no compensation efforts were applied, combined slash and stump harvesting resulted in a decrease in the amount of available habitat by > 50% for 8.4% (= 48) of the species (central Sweden). If all net revenue from slash and stump harvesting were used to create high stumps, the number of species with a habitat reduction exceeding 50% decreased to 1.2% (= 7) (Fig. 3). Fungi and beetles were the dominant groups among both those negatively affected by forest fuel harvesting and those positively affected by the creation of high stumps (Fig. 3).

By combining slash harvesting with the creation of high stumps, it was possible to achieve an outcome that was better both for biodiversity and for the profitability of forestry compared to doing none of that (Fig. 4). In central Sweden, about 40 % of the net revenue from slash harvesting had to be spent on high stumps to maintain the pre-harvest substrate index value (Fig.

4), which required that high stumps are created from about 14 % of all harvested trees (corresponding to c. 120 high stumps per ha). Scenarios including stump harvesting were the best options if the goal was to maximise profitability. However, adding stump harvesting to the slash harvesting never generated a clearly better outcome for biodiversity, even if the entire net revenue was used for compensation. This was observed as only a slight difference between the curves representing slash harvesting and slash and stump harvesting (Fig. 4).

4. Discussion

We show that compensation can sometimes be a useful tool when both economic and biodiversity goals must be achieved in forestry, but in other cases it may be a better alternative to avoid the activity that cause the negative effects. Large scale harvest of logging residues for energy production has a clearly negative effect on habitat amount for many species, but creation of dead wood that is useful for many species can mitigate this effect. By combining slash harvesting with the creation of high stumps, both an economic surplus and significantly more habitat can be obtained in comparison with no slash harvesting and no high stump creation. When stump harvesting is added to the slash harvesting, it is currently impossible to achieve such positive effects compared to slash extraction only.

4.1 Cost-efficiency of combining increased production with compensation

The cost per volume unit for high stump creation is higher than the net revenue per volume unit of slash and stump harvesting. However, the value for biodiversity (as substrate for species associated with dead wood) per volume unit is much greater for high stumps than for harvested slash and low stumps. One reason for this is that high stumps are more persistent. Therefore, creation of high stumps makes more substrate available over time. Furthermore, large-diameter wood is used by more species (Jonsson et al., 2006) and has decreased due to forestry to a higher extent than slash wood. Finally, in contrast to low stumps the main part of the high stumps is aboveground, which for most organisms is the only part of the dead wood item that is available. The persistence and larger proportion aboveground mean that even though e.g. beetle species richness in high and low stumps are similar (Hjältén et al., 2010), high stumps are still more valuable for biodiversity than low stumps, if measured as per cubic metre dead wood created. Therefore, the cost of high stump creation is rather low in comparison to its value for biodiversity. Consequently, creation of high stumps is useful as a compensation measure in boreal forests. In other biomes, forest fuel harvest may affect species communities associated with other microhabitats, and consequently other types of compensation efforts may be more appropriate.

The greater economic surplus and higher habitat amounts obtained by combining dead wood creation with slash harvest could not be achieved by combining dead wood creation with adding stump harvest to the slash harvest. This is because slash harvesting is more profitable than stump harvesting (Fig. 4), which probably is the main reason why slash harvesting occurs much more extensively than stump harvesting in Fennoscandian forestry (Finnish private forests: slash is harvested on about 30% of the final-felled area, and stumps are harvested on 10% of the area; Anonymous 2011e; in Sweden the difference is even bigger, but this is partly due to the certification standards). Stump harvesting is associated with extra costs for extraction, handling, and forwarding (Laitila et al., 2008). However, future technical developments may decrease these costs. Due to environmental concerns, large-scale stump harvest is only permitted in Sweden to a very limited extent according to certification standards that are adopted by most large forest owners. Employing compensation efforts could have been one way to make stump harvest acceptable, however, this analysis suggests that this is currently not a cost-effective alternative.

