

Transient trade-off between climate benefit and biodiversity loss of harvesting stumps for bioenergy

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Abstract

To replace fossil fuel and thereby mitigate climate change, harvesting of wood such as stumps for bioenergy will likely increase. Coarse deadwood is an important resource for biodiversity and stumps comprise the main part of the coarse deadwood in managed forests. We provide the first integrated analysis of the long-term climate and biodiversity impacts of a whole landscape. We simultaneously project climate and biodiversity impacts of harvesting stumps to substitute for fossil coal, assuming scenarios with different proportions of the landscape with stump harvest (10, 50, 80%) the coming 50 years. A life cycle approach was used to calculate future global temperature changes and future metapopulation changes in six epixylic lichens. Metapopulation dynamics were projected using colonization and extinction models based on times series data. Harvesting stumps from $\geq 50\%$ of the clear-cut forest land benefits climate with a net global temperature reduction $>0.5 \cdot 10^{-9}$ K ha⁻¹ after 50 years if assuming substitution of fossil coal. For all scenarios, using stump bioenergy leads to immediate (within 1 year) reductions in temperature of 50% compared to using fossil coal, increasing to 70% reduction after 50 years. However, large-scale stump harvest inflicted substantial metapopulation declines for five of six lichens. High stump harvest levels ($\geq 50\%$) put common lichens at risk of becoming red-listed following the IUCN criteria. The net temperature reduction (cooling effect) from substituting fossil coal with stumps harvested for bioenergy increased over time, while lichen metapopulations stabilized at lower equilibria after two to three decades. This indicates that trade-offs between climate and metapopulations of commons species are transient, where climate benefits become more prevalent in the long term. As both objectives are important for meeting (inter-) national climate and biodiversity targets, integrated analyses such as this should be encouraged and urged to guide policymaking about large-scale implementation of stump harvest.

Keywords: deadwood, epixylic lichens, harvest residues, life cycle assessment, metapopulation dynamics, net global temperature change

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Introduction

Climate change, its projected impacts and alternative mitigation strategies continue being at the forefront of international research and policy agendas. With the negotiations at the Paris Climate Conference (COP21) resulting in the Paris Agreement, 195 nations adhered to limiting the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit this temperature increase to 1.5 °C (UNFCCC, 2015). Parties are to ‘strive to

formulate and implement’ long-term low greenhouse gas emission strategies (Paris Agreement (n 21) art 4 (19)). Such strategies mean that the promotion of renewable energy remains on the rise, with aims of tripling investments in renewables worldwide by the year 2030 (Banja *et al.*, 2015; IRENA, 2015). Biomass extraction for renewable energy and bioeconomy strategies are also receiving strong support from society at the EU level, for example, as reflected in the EU Renewable Energy Directive (European Commission, 2009) and the European Bioeconomy Strategy (European Commission, 2012). In Sweden, stump harvesting is currently only implemented to a very small degree (around 0.3 TWh), although the Forest Agency has opened up for

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implementation on c. 20 000 ha initially. An expansion beyond this level would require a new environmental impact assessment.

Bioenergy contributed over two-thirds of the EU's primary renewable energy production in 2014 (Eurostat, 2014) and is expected to account for more than half of the fossil emission reductions planned for 2020. At the same time, the annual demand for bioenergy is estimated to increase from the present 5.7–10 EJ by 2020 (Bentsen & Felby, 2012). One way to meet the growing need for bioenergy is to increase the use of forest harvest residues such as branches and tops (slash henceforth) and stumps for energy production. In forested member states, the interest in harvesting forest slash and stumps on clear-cuts for bioenergy production keeps increasing (Björheden, 2006; Gan & Smith, 2011). Among these countries, Sweden has a long history of transition toward the use of forest residues as a leading bioenergy source (Andersson, 2015). A substantial share originates from slash, but increasing demands for bioenergy in Sweden and Finland during the recent decade has also led to a growing interest to harvest the typically overlooked stumps left after clear-cutting (Jonsson, 2013; Helmisaari *et al.*, 2014). Theoretical work on the potential supply of woody biomass for bioenergy at the EU level has shown that stumps may contribute as much as 25% of the bioenergy supply (Verkerk *et al.*, 2011). Sweden and Finland can be expected to be major contributors as these countries already now are the third and fourth largest contributors to the global wood market. In Finland, the extraction of stumps after clear-felling has already become common. There, stumps are currently removed from 10% of the clear-fellings (Juntunen, 2012) and the harvested area increased from 1000 to 2500 ha per year between 2003 and 2005 (Hakkila, 2006). In Sweden, the gross potential is larger for stumps (21–34 TWh per annum) than for forest residues (16–25 TWh per annum) (Claesson *et al.*, 2008), and the Swedish Forest Agency (2009) and government (Anon, 2008) considers large-scale utilization of stumps for energy production as accepted practice within certain restrictions.

The intensification of biomass removal from forests has also raised concerns about the actual climate change mitigation potential of forest bioenergy. Some of the concerns relate to its carbon or climate footprint (e.g., Repo *et al.*, 2011, 2015; Holtsmark, 2012; Schulze *et al.*, 2012; Zanchi *et al.*, 2012; Jäppinen *et al.*, 2014), which in turn depends on what forestry residues are employed and what time horizons are considered. The impact on the atmospheric temperature from bioenergy produced from (residue-based) forest fuel will exhibit temporal dynamics due to (1) the time difference between the combustion emissions and the carbon emissions of the

