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Slash and stump harvest have no general impact on soil and tree biomass C pools after 32–39 years ☆

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ABSTRACT

The energy from forest biomass is central in achieving climate mitigation goals in the European Union (EU). The carbon (C) balance and climate mitigation benefits of this strategy are, however, questioned; particularly, when stumps and slash are also removed during harvest. Stump and slash harvest result in nutrient loss, which might cause reduced growth and thereby decrease C sequestration of the next generation of trees. In addition, the removal of the slowly decomposing biomass may lead to a depletion of the soil C pool. In the case of stump harvest, these negative effects may be partly compensated for by increased nutrient availability due to a stimulated mineralization and reduced competition from understory vegetation as a result of the soil disturbance caused by the stump harvest.

Here we analyze the effect of different harvest intensities on total, soil (humus and mineral down to 10 cm), and tree biomass C pools based on data from eight field experimental sites across Sweden regenerated with Scots pine (*Pinus sylvestris* L.) or Norway spruce (*Picea abies* (L.) Karst.) 32–39 years after clear-cut with (i) stem-only harvest; (ii) stem and stump harvest; (iii) stem and slash harvest; and (iv) stem, stump and slash harvest. Due to a lack of replicates at the site level we focused our analyses on general treatment effects across all sites and on species level effects ($n = 4$). The main hypotheses were that across all sites (i) the total C pool is generally unaffected by stump harvest, (ii) whereas the total C pool generally decreases after slash harvest. We also hypothesized that (iii) the total C pool of spruce stands is more negatively affected by slash harvest in comparison to pine stands.

Despite considerable variation, there was no significant general effect of harvest treatments on the total, soil or tree biomass C pools across all sites, thus hypothesis (i) was confirmed, whereas hypothesis (ii) was rejected. As compared to the total C pool following stem-only harvest the average total C pool was reduced following the two treatments which included slash harvest in spruce stands, whereas the C pool was unaffected or increased in pine stands, indicating a species-specific effect. However, these differences were not statistically different and hypothesis (iii) was therefore also rejected. Based on the results presented here we conclude that stump and/or slash harvest have no general medium-term effects on the total forest C pool. However, given the limitations of the experimental design in this study and the general lack of studies investigating stump and slash harvest effects on the C balance, we call for more studies with focus on long-term field experiments that are replicated at the site level to be able to reveal potential site- and species-specific responses to slash and stump harvest.

1. Introduction

Currently, more than half of the renewable energy in the EU comes from biomass due to a well-established infrastructure and market (Mantau et al., 2010; Pelkonen et al., 2014). For example, forest industry residues are fully utilized in Sweden and Finland (Saal, 2010). Furthermore, the EU member states have accepted binding targets to reduce greenhouse gas emissions and increased share of renewable energy (EC, 2009). Demand and use of forest biomass will likely continue to increase (UNECE/FAO, 2011). To satisfy an increasing demand, one option is to increase the harvest intensity by including stumps and slash (i.e. tree tops and branches).

The climate benefits of using forest biomass instead of fossil energy have been questioned, particularly when coarse logging

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residues like non-merchantable stemwood and stumps are harvested and combusted (Hannam, 2012; Zanchi et al., 2012). Stump harvest has been disputed, firstly, because of the direct removal of C stored in the stump biomass and its combustion which results in an instant emission of carbon dioxide (CO_2) (Hope, 2007). Left in the forest, stump biomass would slowly decompose and release CO_2 into the atmosphere at a much slower rate (Repo et al., 2012; Shorohova et al., 2012) and possibly add some recalcitrant fractions to the soil C pool (Berg et al., 2009). Secondly, there is a concern that stump harvest causes soil disturbance that may increase C mineralization and release CO_2 from the soil organic matter (Grelle et al., 2012; Walmsley and Godbold, 2010), although this effect has been disputed (Strömgren and Mjöfors, 2012; Strömgren et al., 2012).

There are other effects of stump harvest that potentially will increase nutrient availability and thus forest production, at least in the short run. If soil disturbance causes increased mineralization of soil organic matter it will likely increase nutrient availability (Kataja-aho et al., 2012a). Furthermore, exposed mineral soil following stump harvest reduces competition from vegetation and thereby creates better conditions for seedling establishment (Nilsson and Örlander, 1999) and seed germination (Winsa, 1995). Stump harvest might therefore promote planted and naturally regenerated seedling establishment (Karlsson and Tamminen, 2013; Tarvainen et al., 2015) and subsequent tree growth (Kataja-aho et al., 2012b; Örlander et al., 1996). Subsequently, increased tree growth will result in a higher C pool and provide more above- and belowground litter that will add to the soil C pool, eventually compensating for soil C losses (Egnell et al., 2015).