4.2 Regional variation

Biomass harvesting for energy production is more profitable in regions with more productive forests (i.e. in the south, Fig. 4). This is because the biomass volumes become larger, and for stump harvesting, production costs fall because the stumps are larger (Laitila et al., 2008). However, we also found that forest fuel harvesting has a greater negative effect on the habitat amount in the south (Fig. 3). To some extent the difference among regions is due to species richness; central Sweden has the largest number of species associated with spruce, and consequently the range of substrate index values among various scenarios was wider there in comparison to northern and southern Sweden (Fig. 4). However, the main reason for the regional variation is that in the south, a higher proportion of the total dead wood volume present during a rotation period is potentially harvested for forest fuel, because the rotation period is shorter and the standing tree volume at felling is larger. Consequently, the greatest conflicts between biodiversity conservation and forest fuel harvesting occur in regions with the most productive forests. Using high stumps as a compensation measure could not solve this conflict; in contrast to the other regions all net revenue from slash harvesting must be spent on compensation efforts to avoid a negative effect on substrate availability (Fig. 4). This conforms to a general pattern in nature conservation; less productive areas tend to be set aside for nature conservation, because the pressure to use them for other purposes is lower (Pressey, 1994). Consequently, the original habitat is more often replaced in more productive areas. This results in more species extinctions, because biodiversity is generally higher in areas of intermediate productivity rather than in less productive areas (Chase and Leibold, 2002).

In each region, we only analyzed one representative forest stand. In the real world, forest stands vary within a region, in a similar way as between regions. Our comparison of regions suggests that this variation will result in differences in the profitability of forest fuel harvest and in the consequences for biodiversity. However, since we obtained a better outcome from slash harvesting combined with high stump creation in comparison with adding stump harvesting to the slash harvesting in all regions, most likely this result would remain, even if the variation among stands was considered. In this study, we used total habitat amount as a proxy for biodiversity. To maintain biodiversity at a landscape level, the best strategy is probably not only to maximize habitat amount but also to obtain a variation in substrate types among stands (cf. Michel et al., 2009). In this study we only analysed the creation of high stumps, because an earlier study revealed this to be a cost-efficient measure to increase the amount of dead wood, in comparison to other measures that are taken in Swedish forestry (Jonsson et al., 2006). However, a combination of different measures, involving several different tree species and the retention of felled boles and live trees, is desirable in order to obtain a higher diversity of created substrates (e.g. Jonsell and Weslien, 2003). Therefore, it is desirable to have different management regimes (including forest fuel harvest and compensation efforts) among stands in a forest landscape.

4.3 Conclusions: compensation measures in forestry

Creation of high stumps could be useful as a compensation measure at biofuel harvest. This is because slash harvesting combined with the creation of high stumps can generate both an economic surplus and significantly better conditions for biodiversity in comparison with no slash harvesting and no high stump creation. Another important factor making high stumps useful as a compensation measure is that most species that use the dead wood removed during forest fuel harvesting also use high stumps as a substrate (compare the number of species suffering negative effects in “No comp.” and “Full comp.” in Fig. 3). Thus, creation of high stumps constitutes an in-kind compensation, since the high stumps host species pools similar to those lost by forest fuel harvesting. Compensation efforts have been questioned since, often, they do not specifically mitigate the negative effect caused by the activity (i.e. they are out-of kind) (McKenney and Kiesecker, 2010).