slash or stumps had they been left in the forest to decompose, (2) the decay or fate of greenhouse gases (GHGs) released into the atmosphere and (3) the time lag in the warming effect due to the inertia of the atmosphere. As regards stump harvest, it remains debated from many environmental aspects, including the actual climate impact (e.g., Walmsley & Godbold, 2010; Berch *et al.*, 2012). Some studies conclude that stump bioenergy has the potential to decrease climate warming compared to fossil alternatives in the short (2–3 decades) term (Melin *et al.*, 2010; Zetterberg & Chen, 2015; Ortiz *et al.*, 2016), while others find no short-term reduction in carbon emissions (Mäkipää *et al.*, 2015; Repo *et al.*, 2015). In the longer-term, however, bioenergy from slash and stumps has the potential to contribute significantly to carbon emission reductions in Europe, compared to using fossil fuels (e.g., Repo *et al.*, 2015). Although these studies operate over different spatial scales, analyses of the effect of varying the frequency of stem harvested stands over the landscape are lacking. Consequently, we lack knowledge of what levels of stump harvest and which time frames that are needed in managed forest landscapes to mitigate climate warming. The landscape perspective is important for studying the effects of intensified stump harvesting, as this is the operational scale for most conventional forestry management, where final felling and residue harvest of individual stands occur once for each rotation period over a fraction of the whole landscape. Moreover, to assess the climate impact the whole system of extracting stumps and substituting fossil fuel should be analyzed (Lamers & Junginger, 2013) over relevant timescales (e.g., 2050 was considered as a policy-relevant carbon level reference point due to bioenergy system lifetimes of 20–30 years). Indeed, such life cycle assessment (LCA) of biomass to energy value chains, quantifying additional fossil fuel emissions as well as carbon emissions due to direct land-use change, have been incorporated in policies, for example, the European Renewable Energy Directive 2009/28/EC.

Other concerns with intensification of biomass removal from forests relate to the often unaccounted impacts on biodiversity (Paterson *et al.*, 2008). Removal of forest residues has often been assumed to have little impact on forest biodiversity, although these practices further reduce the low amounts of coarse deadwood in intensively managed forests (Siitonen, 2001). Such a reduction in deadwood directly affects epixylic and saproxylic (i.e., deadwood-dependent) organisms (Siitonen, 2001; Dahlberg *et al.*, 2011; Stokland *et al.*, 2012; de Jong & Dahlberg, 2017), which count as one of the most threatened groups in intensively managed landscapes such as the boreal forests of Fennoscandia (Rassi *et al.*, 2010; Artdatabanken, 2015).

Stumps on clear-cuts may constitute up to 80% of the total volume of coarse deadwood in young managed forests (Fridman & Walheim, 2000) and may therefore constitute an important habitat legacy and a large proportion of the available habitat for many deadwood species (Hjältén *et al.*, 2010; Svensson *et al.*, 2013; Jonsell & Schroeder, 2014). Stump harvest has been shown to reduce the number of species of saproxylic fungi (Toivainen *et al.*, 2012) and beetles (Victorsson & Jonsell, 2013) at forest stand level, and impacts can also extend to other organism groups (Bouget *et al.*, 2012), such as lichens. Lichens are diverse and functionally important, albeit an understudied taxonomic group, in ecosystems worldwide (Asplund & Wardle, 2016). Knowledge about likely population outcomes of increased woody bioenergy extraction is generally lacking, although needed for the large number of species utilizing deadwood. These studies confirm previous concerns about the environmental impact of stumps harvesting on, for example, biodiversity (Walmsley & Godbold, 2010).

Policy-relevant studies of biodiversity effects from different levels of stump harvesting (e.g., retention targets) at the landscape scale are still lacking (de Jong *et al.*, 2017). However, theoretical work using fictive species suggest that even low levels of stump harvest have the potential to threaten species specialized on sun-exposed coarse deadwood (Johansson *et al.*, 2016). They applied dynamic models simulating colonization and extinction events, in contrast to preceding studies that made inferences from single snapshot field surveys. Models that capture the dynamic nature of species are likely to yield more accurate projections of future population development than static models fitted to data from single snapshot surveys (Yackulic *et al.*, 2014). However, we are not aware of any studies of effects of stump harvest on true species applying this dynamic simulation approach in a landscape context. Moreover, we are not aware of any studies of trade-offs between climate effects and species population viability using LCA.

Stump harvesting for bioenergy represents an important case of ecological trade-offs, where long-term potential benefits for climate need to be balanced against potential negative effects on biodiversity. Quantitative assessments of such trade-offs are lacking, despite their importance for formulating and implementing sustainable long-term strategies for climate mitigation and biodiversity conservation. Previous studies have investigated climate and biodiversity impacts as two separate aspects, and often for different scenarios of bioenergy harvest, localities or spatial scales (e.g., Geijer *et al.*, 2014; Johansson *et al.*, 2016). Understanding these trade-offs is also required in the balance and political decision among potentially conflicting

environmental targets such as the European Renewable Energy Directive 2009/28/EC, the European Bioeconomy Strategy (European Commission, 2012) and the European Biodiversity Strategy (European Commission, 2011).

The aim of this study was to investigate the impacts of stump harvesting for generating bioenergy on the future global temperature and future metapopulation size of affiliated deadwood species assuming three stump harvesting scenarios. The stump bioenergy was assumed to replace fossil coal, either for current usage or for future increased energy consumption. Specifically, we simultaneously simulate global temperature changes and metapopulation changes in six epixylic lichens based on ecosystem modeling, climate impact assessment and species-specific colonization and extinction models for the coming five decades in a Swedish model landscape. We hypothesize that there is a trade-off between temperature change and biodiversity from stump extraction, where the climate benefit (net temperature reduction) increases over time with increasing stump harvest at the cost of reduced lichen metapopulation sizes. We furthermore investigate whether these stump harvest levels may lead to metapopulation reductions that put individual species at risk becoming red-listed according to IUCN criteria (IUCN Standards and Petitions Subcommittee, 2016).

Materials and methods

System boundaries

A life cycle assessment (LCA) was performed of the stump bioenergy system with respect to the two environmental impact categories climate impact and impact on lichen metapopulation size. The LCA included the stump energy supply chain (from stump excavation to combustion at a district heating plant), carbon stock changes and changes in lichen metapopulation sizes. The LCA was performed using the functional unit hectare (ha), and a landscape perspective was applied.

