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Cost of turning forest residue bioenergy to carbon neutral

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ABSTRACT

Harvesting branches, unmerchantable tree tops and stumps for bioenergy reduces the carbon stock and the sink capacity of forest. We analyzed forest management changes that are financially viable for a forest owner to compensate for carbon loss resulting from the forest harvest residue extraction, and thus lead to truly carbon-neutral forest bioenergy. The management options studied included forest fertilization, elongated rotation periods, varying the type of forest residues extracted, and leaving high stumps. The costs of carbon loss compensation varied widely from 5 to 4000 € ha^{-1} between the management options. The lowest costs resulted from harvesting quickly decomposing branches combined with low levels of fertilization. Harvesting all residues and applying intensive fertilization regimes or postponing final felling generated the highest costs. A requirement for fast carbon loss compensation increased the costs. The results indicated that changes in the forest management improve the carbon benefits of forest bioenergy, and some of these changes are inexpensive for the forest owner. The optimization results suggested that the longer time period was allowed for the carbon loss compensation, the fewer cost-effective silvicultural measures existed in the optimal combination of management regimes for the compensation.

1. Introduction

Intensifying biomass removals from forests reduces forest carbon stocks and carbon sink capacity, and thus may partly offset the climate benefits of forest bioenergy (Haberl et al., 2012; Holtsmark, 2012; Repo et al., 2011, 2012; Schlamadinger et al., 1995; Schulze et al., 2012; Walker et al., 2010; Zanchi et al., 2011). Forest harvest residues, such as branches, unmerchantable tops and stumps, are an important source of bioenergy from northern temperate and boreal forests, and the use of these residues is expected to grow in the future (Díaz-Yáñez et al., 2013; Fritsche and de Jong, 2013; Mantau et al., 2010; Scarlat et al., 2013). Increasing harvesting of forest residues decreases carbon input to the carbon pools of dead wood, litter and soil, and consequently results in forest carbon losses (Mäkipää et al., 2014; Palosuo et al., 2001; Schlamadinger et al., 1995; Schulze et al., 2012; Zanchi et al., 2011). Bioenergy production releases the carbon stored in the harvested residues into the atmosphere at once. If left on the forest ground, the decomposition of the residues would still release the carbon, but the process would take years or decades (Repo et al., 2011). Consequently, the use of forest harvest residues to energy decreases forest carbon stocks and increases atmospheric concentration of CO_2 compared to a situation in which the residues are left to decompose in forests. These emissions that result from a decrease in the forest carbon stocks are similar to those occurring with land-use change (Fargione et al., 2008; Melillo et al., 2009; Searchinger et al., 2008, 2009).

Changes in forest management may compensate for the carbon loss, and hence improve the climate impacts of bioenergy produced from forest harvest residues (Cherubini et al., 2011b; Repo et al., 2014; Routa et al., 2012b; Sathre and Gustavsson, 2012). An increase in carbon sequestration after residue harvesting can balance for the carbon loss in such a way that the net CO_2 emissions are zero over a certain period of time, such as, a forest rotation period (Pyörälä et al., 2014; Repo et al., 2014). In this case, it is justified to claim that forest bioenergy is carbon neutral. Examples of strategies to increase forest carbon stocks include, extending rotation lengths (Cooper, 1983; Kaipainen et al., 2004; Liski et al., 2001), changes in initial stand density and thinning strategies (e.g. Niinimäki et al., 2013; Pihlainen et al., 2014) and forest fertilization (Boyland, 2006). Extending forest rotation period allows trees to grow larger and forests to accumulate more litter and soil organic matter, whereas forest fertilization increases tree growth and litter input to the soil from living biomass and forest thinnings. Previous studies show that nitrogen fertilization reduces net greenhouse gas (GHG) emissions of forest residue bioenergy production over a forest rotation period (Alam et al., 2013; Eriksson et al., 2007; Routa et al., 2012b), and decreases the climate warming impact measured in terms of changes in radiative forcing (Cherubini et al., 2011b; Sathre and Gustavsson, 2012). The magnitude and duration of the carbon loss depend on the decomposition rate of the harvest residues, with the

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decay rate decreasing with an increasing size of woody litter (Harmon et al., 1986; Janisch et al., 2005; Repo et al., 2011; Tuomi et al., 2011a). Therefore, prioritizing quickly decomposing residues in forest residue harvesting reduces the carbon loss from forest, and improves the climate impact of forest residue bioenergy (Eriksson et al., 2007; Repo et al., 2012). The climate impact could be further improved by combining harvesting of quickly decomposing slash with fertilization (Eriksson et al., 2007). Another possible means of balancing for the carbon loss resulting from forest residue harvesting is to leave higher stumps at the clear-cut site.

Changes in forest management increase forest carbon stocks, but these changes often come with a certain cost to a forest owner. Maintaining financial profitability while increasing the carbon stocks poses a challenge because of long planning horizons and slow carbon sequestration in forests (Boyland, 2006; Richards and Stokes, 2004). Forest fertilization generates costs to the forest owner, extending rotation length postpones income from final felling, and cutting stems at higher level to leave higher stumps reduces income from timber. One the other hand, some changes in the forest management and residue harvesting practices may even result in financial surplus. For example, fertilization increases income from timber and energy wood, and combining slash harvesting with the creation of high stumps may be a financially profitable management option (Ranius et al., 2014; Routa et al., 2012b). However, previous studies suggest that the forest owner cannot simultaneously maximize financial profitability of biomass production for timber and energy, and carbon sequestration in the forest (Pyörälä et al., 2014; Routa et al., 2012b). These prior studies show the effects of alternative forest management regimes on the energy wood production, carbon balance or net present value (NPV) (Pyörälä et al., 2014; Routa et al., 2011, 2012b). However, the cost-effectiveness of alternative measures, or measure combinations, to compensate for the carbon loss and produce carbon-neutral forest residue bioenergy have not been studied. Such analyses on the costs and the effectiveness of compensatory measures are needed to support decision-making.