Creation of high stumps has the potential to be applied as an on-site measure, since high stumps can be created in the same forest landscape. This is a relevant scale, because it is at the landscape scale, rather than in individual stands, saproxylic insects (Schroeder et al., 2007) and cavity-nesting birds (Kroll et al., 2012) respond to habitat availability and persist in the long run. In many cases, it is possible to create high stumps even at the specific stands where slash and stumps are harvested. This could be a required activity under future forestry laws or as part of forest certification standards. The promise of compensation may lead to that more activities that damage biodiversity are permitted, and often there is little evidence that compensation efforts are efficient (Maron et al., 2012). However, field studies in Northern Europe have shown that created high stumps are, indeed, used by hundreds of insect species, including many that are red-listed (Lindhe and Lindelöw, 2004), and in Northern America several cavity-dependent bird species nest successfully in high stumps (Hane et al., 2012). It makes a difference where and of which trees the high stumps are created (Jonsson et al., 2010; Lindhe and Lindelöw, 2004). If creation of high stumps is required as a compensation effort, there is a need for monitoring of how it is conducted and to what extent the high stumps are used by species of conservation concern.

Analyses of compensation efforts often focus on how much is needed to maintain a certain amount of habitat (e.g. Quigley and Harper, 2006) or species abundance (e.g. Dalang and Hersperger, 2010). There are also an increasing number of studies on the cost-efficiency of conservation efforts that may be used as compensation measures (e.g. Wätzold and Schwerdtner, 2005; Jonsson et al., 2006). The present study shows the need for including both possible compensation measures and the activity responsible for the negative effects that are to be mitigated in the same analyses, because only then it is possible to understand the effectiveness of applying compensation measures.

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Table 1. Stand characteristics used in the simulations. All stands were assumed to be 5 ha, even-aged and planted with 100% Norway spruce (from Ranius et al., (2005)).

Stand variable	Northern	Central	Southern
County	Västerbotten (montane part)	Gävleborg	Kronoberg
Vegetation zone[a]	northern boreal, subalpine	southern-boreal	hemiboreal
Site index [b,c]	16	24	32
Age at felling (years)	130	82	70
Number of thinnings	2	4	4
Distance to forest road, m	500	300	200
Distance to power plant, km	38	38	38
Pulp wood, m^3ha^{-1} [d]	91	200	288
Logs, m^3ha^{-1} [d]	98	203	191
Stems, ha^{-1} [d]	570	832	953
Stump diameter, cm[d]	29	35	42

a) According to Ahti et al. (1968).

b) Height (m) of the spruce trees at the age of 100 years.

c) Means + standard deviations were 16 ± 2, 24 ± 2, 32 ± 3 in northern, central and southern Sweden, respectively.

d) At felling.

Table 2. Number of high stumps created per hectare, when various percentage of the net gain from forest fuel harvest is used for compensation.

Region	Harvesting of forest fuel at felling	0%	25%	50%	75%	100%
Northern	None	0	na	na	na	na
	Slash	0	50	101	151	202

	Slash + stumps	0	54	123	162	216
Central	None	0	na	na	na	na
	Slash	0	71	142	213	283
	Slash + stumps	0	83	192	250	333
Southern	None	0	na	na	na	na
	Slash	0	54	108	162	216
	Slash + stumps	0	73	168	220	293

na = not analyzed

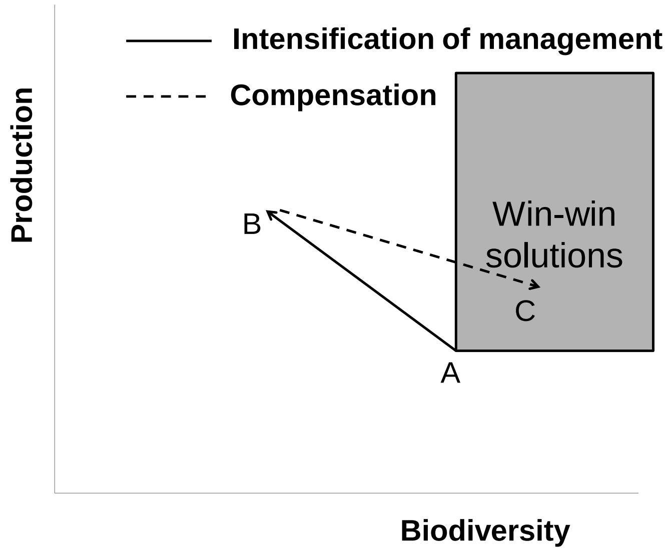


Fig. 1. Intensification of a management practice, for instance biomass harvest for energy production, tends to decrease biodiversity and increase production. This is represented by the arrow from starting point A to B. Compensation measures may be useful if it results in a change like that represented by the arrow from B to C. The overall outcome is represented by point C, which is better than point A with respect to both biodiversity and production.