To assess the climate impact of stump bioenergy, emissions of CO₂, N₂O and CH₄ from the supply chain and carbon stock changes were calculated on a yearly basis. The carbon stock changes were defined as the net effect of removing stump biomass from the forest site, that is, the yearly difference between CO₂ fluxes from combustion (harvest) and CO₂ fluxes from decomposition (no harvest). The climate impact was assessed using the metric absolute global temperature change potential (ΔT). Further, a comparison was made to the case when the same energy was supplied from a fossil (hard) coal energy system. The climate impact of fossil coal was calculated based on emission factors from previous LCAs, which included production, distribution and combustion of fossil coal for heat production (Supporting Information). To evaluate the impact of biodiversity, the development of metapopulations of lichen

species was simulated (see Lichen metapopulation sizes below).

Simulations of the model forest landscape

We conducted the study using a model landscape with 650 forest stands located in the Uppsala region in Sweden, latitude 60°N. We assumed that the stand ages followed an even distribution ranging 1–65 years, with each age class being represented by 10 stands. The typical rotation time for stands dominated by Norway spruce (*Picea abies*) in central Sweden is 65 years. For simplicity, all stands included only spruce, were one hectare in size, and had the same age-specific forest structural properties, soil conditions and productivities as the average for the region according to statistics from the National Forest Inventory (SLU, 2014a) and the Swedish Forest Soil Inventory (SLU, 2014b). The forest dynamics and management were simulated with the forest decision support system Heureka (Wikström *et al.*, 2011), using the stand-based version Standwise, assuming conventional forest management for Sweden. The thinning regime simulated in Heureka followed the planning tool INGVAR (Jacobson *et al.*, 2008). Within Heureka, the biomass of stumps was estimated from the tree diameter using allometric functions by Marklund (1987, 1988), which were based on destructive sampling of tree of Norway spruce, Scots pine (and Silver birches) throughout Sweden. The biomass for medium sized roots was estimated from functions by Petersson & Ståhl (2006).

In each stand where a clear-cutting event had taken place, the creation and decomposition of 449 stumps were simulated. This corresponds to the average stump numbers per hectare clear-cut in the region. The stump decomposition for the time dynamic climate assessment was simulated with the Q model (Rolff & Ågren, 1999), which simulates the mass loss and deterioration of organic matter (i.e., litter and soil carbon) over time (Supporting Information). We used parameter values (including uncertainties) for coniferous forests in central Sweden according to Ortiz *et al.* (2011). The simulation of stump substrate decomposition used when simulating lichen dynamics was conducted using a separate model, see Lichen and stump field data and model fitting below.

Stump harvest scenarios

Future global temperature change and lichen metapopulation sizes were investigated with three stump harvest scenarios where 10% (S1), 50% (S2) and 80% (S3) of the newly created clear-cut stands in the model landscape were harvested for stumps each year (Table 1). The first scenario (S1) represents the likely future level of stump harvest according to the Swedish Forest Agency (Official Statistics of Sweden, 2014), and the last scenario (S3) represents the level of stump harvest that is required to reach the level of energy that corresponds to the level required for Sweden to reach its commitment of the EU goal of 11 TWh yr⁻¹ from bioenergy by 2020 (Swedish Energy Agency, 2011). The middle scenario (S2) was included to investigate potential nonlinearity between the level of stump harvest and global temperature change or lichen metapopulation sizes.

Table 1 The simulated annual stump harvest scenarios applied in the model landscape

Scenario	Proportion of clear-cut stands where stumps are harvested (%)	Proportion of stumps harvested on each clear-cut (%)
S1	10	80
S2	50	80
S3	80	80

For technical and environmental reasons, we assumed that only 80% of the stumps on individual clear-cuts were extracted (Pelto *et al.*, 2011; de Jong *et al.*, 2017). The estimated harvested stump biomass for the individual stand was 18.7 t_{DM} ha⁻¹.

Stump energy supply chain

Data for the stump harvest supply chain were retrieved from Ortiz *et al.* (2016) which included the processes excavating, forwarding, storage, transport, comminution, combustion and ash recycling to compensate for any future production losses (Fig. 1, Supporting Information). The transport distance was set to 100 km (round-trip). The biomass was assumed to be stored for 8 months with a dry matter loss of 1% per month before comminution, which gave an additional loss of 3.6% (Lindholm *et al.*, 2010). A moisture content of 30% and a lower heating value of 20.5 MJ Mg⁻¹ dry matter were assumed. The heating plant was assumed to be equipped with flue-gas recovery which increases the conversion efficiency by recovering heat that otherwise would be lost by water vaporization. This gave a total conversion efficiency of 106% (Uppenberg *et al.*, 2001).

Forest carbon stock change

The change in forest carbon balance by stump harvesting was determined from the simulations with Heureka and the coupled soil decomposition model Q. The avoided emissions from the forest by stump harvesting were calculated as the difference between the harvest scenarios (S1–3) and a reference scenario where stumps were left in the forest to decompose. The stand level results were given as time series of annual GHG emissions. The sum of these emissions across all stands in the landscape for each year in the 50 years simulation period was used as the input in the climate impact calculations.

Climate impact assessment

The climate impact of stump harvest was assessed by calculating the absolute global temperature change potential where the life cycle inventory of yearly greenhouse gas emissions and carbon fluxes (due to changes in forest carbon balance) was used as input. The release of GHGs alters the atmospheric concentration, which perturbs the energy balance on Earth by affecting the balance between the incoming solar radiation and the