Compared to stump harvest, slash harvest has potentially less negative short-term effects on the soil C pool as a result of lower soil disturbance and faster decomposition rate (Hyvönen et al., 2000). On the other hand, slash biomass contains more nutrients than stump biomass (Hellsten et al., 2013; Ouro et al., 2000) and therefore more nutrients are directly lost from the site during slash harvest. Additionally, slash left on-site may have a short-term mulching effect resulting in an increased nutrient availability for the subsequent stand (Bai et al., 2014; Emmett et al., 1991). Consequently, nutrient losses during slash harvest may potentially reduce tree growth (Egnell, 2011) and thereby decrease C sequestration in the subsequent stand. Overall, this suggests that slash harvest might reduce subsequent tree growth and thereby C sequestration, whereas stump harvest might increase tree growth at the expense of a decreased soil C pool. Thus, the combined effects from stump and slash harvest on the total C pool (soil + tree biomass) might counterbalance and therefore have no or a smaller net effect relative to the individual impacts of stump and slash harvest.

Recent reviews have highlighted that the knowledge on the long-term effects of stump and slash harvest on the total forest C pool is still limited (Clarke et al., 2015; Walmsley and Godbold, 2010). Egnell et al. (2015) recently reported a significantly reduced soil C pool and a significantly increased C pool in tree biomass with no significant net effect on the total C pool 24 years after stump harvest in combination with deep soil cultivation. However, slash was not harvested in that study and the extreme harvest intensity (100% of stumps harvested) and soil disturbance (up to 100% soil disturbance down to a depth of 50 cm) was beyond what could be expected following a practical stump harvest operation (Kataja-aho et al., 2011; Tarvainen et al., 2015). Consequently, there remains a need to explore different effects from slash harvest and stump harvest as well as more realistic soil treatments. Furthermore, Strömgren et al. (2013) investigated effects on C pools in soil and biomass for harvest of (i) stem-only, (ii) stem and stump, and (iii) stem, stump and slash in four stands. They found a lower total C pool 25 years after stem, stump and slash harvest in comparison to the two lower harvest intensities. However, to our knowledge, no empirical study to date has compared the separate and combined effects of stump and slash harvest on the total C balance in the forest.

In addition, the impact of stump and slash harvest on soils may be further modified by the response of the new stand which may differ between species (Walmsley and Godbold, 2010). These differences might result from contrasting adaptation potentials of pine and spruce to disturbance caused by stump harvest operations (Saksa, 2013). For example, Hope (2007) reported increased growth of lodgepole pine (*Pinus contorta* L.), but not for hybrid spruce (*Picea glauca* (Monech) Voss × *Picea engelmannii* Parry) after stump harvest. Likewise, Karlsson and Tamminen (2013) found significantly increased stem biomass production in Scots pine (*Pinus sylvestris* L.) whereas no effect was detected in Norway spruce (*Picea abies* (L.) Karst.) planted at the same site following stump and slash harvest.

In this study, we compared C pool data for soil (humus and 10 cm down into the mineral soil) and tree biomass from eight field experiments in Sweden 32–39 years after conventional clear-cut with (i) stem-only harvest; (ii) stem and stump harvest; (iii) stem and slash harvest; and (iv) stem, stump and slash harvest. The main objective was to study the effect of the different harvest treatments on the total C pools including C in soil and tree biomass across all sites. Our main hypotheses were that across all sites (i) the total C pool will be generally unaffected after stump harvest, whereas (ii) the total C pool will generally decrease after slash harvest. Consequently, the total C pools will differ in the order: stem-only harvest = stump harvest > slash harvest = stump + slash harvest. We also hypothesized that (iii) the total C pool of spruce stands is more negatively affected by slash harvest in comparison to pine stands.

2. Materials and methods

2.1. Study sites

Eight field experiments were established between 1978 and 1980 after clear-cutting of mature Scots pine, Norway spruce or mixed conifer stands with the aim to study long-term effects of stump and/or slash harvest (Table 1, Kardell and Wärne, 1981). They were geographically distributed over the whole of Sweden, covering most climate regions (Fig. 1) with climatic, site productivity and nitrogen (N) deposition gradients. The altitude of the study sites ranged from 30 to 530 m a.s.l. The soils were mesic sandy–silty till with developed haplic podzols, although with a poorly developed E-horizon at Tagel, Remningstorp and Ekenäs.

2.2. Experimental design and treatments

At all study sites, four treatments were applied on 30 × 30 m plots with a 10 m buffer (Fig. 1 and Table 1). The original design included two blocks per site, however, as the soil sampling was limited to one of the blocks, only one block per site was used in the analyses. The treatments were: conventional clear-cut with (i) stem-only harvest (stem-only); (ii) stem and stump harvest (stump); (iii) stem and slash harvest (slash); and (iv) stem, stump and slash harvest (stump + slash). Treatments were randomly allocated within the used block. The study sites were clear-cut in 1978–1980, primarily during winter time with sufficient snow cover; however, at Tagel, Grävsvinsberget and Rackasberget harvest was done without snow cover. At Kvisslevägen and Grävsvinsberget, a feller-buncher was used for clear-cutting. At Garpenberg and Rackasberget the trees were felled manually and delimbed