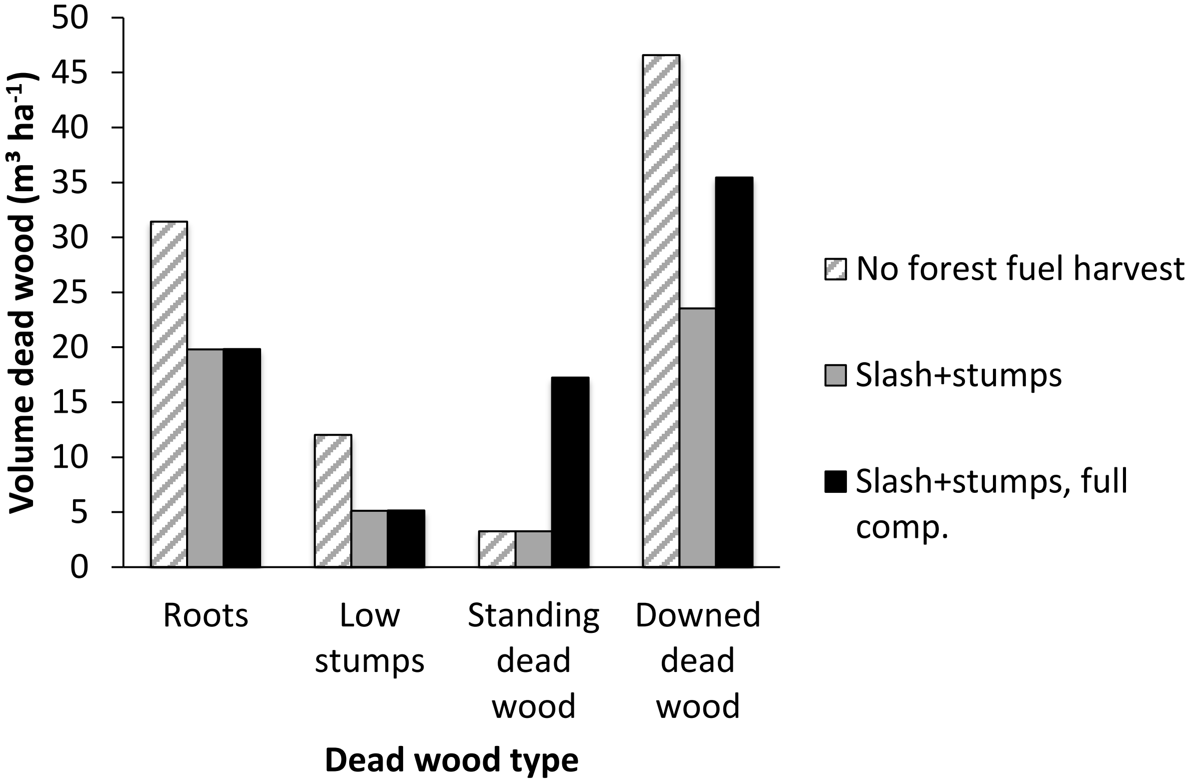


Fig. 2. Volume of various types of dead wood (average during a forest generation) at (i) no forest fuel harvest, (ii) harvest of slash and stumps, and (iii) harvest of slash and stumps with all net gain from forest fuel harvest used for compensation.