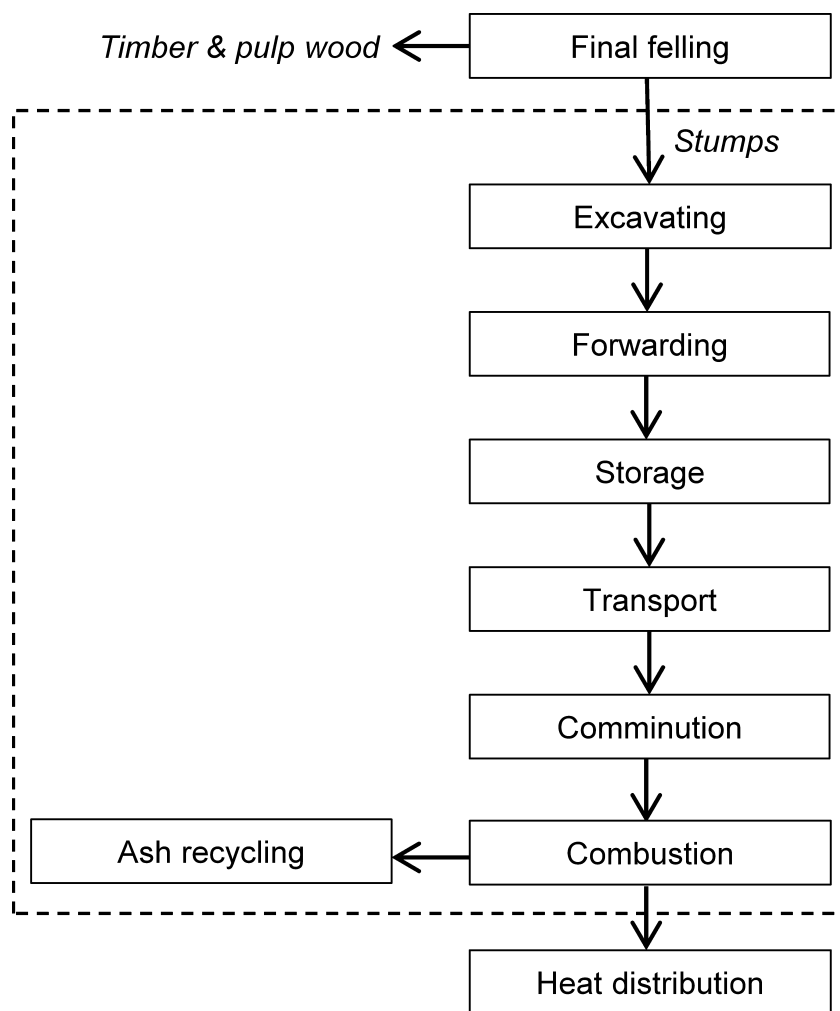


Fig. 1 Flowchart of the stump harvest system. The dashed line shows the system boundary. Emissions occurring during the final felling were allocated to the production of timber and pulp wood and hence disregarded in the current study.

outgoing terrestrial radiation. A change in the radiative balance of the Earth is referred to as radiative forcing (RF) and is measured in Wm^{-2} (IPCC, 2007). When studying forest systems, it is important to consider the temporal aspects due to the dynamics of the forest carbon balance over a forest rotation period and to use a time-dependent climate metric (Ericsson *et al.*, 2013).

The characteristics of each GHG determine how strong climate agents they are, which is referred to as the radiative efficiency. The radiative forcing of a unit emission of a gas is described by the radiative efficiency and the perturbation lifetime of the gas, that is, the atmospheric residence time before the gas decays. CH_4 and N_2O break down chemically in the atmosphere (average decay times of 12.4 and 121.0 years, respectively, Myhre *et al.*, 2013a), which was modeled using simple decay functions. CO_2 on the other hand is taken up by oceans and the terrestrial biosphere while a fraction of the emitted gas will stay airborne (Joos *et al.*, 2001). The decay of CO_2 was modeled using the Bern carbon cycle model (Joos *et al.*, 2013).

The global mean surface temperature response (ΔT_S) to a unit change in radiative forcing was modeled as

$$\Delta T_S(H) = \int_0^H \text{RF}(t) R_T(H-t) dt,$$

where RF is radiative forcing, R_T is the temperature impulse response function to a unit change in radiative forcing, and H is the timeframe (Myhre *et al.*, 2013b). The temperature response to the emission of each GHG is summed up for the entire timeframe of the studied system.

Finally, the temperature change was calculated and reported for the case when the same amount of energy as was obtained from stumps was instead provided by fossil coal. The resulting climate impact was presented for the fossil coal system (Fossil coal), the stump energy system (Bioenergy) and the difference between the two (Substitution (difference), Fig. 1).

Lichen metapopulation sizes

We study future metapopulation size of six epixylic lichen species that are confined to deadwood (Spribille *et al.*, 2008), but variable in term of colonization and extinction rates,

metapopulation sizes, habitat specificity for certain deadwood types and forest stand ages (Table 2). Given their dependency on deadwood and variety of ecological traits, they should be useful in gauging the effectiveness of different levels of stump harvest in the landscape.

The effects of the stump harvest scenarios in the model landscape on the future lichen metapopulation sizes were projected using Bayesian species-specific colonization–extinction models fitted to empirical data (see Lichen and stump field data and model fitting below). Stumps are their primary substrate on clear-cuts (Svensson *et al.*, 2013, 2016). In 3-year steps, we simulated the colonization–extinction dynamics of each lichen species on the stumps that had been created at clear-cutting using Heureka (see Simulations of the forest model landscape above).

We started each simulation with zero stumps and ran it until the number of stumps and lichen metapopulations had reached equilibria (approximating 140 000 stumps). We then kept the equilibrium levels for five more time steps before starting to simulate stump harvest. Stump harvest was simulated by randomly removing 80% of the individual stumps in either 10%, 50% or 80% of the newly clear-cut stands (Table 1).

For each scenario (Table 1) we used 500 replicates, and for each replicate, we randomly selected a new combination of parameters values from the joint posterior distribution of the parameters obtained from the Bayesian model fitting. We used the statistical software R 3.0.2 (R Development Core Team, 2013) for running the lichen-stump simulations.

The projections of the future lichen metapopulation sizes included calculating whether the individual species risked becoming red-listed (Near Threatened) according to the A criterion of the IUCN red list categories, specifically a 15% population decrease during a period corresponding to three times the generation time (Table 2; IUCN Standards and Petitions Subcommittee, 2016).