The aim of this study was to analyze which changes in forest management and forest residue harvesting, or combinations of these two, would be financially viable to compensate for the carbon loss resulting from forest residue extraction for bioenergy, and thus improving the climate impacts of forest residue bioenergy. This study had three objectives. The first objective was to determine direct costs to the forest owner resulting from the compensation of the carbon loss by different levels of forest fertilization, elongated rotation periods, the choice of the type of forest residues harvested, and leaving high stumps, at different time periods and different discount rates. Since it is debatable, who the actual payer of the carbon loss compensation should be, the second objective was to estimate the additional cost of carbon neutrality to the end-user of forest residue bioenergy. The third objective was to identify a combination of different forest management and residue harvesting regimes that produces an optimal financial outcome for the forest owner from carbon-neutral forest bioenergy production. This study focused on the point of view of the forest owner at stand-level whereas analyses of economy-wide effects (e.g. Lintunen and Uusivuori, 2014), or impacts on a national level are beyond its scope (e.g. Latta et al., 2013; Lintunen and Uusivuori, 2014; Ochuodho and Lantz, 2014). The stand-level estimates of the costs of carbon loss compensation presented in this study may be utilized in economic analysis on socially optimal carbon policies.

2. Methods

2.1. Carbon budget of a forest stand

We simulated carbon budgets of differently managed Norway spruce stands in southern Finland with and without forest residue harvesting for bioenergy, and analyzed the possibilities to compensate for the carbon loss resulting from the residue harvesting. The carbon loss was defined as the difference in the forest carbon stocks between forest harvesting options with and without bioenergy production. The residues were only collected from final fellings, and bioenergy was produced from the residues on the harvest year. The simulated options of forest residue harvesting were i) no residue harvesting ii) all residues, iii) branches, iv) branches and unmerchantable tops, v) unmerchantable tops, stumps and coarse roots, and vi) stumps and coarse roots. Only 75% of coarse roots were extracted. To follow the recommended practices for energy wood harvesting in Finland, needles were assumed to be left in the forest to avoid nutrient loss (Äijälä et al., 2010). Forest residue harvesting was assumed to have no effects on the growth of the next tree generation.

To study means to compensate for the carbon loss, we simulated regimes of forest management and residue harvesting that differed in type of forest residues harvested, the intensity of forest fertilization, and the rotation period. We simulated five residue harvesting options (described above ii)–vi)) combined with four levels of carbon loss compensation with fertilization (growth increase 0, 10, 20 and 30%), and with four different rotation periods (90, 100, 110 and 120 years). In addition, we simulated carbon dynamics in three regimes including high stumps. These high stumps are created by cutting stems at higher level than the usual (Ranius et al., 2014). The creation of high stumps is a means to increase the amount of slowly decomposing residues. In these three regimes branches and unmerchantable tops were harvested for energy assuming that i) all income from forest residues was used to create high stumps (20 high stumps), ii) half of the income was used to create high stumps (9 high stumps), or iii) 60 high stumps were created. The height of the high stumps was 4 m and diameter 30 cm (Liski et al., 2013; Ranius et al., 2014). In total we simulated 39 different forest management and residue harvesting regimes (Table 1).

The carbon loss was considered to be fully compensated for when both the total forest carbon stock (aboveground and belowground biomass, and soil) and the soil carbon stock were equal to or larger than these stocks in no forest residue harvesting regime after the studied time period. This very strict requirement for carbon neutrality was applied to avoid reduction both in biomass carbon stock and in soil carbon stock because measures that balance for the total forest carbon loss (biomass and soil) do not necessarily prevent soil carbon loss (Repo et al., 2014). The fertilization options required an additional increase in carbon sequestration to balance for the GHG emissions over a life cycle from fertilizer production and nitrous oxide emissions from soil (Koponen et al., 2013). Exclusion of these emissions would result in an overestimation of the positive effect of forest fertilization.

The forest carbon dynamics were simulated with a combination of two models, the forest growth and stand level carbon budget model CO2FIX 3.2 (Masera et al., 2003; Schelhaas et al., 2004) and the litter and soil carbon model Yasso07 (Tuomi et al., 2009, 2011a,b). The CO2FIX is a bookkeeping model that simulates annual forest carbon stocks and fluxes on a hectare scale. The litter input from the CO2FIX model and the decomposition of the organic matter, simulated with the Yasso07, determined the size of litter and soil carbon stock (Repo et al., 2014). The values of current annual increment, and the timing and the quantity of forest thinnings were adopted from Kaipainen et al. (2004), because these values are based on Finnish growth and yield tables. In addition, the timing of thinnings is in line with the current good practice guidance to forestry in Finland (Äijälä et al., 2014). The forest was thinned at the ages of 40, 60 and 80 years. In the no residue removal regime all foliage, branches and roots of the trees cut in the thinnings and final fellings were directed to litter. As much as 15% of stem wood cut in the thinnings and 10% of final fellings, were added to the litter pool, half of these amounts as unmerchantable tops and half as stumps (Repo et al., 2014). The CO2FIX model does not include fine roots. Fine roots comprise only few percent of the total biomass, and therefore inclusion or exclusion of fine roots does not have a significant effect on the results.