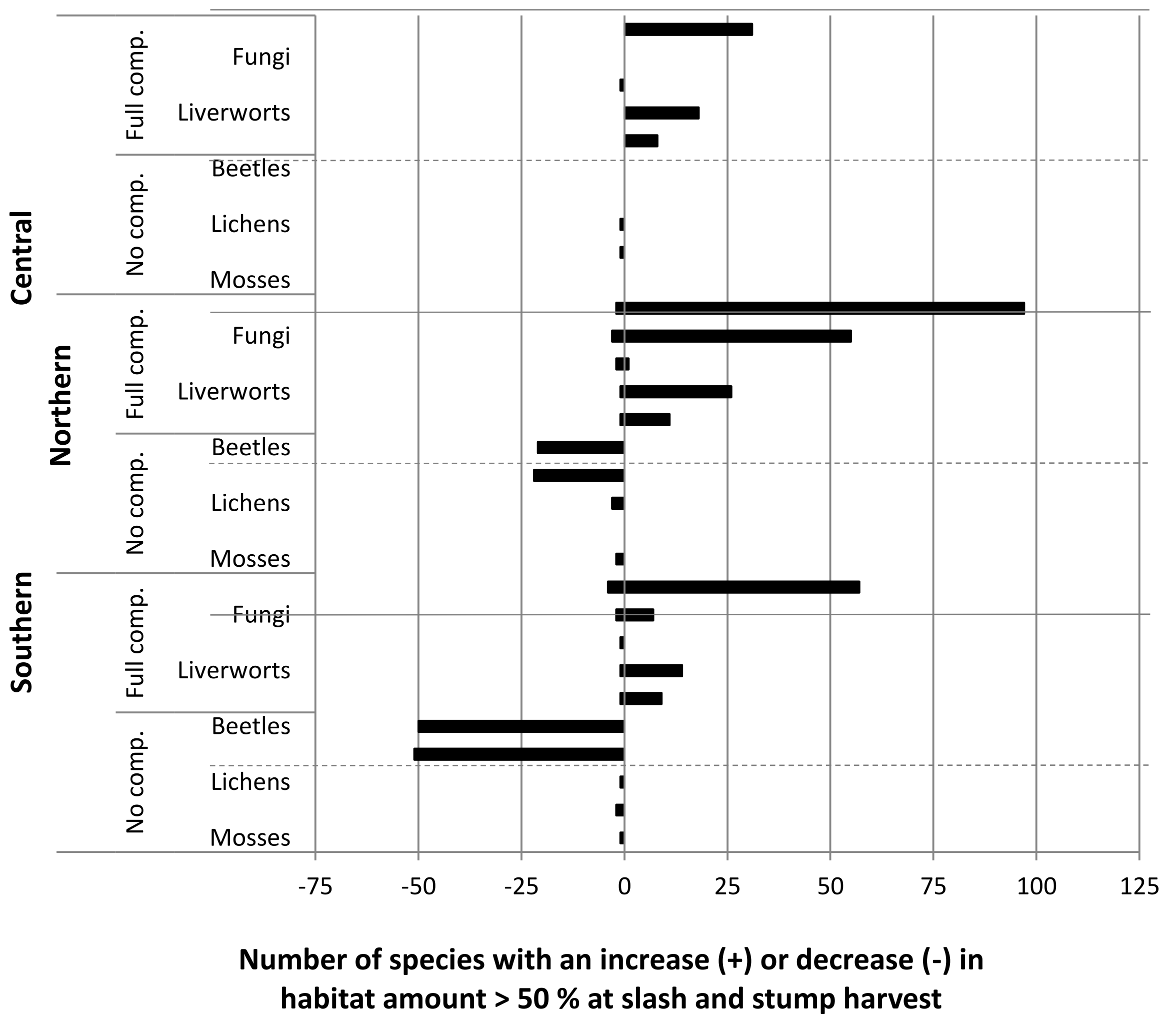
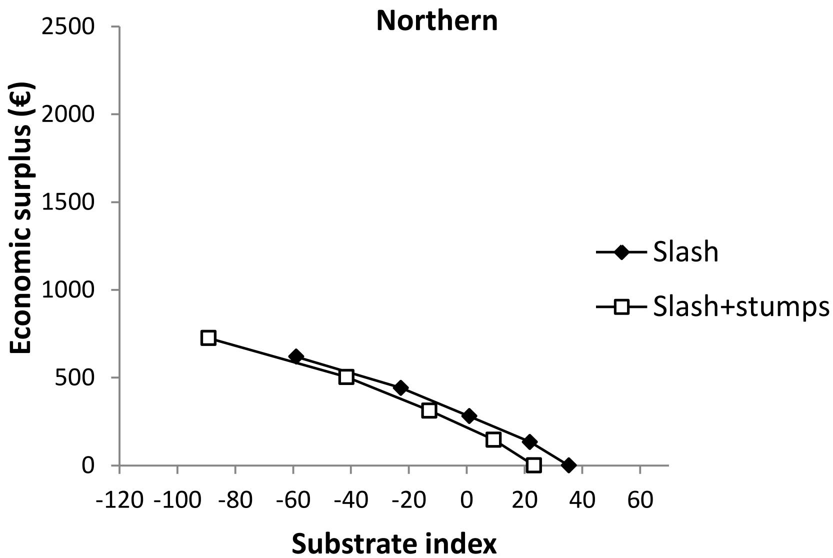