Lichen and stump field data and model fitting

The empirical data used to fit the lichen colonization–extinction models used for the simulations were collected in the county of Uppland, southern Sweden (59°43'N, 17°30'E). In 2003, we selected 29 spruce-dominated stands between 4 and 18 years by stratified random sampling in forestry databases. A pilot study showed that stumps younger than 4 years are not suitable substrate for epixylic lichens. In each stand, we selected 15 spruce stumps along a four-meter-wide transect that was placed across the stand at the longest distance from one stand edge to the opposite. Stumps were mapped using GPS and permanently marked. For more information on stump selection see Caruso *et al.* (2008). The study stands were surveyed four times: 2003, 2006, 2009 and 2012. In every survey, we recorded if the stump remained being a substrate (i.e., not too decomposed) and the presence/absence of all lichen species confined to deadwood (Spribille *et al.*, 2008). In total, we found six epixylic species that were obligately confined to deadwood: *Absconditella lignicola*, *Cladonia botrytes*, *Mycocalicium subtile*, *Puttea caesia*, *Xylographa parallela* and *Xylographa vitiligo*. The study lichens do not only occur on stumps (Spribille *et al.*, 2008), and we therefore adjusted our predicted metapopulation sizes based on their occupancy on other deadwood substrates in the landscape (e.g. branches, logs and tops; Table 2).

The adjustment was conducted based on data used by Svensson *et al.* (2013, 2016), who estimated how large proportion of the total metapopulation of each species in the landscape occur on different substrate types (including stumps) in different forest age classes. Specifically, we adjusted our landscape-level population sizes according to the data for spruce and stands up to 60 years, as this was the age category closest to our rotation period (65 years). We assumed that slash was removed in the same proportion as stumps (80% on harvested clear-cuts) and adjusted the metapopulations accordingly based on data from Svensson *et al.* (2013, 2016).

Table 2 Lichen study species obligately restricted to deadwood in Fennoscandia. Life form and reproductive mode after Spribille *et al.* (2008). Affinity for Norway spruce stumps in young forests stands 0–20 years old; that is, proportion of metapopulation occurring on spruce stumps in young forests in relation to other deadwood substrates and older forests (in this study 20–65 years) based on Svensson *et al.* (2013, 2016). Stump age of first colonization after Caruso *et al.* (2008) and generation time according to G. Thor (pers.comm.). Colonization and extinction rates were based on the empirical data of the current study. The species nomenclature follows the Swedish Taxonomic Database (www.dyntaxa.se). *Xylographa parallela* may include also include *X. pallens*, which is likewise restricted to wood (Spribille *et al.*, 2014)

Species	Life-form*	Reproductive mode†	Pop. prop. on stumps	Stump age (years)	3 × gen. time	Col rate	Ext rate
<i>Absconditella lignicola</i>	Cr	S	0.45	7	10	0.001	0.985
<i>Cladonia botrytes</i>	Fr	S	0.67	4	20	0.208	0.354
<i>Mycocalicium subtile</i>	Ca	S	0.76	4	20	0.127	0.775
<i>Puttea caesia</i>	Cr	S	0.54	7	20	0.039	0.784
<i>Xylographa parallela</i>	Cr	S	0.43	4	50	0.201	0.495
<i>Xylographa vitiligo</i>	Cr	As	0.01	4	20	0.001	0.802

*Life form is either crustose (Cr), fruticose (F) or calicioid (Ca).

†Reproductive mode is either sexual (S) or asexual (As).

We fitted the models for lichen colonization and extinction for stumps in the 3-year time steps, (the time passed between the field surveys) using the hierarchical Bayesian framework. As stumps in a stand are not independent, stands constituted a random effect. Models and parameter estimates used for projecting the lichen colonization–extinction dynamics into the future are shown in Supporting Information. As stumps decompose over time, we also fitted a model for stump occurrence probability as a function of stump age. Also this model and parameter estimates are presented in Supporting Information. As opposed to the Q model which simulates mass loss (see Simulations of the forest model landscape above), this model is simulating stump substrate occurrence from the perspective of the lichens. The models were fitted using the software OpenBUGS 3.2.2 (Thomas *et al.* 2006), and the subsequent simulations were conducted using the software R 3.2.0 (R Development Core Team 2013). We ran two MCMC chains for 110 000 iterations. A total of 10 000 iterations were used for estimation, after removal of the first 10 000 iterations (burn-in) and thinning by 20. See Supporting Information for further details.

Results

The net global temperature effect from the use of stump biomass for energy varied through time and between the scenarios (Table 1, Fig. 2). After a few decades, the temperature impact for the stump bioenergy leveled out, while for combustion of fossil coal, it continued to increase incessantly. There was a decrease in average global temperature as more fossil coal was replaced by stump energy, and the decrease was linearly related to the proportion of stands where stumps were harvested (Substitution (difference); 10, 50, and 80%; Fig. 2). The LCA showed that implementing stump harvesting on clear-cut forest land had a climate benefit, that is, a net global temperature reduction (ΔT_s) amounting to $0.1\text{--}0.8 \cdot 10^{-9} \text{ K ha}^{-1}$ after 50 years depending on scenario compared to fossil coal (Fig. 2). This climate benefit increased over time and was also increasing linearly with the harvesting intensity in the forest landscape.

There was an immediate (within 1 year) net global cooling effect (negative values, Fig. 2) of all stump harvest scenarios, because the climate effect of procurement and combustion of fossil coal was larger than the climate effect of the bioenergy system. However, the net global cooling effect was small when limiting stump harvest to 10% of the landscape, and it accumulated at a low rate over time. The temperature impact from stump bioenergy (Bioenergy, Fig. 2) was ca. 50% smaller compared to fossil coal (Fossil coal, Fig. 2) after 10 years and ca. 70% smaller after 50 years, assuming the same harvesting scenario ($1 - (\text{Bioenergy}/\text{Fossil coal})$).