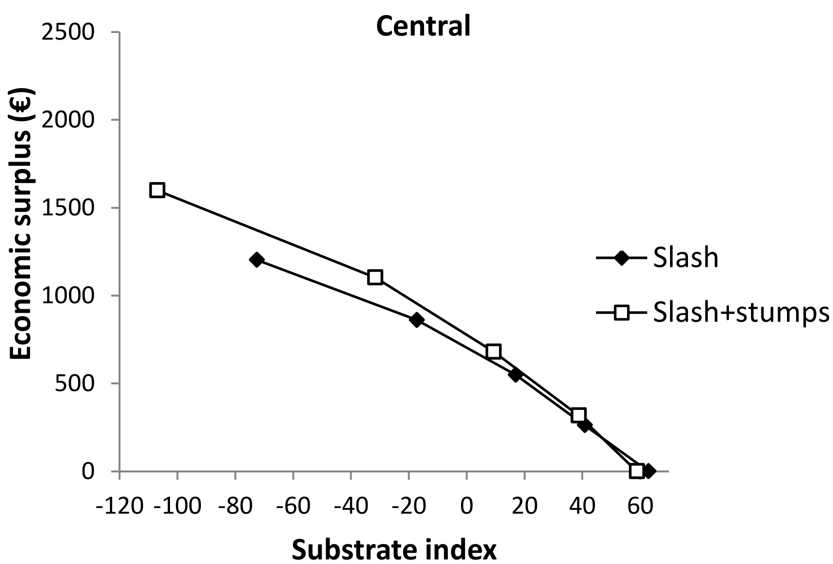