There was a clear trade-off between increasing climate benefit resulting from increasing the proportion of

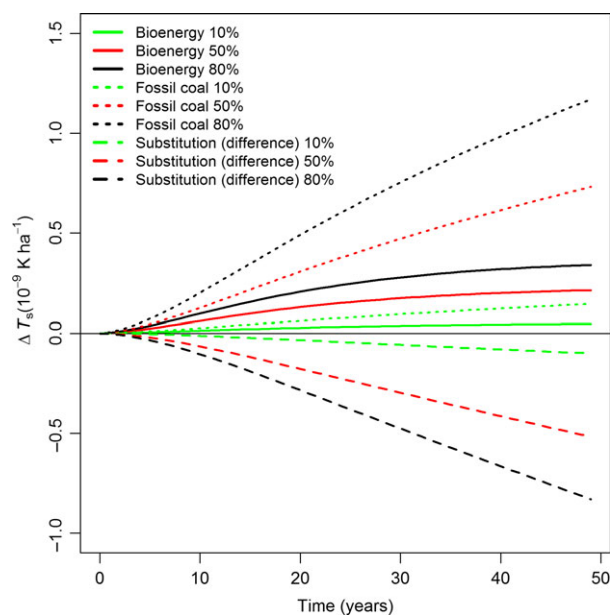


Fig. 2 Net global temperature effect (ΔT_s) of produced district heating projected into the future based on emissions from stump bioenergy (accounting for emissions from biomass production and carbon stock changes due to removal of stumps from the forest), compared to energy produced from fossil coal. The graph shows the net temperature effects for three levels of stump harvest (10, 50 and 80% of harvested stands) for the fossil coal system (Fossil coal), for the bioenergy system alone (Bioenergy), and when fossil coal is replaced with stump bioenergy, specifically the difference between Fossil coal and Bioenergy (Substitution (difference)).

stands where stumps are harvested and the future metapopulation size of the lichens (Fig. 3). The rate of metapopulation decline was proportional to the intensity of the stump harvest scenario (Table 1) with large metapopulation declines in some species (20–50% reductions) at the high stump harvest levels. However, the effects on the metapopulations were negligible at the lowest harvest level (10%). Biological properties of the species (Table 2) also explained the declines. Most important was the proportion of the population which was confined to spruce stumps with *Mycocalicium subtile* and *Xylographa vitiligo* showing contrasting results. However, also the age when stumps become suitable for colonization and the ratio between the colonization and extinction rates explained the declines. For example, the metapopulation size at the end of the projection period assuming stump extraction on 80% of the clear-cuts is larger for *Xylographa parallela* starting to colonize early and having a high colonization:extinction rate ratio than for *Absconditella lignicola* starting to colonize later and having a low ratio. The rate of decline was also related to reproductive mode but only

X. vitiligo had a different main reproductive mode and this species also had only a minor proportion of the population on stumps. It is thus the low proportion on stumps that explained its negligible metapopulation response. Life form did not explain the results.

All species, except *Xylographa vitiligo*, declined more than 15% within three generations over some time period under 50% or 80% stump harvest scenarios (Fig. 3). They may therefore become red-listed in Sweden given these scenarios. In the 10% scenario, no species risked population declines warranting red-listing. However, most species reached new equilibrium levels at lower metapopulation sizes within two to three decades. They are therefore unlikely to go extinct given these scenarios. The lichen *Xylographa parallela* also reached new metapopulation equilibrium, but continued to be red-listed over the projected time period due to the long generation time ($50/3 = 17$ years) of the species. *Xylographa vitiligo* was an exception remaining unaffected by stump harvest as a result of only a small proportion of the metapopulation on spruce stumps (Table 2).

Discussion

Trade-offs between climate benefit and biodiversity loss from stump harvest

To our knowledge, this is the first study to simultaneously investigate future climate and biodiversity impacts when harvesting stumps for bioenergy, highlighting a clear trade-off between the two environmental objectives. Earlier studies of trade-offs between conflicting environmental objectives from stump harvesting have been theoretical or not used field data on the dynamics of species through the existence of the stumps constituting substrate for the true species (Geijer *et al.*, 2014; Johansson *et al.*, 2016). We show that when initiating stump harvesting for bioenergy on at least half of the forest land, metapopulation declines will be 3–4 times as fast as climate benefits for most lichen species over the first few decades. The resulting rapid future metapopulation declines will lead to red-listing of the majority of these currently common epixylic species. However, as the lichen metapopulations stabilize at lower equilibrium levels after two to three decades and as climate benefits continuously increase, these trade-offs may be transient. This is important to consider when balancing environmental targets with fixed time frames, such as the European Renewable Energy Directive 2009/28/EC by 2020 and the European Biodiversity Strategy (European Commission, 2011) by 2020. Increased stump harvesting will reduce the possibility for achieving biodiversity objectives in the short term, but maybe not in the long term. While biodiversity (i.e.,

metapopulation sizes) stabilizes (albeit at lower levels), the climate benefits may become more influential over the longer-term perspective. Importantly though, this conclusion concerns common species. Rare species with a large proportion of their populations on stumps may be threatened by high stump harvest levels (Johansson *et al.*, 2016; de Jong & Dahlberg, 2017).

Stump harvest as a sustainable climate change mitigation strategy

There is a debate about the climate benefit of forest bioenergy where deviating views are partly due to differences in assumptions about the bioenergy system and product use (Lamers & Junginger, 2013). Increased harvests of trees from old growth forests, not part of the managed forest landscape, to get biomass for bioenergy have been claimed of limited benefit or even unfavorable for the climate (Holtmark, 2012; Schulze *et al.*, 2012), as the carbon released immediately by combustion needs to be resequenced again in the next forest generation. The length of the payback time of the carbon debt is, however, dependent on the type of fossil fuel that such wood energy replaces (Gustavsson *et al.*, 2015). In contrast to harvesting whole trees, our study together with others (e.g., Melin *et al.*, 2010; Repo *et al.*, 2011, 2012; Zetterberg & Chen, 2015; Ortiz *et al.*, 2016) shows that residue-based forest bioenergy from slash or stumps after final felling does reduce GHG emissions and global net temperatures when replacing fossil coal. Harvesting slash and stumps involves release of biogenic carbon that would have been released anyway (Repo *et al.*, 2012; Zetterberg & Chen, 2015; Ortiz *et al.*, 2016).

Although earlier studies operate over different spatial scales, none provide an LCA of the net global temperature reductions from harvesting stumps over different proportions of the landscape. Our LCA showed that aggregated over a typical managed boreal forest landscape and rotation period, the net global temperature reduction increased gradually over time when replacing fossil coal with stump bioenergy. Provided that current management recommendations of harvesting stumps on 10% of the landscape remain unchanged, the net global temperature reduction over time will be very small, almost reaching a steady state after a few decades. The net global temperature reduction increased more steeply over time at 50 and 80% stump harvest. The reason is mainly that the emissions from fossil coal were larger than the emissions from the stump procurement chain and combustion. Consequently, by extracting stumps on a larger proportion of the clear-cut forest land, more fossil coal-based energy can be replaced by stump bioenergy.

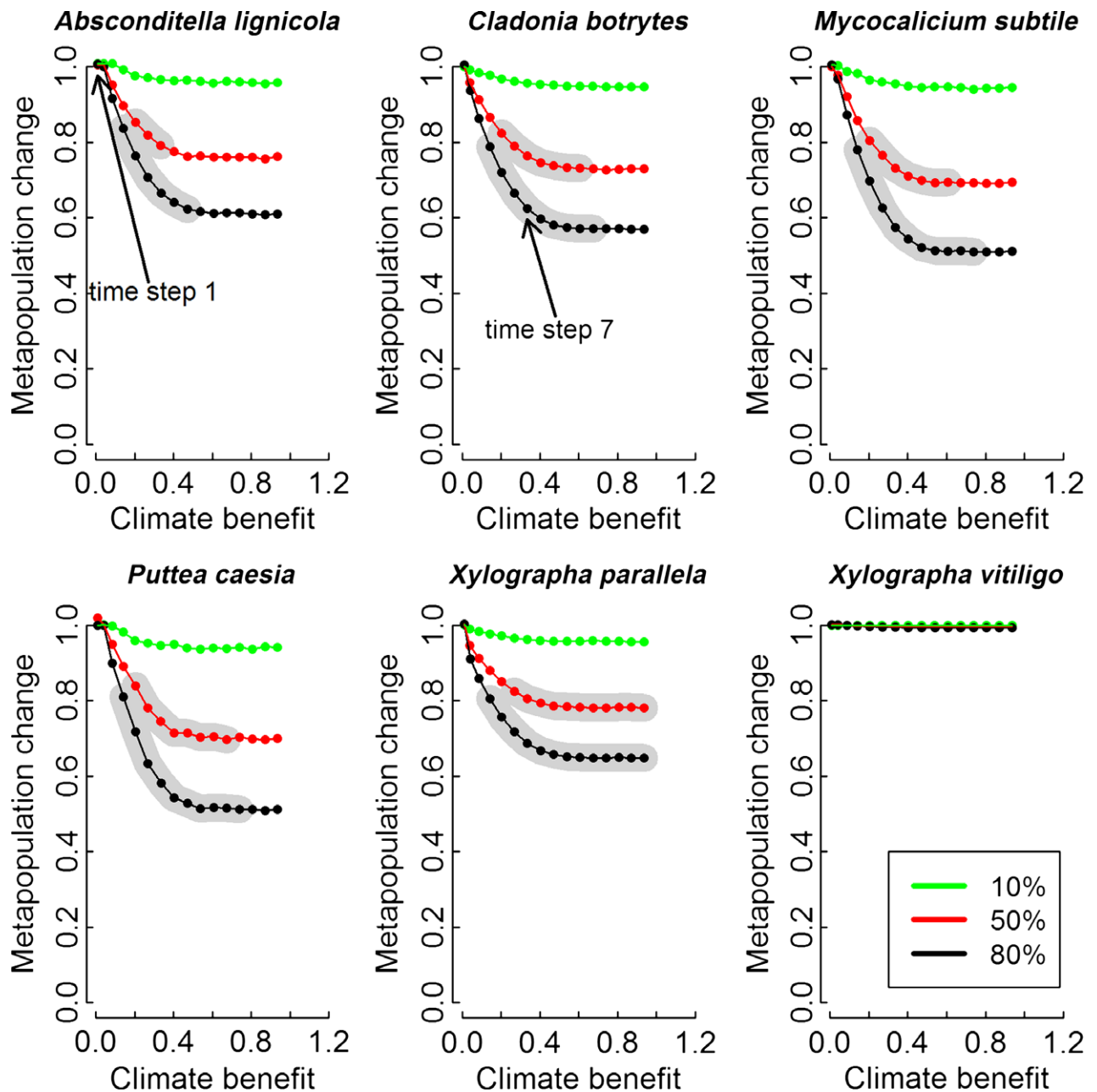


Fig. 3 Relationships between metapopulation change of six epixylic lichens and climate benefit (i.e., net global temperature reduction when replacing fossil coal) assuming three levels of harvesting of stumps for bioenergy. Each dot represents one time step (3 years), and time starts to the left and proceeds to the right. Climate benefit is scaled in relation to the largest benefit, 1.0, which is at the end of the simulation period, see Fig. 2 showing actual net temperature changes. Shaded areas are periods where a species is projected to decline more than 15% over the last three generations and therefore may become red-listed as Near Threatened according to IUCN criteria (IUCN Standards and Petitions Subcommittee, 2016).

In this study, we did not account for any feedbacks between stump harvesting and soil carbon turnover through enhanced soil disturbances, although stump extraction might lead to soil mixing, compaction, temperature increases, wetter soils and damage on decomposers

(Walmsley & Godbold, 2010). These different effects might lead to both faster and slower decomposition rates, but still, field experiments indicate no significant net effects on soil C mineralization rates in boreal forests (Karakka *et al.*, 2016). In case of increased soil carbon turnover, the

negative climate effects might be long-lasting, though (Ortiz *et al.*, 2016).