Fig. 3. Number of species for which there was a decrease or increase in habitat amount > 50 % at slash and stump harvesting. “No comp” indicates no compensation efforts, and “Full comp” that all net revenues from slash and stump harvesting are used for high stump creation. Predictions are for typical forests of Norway spruce in northern, central, and southern Sweden, respectively.


Northern
Economic surplus (€)
2500
2000
1500
1000
500
0
-120 -100 -80 -60 -40 -20 0 20 40 60
Substrate index
Slash
Slash+stumps


Central
Economic surplus (€)
2500
2000
1500
1000
500
0
-120 -100 -80 -60 -40 -20 0 20 40 60
Substrate index
Slash
Slash+stumps

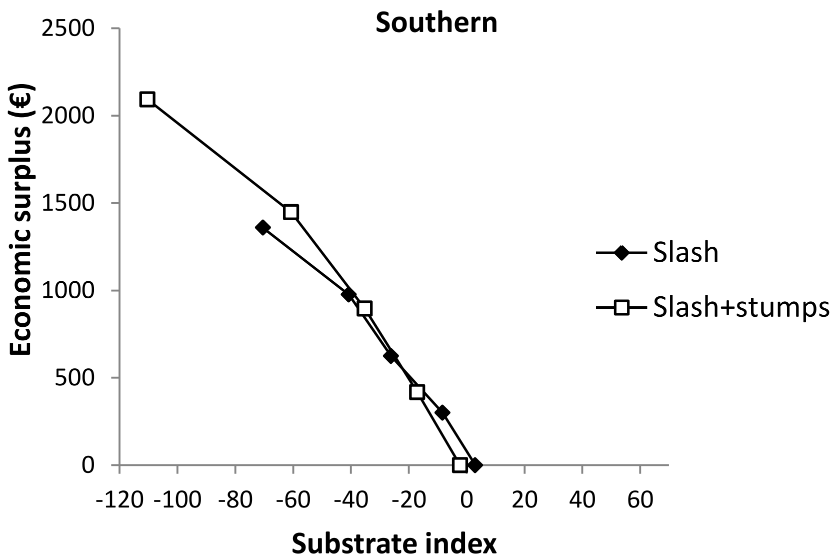


Fig. 4. Effect on economic outcome and biodiversity for management scenarios combining biomass harvesting for energy production with compensation measures. Forest fuel harvesting was combined with varying levels of compensation (0 %, 25 %, 50 %, 75 %, and 100 % of the net revenue from slash harvesting spent on compensation measures, represented by the 5 points on the curve, respectively, starting from the left). The economic surplus was the net revenue from forest fuel harvesting minus the cost of compensation measures, i.e. creation of high stumps. The biodiversity was measured as an index reflecting the amount of habitat available for species associated with the wood or bark of Norway spruce. The outcome is for 5 ha forest stands in northern, central and southern Sweden, respectively.

Appendix A

Variables used to describe substrate associations of the species.

Variable	Category
Microhabitat type	1) Wood (except roots) with bark
	2) Wood (except roots) without bark
	3) Roots below ground
	4) Exposed roots of uprooted trees
Position	1) Standing (both whole trees and high stumps)
	2) Stumps
	3) Lying
Diameter	1) 0–5 cm
	2) 5–10 cm
	3) 10–30 cm
	4) >30 cm
Decay stage[a]	0) Living wood/bark
	1) Recently (< 1 year) dead. Bark still attached to stem.
	2) Slightly decayed. Bark loose, decay penetrating less than 3 cm into wood from the surface, initial mycelium under bark.
	3) Moderately decayed. Decay penetrating more than 3 cm into wood, core (or hollow tree surface) still hard.

	4) Thoroughly decayed / almost decomposed. Stem rotten throughout, no (or few) hard parts, ellipsoid cross-section, fragmented outline of stem.
Sun exposure	1) Fully sun-exposed, as in young clear cuts.
	2) Partly sun exposed / shady, as at the edge of a clear cut not facing southwards, or in an open spruce forest.
	3) Shaded, as in a spruce forest with a closed canopy.

[a] For wood with a diameter <10 cm, decay classes 3 and 4 are pooled.

Appendix B.

Unit production costs of slash and stump harvesting in Norway spruce stands in three different Swedish regions when no high stumps are created.

	Slash harvesting		Stump harvesting	
Region	Cost per volume	Cost per energy unit	Cost per volume	Cost per energy unit
	€ m^{-3}	€ MWh^{-1}	€ m^{-3}	€ MWh^{-1}
Northern	24.0	11.1	32.0	14.8
Central	22.1	10.2	28.8	13.3
Southern	21.3	9.8	28.2	13.0