Implementing stump harvest on more than half of the clear-cut forest land gave net global temperature reductions $>0.5 \cdot 10^{-9}$ K ha⁻¹ after 50 years. There is currently no sustainability criteria for solid fuels within the EU, but for liquid fuels, the threshold is 35% reductions in CO₂ emissions according to European sustainability criteria (2009/28/EC), suggested to increase to 50%. Our results are not fully compatible with this criterion as the climate metrics differ, although our results reflect better the actual climate impact. Nevertheless, our results show reductions in temperature impact from stump bioenergy compared to fossil coal of 50% after 10 years increasing to 70% reduction after 50 years. This implies that the sustainability criteria should be fulfilled.

Stump harvest as a potential threat to lichen metapopulations

Large stump harvest levels had large negative effects on epixylic lichens, as a result of decreasing the amount of suitable deadwood substrate in the landscape. Assuming 50–80% stump harvest, most species experienced 20–50% metapopulation declines, while the effects of the lowest 10% stump harvest level were negligible. *Xylographa vitiligo* was the exception, being tolerant to all scenarios due to the low proportion of its metapopulation on spruce stumps. However, the declines were transient and new metapopulation equilibria were reached within two to three decades for all declining species. This finding of potentially smaller future equilibrium sizes has rarely been found, especially not in relation to bioenergy-related land-use changes. The time lags of two to three decades for reaching new equilibria were also considerably shorter than the 100 years that have been found for fictive epixylic species in landscapes with 50% stump harvest (Johansson *et al.*, 2016). Several biological properties of the species affected the predicted future metapopulation sizes. In particular, the proportion of the metapopulation which was confined to spruce stumps had large influence, but also the stump age at which the species start colonizing and the relationship between the colonization and extinction rates. The three species *Cladonia botrytes*, *Mycocalicium subtile* and *Puttea caesia*, with more than 50% of their metapopulations on Norway spruce stumps, declined the most. Among these, *Cladonia botrytes* with the largest colonization:extinction ratio declined the least.

While the species investigated here are rather common and currently not of conservation concern in the Nordic boreal countries, we note that the rapid declines induced by high stump harvest levels will be

enough to push the species to Near Threatened status, following criterion A of IUCN (IUCN Standards and Petitions Subcommittee, 2016). This is not unreasonable, considering that a species like *Cladonia botrytes* is indeed already listed as a conservation target species in several central European countries (Yahr *et al.*, 2013). Moreover, considering that stumps left after clear-cutting constitute the most common type of coarse woody debris in Fennoscandian managed forests, it is not surprising that a landscape-level stump extraction of more than 50% potentially leads to substantial future declines of rather common deadwood organisms (e.g., Andrén, 1994; Hanski, 2011). Declining species were indeed only red-listed over a few decades, but it is still difficult to foresee how the smaller metapopulation sizes potentially reduce the viability and resilience to future catastrophes and environmental stochasticity (e.g., Hanski & Ovaskainen, 2000). Johansson *et al.* (2016) indeed found potentially negative effects on already rare species, and de Jong & Dahlberg (2017) points out that high levels of stump extraction will likely affect species of conservation interest. At the same time, reductions of these and other species due to a warming climate may be even more severe (Ellis, 2013; Meller *et al.*, 2015).

Limitations of the study

One limitation is that the simulations of forest and metapopulation dynamics were conducted from only one region in central Sweden. Simulating these dynamics in other regions of Fennoscandia may give somewhat different metapopulation declines, as rates of colonization–extinction, the local substrate availability, harvest rotation times and stump decomposition rates vary among regions. It is, for example, known that the total metapopulation sizes of the study species increase toward the north and decrease toward the south (Svensson *et al.*, 2016; except *Absconditella lignicola*). However, the most important factor when assessing stump harvest impacts is not the absolute metapopulations size, but the *proportion* of the metapopulation that is confined to spruce stumps (Table 2). Another limitation is that we did not account for the direct impact of climate change in lichen or stump dynamics. Nordic species are anticipated to track suitable climate conditions northwards, leading to future range contractions or reduced species' performances (e.g., Bellard *et al.*, 2012; Ellis, 2013). In Sweden, northeastward shifts have already been suggested for two lichen species (Lättman *et al.*, 2009) and the decline of *Vulpicida pinastri* in Britain has been attributed to warming (Ellis & Binder, 2007). The direct effect of stump extraction is thus negative, but on the

other hand, mitigating climate change has the potential to reduce the rate of range contractions leading to a positive net effect on the metapopulation sizes. Moreover, reduced global coal usage should decrease the negative effects of coal mining where it takes place (Wickham *et al.*, 2013). There is a clear risk for continued coal mining in biodiversity hotspots in the future (Abood *et al.*, 2015).

Climate assessments of forest bioenergy based on residues are strongly influenced by the simulated decomposition rate, which include marked uncertainties. For stumps, one important reason for this is the sparse long-term experimental decomposition data beyond ca. 50 years (Stendahl *et al.* 2017). Applying different stump decomposition rates based on different calibration data and theoretical assumptions may give rise to different net forest carbon balances (Gustavsson *et al.* 2015; Zetterberg & Chen, 2015), although conclusions on potential climate benefit will be similar (Stendahl *et al.* 2017). Another factor that will have large influence on the end result is the choice of fossil alternative (Gustavsson *et al.* 2015). We assume fossil coal, and when compared to natural gas, the climate benefit of stump bioenergy is postponed for two to three decades (Ortiz *et al.*, 2016).

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Figure S1. The decomposition of stumps including uncertainties as modelled by the Q-model for the investigated area according to Ortiz *et al.* (2011).

Table S1. Emission factors ($\text{g MJ}^{-1}_{\text{fuel}}$) for the fossil reference fuel hard coal (Ortiz *et al.*, 2016).

Table S2. Primary energy use ($\text{GJ ha}^{-1} \text{yr}^{-1}$) and emission of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) ($\text{kg ha}^{-1} \text{yr}^{-1}$) from the stump supply chain (excluding CO_2 emissions from combustion, storage losses and decomposition).

Table S3. Parameter estimates of models for the metapopulation dynamics of the lichen study species.

Data S1. Models and parameter estimates for lichen colonization-extinction dynamics and stump occurrence.