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Stump harvesting in *Picea abies* stands: Soil surface disturbance and biomass distribution of the harvested stumps and roots

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A B S T R A C T

Finland has a long tradition of utilizing forest-based biomass for energy and industry purposes and the use has steadily increased in the past decade due to changes in international and regional energy policies. Intensive harvesting practices, in which a larger proportion of the woody biomass is removed from the forest stand, are becoming more common. The objectives of this study were (i) to evaluate the spatial and temporal extent of soil surface disturbance caused by stump-root system harvesting and (ii) to quantify how much biomass and nitrogen is removed from the stand in stump and coarse root harvesting. The extent of surface disturbance was assessed in three clear-cut Norway spruce (*Picea abies*, (L.) Karst.) stands in southern and central Finland, differing in time since harvest. To determine the biomass distribution of the stump-root system, stumps and coarse roots were excavated at one of the experimental stands.

Across all age classes (time since harvest) less soil surface had remained undisturbed at the stump harvesting sites (52%) than at the sites where only mechanical site preparation (28%) had been carried out. Thus, the findings of this study indicate that soil disturbance caused by stump harvesting can exist on forest soil surface for more than a decade following harvest. The total biomass of the stump-root system in the stand was estimated to 39.3 Mg ha^{-1} and 79% of this biomass was removed during stump harvesting and consequently, 8.3 Mg ha^{-1} of stump-root biomass remained in soil. The stump-root system accounted for 17% of the whole-tree biomass, and coarse roots and fine coarse roots represented a significant portion of it (73%). Thus, the stump-root system represents a large biomass component in boreal forest stands. However, forest management utilizing stumps may result in carbon losses from the stand.

1. Introduction

There is an increasing interest for using renewable sources to replace a part of the fossil fuels in energy production in the European Union. In Finland, like in many forested countries, forest bioenergy is considered a sustainable and easily accessible energy resource. The use of wood-fuels has steadily increased within the last century, with the current share of wood-based fuels (this includes forest biomass and industrial by-products such as saw dust and black liquor) being 75% (in 2017) of renewable energy consumption and 26% of the total energy consumption (19.5 million m^3 – increase of 6% from 2015; LUKE, 2017). Forest bioenergy includes logging residues, stumps and small-size or inferior-quality tree stems that are normally not harvested in conventional, stem-only harvesting (Helmisaari et al., 2014). In Finland, stump harvesting started in 2000 and peaked in 2010–2013 with 1.1 million m^3, the current annual harvest being 0.76 million m^3 (LUKE, 2017). In practice, stump harvesting is currently predominantly carried out in fertile and moderately fertile Norway spruce (*Picea abies* (L.) Karst.) stands.

The effects of forest bioenergy harvesting on forest soil and tree growth have been shown to be site-, soil- and practice-specific (Walmsley and Godbold, 2009; Thiffault et al., 2011; Strömgren et al., 2013; Egnell, 2016). Stump harvesting is often combined with logging residue harvesting, after which the soil is prepared mechanically for the planting of the next tree generation. Mounding is the most common method used in Finland for planting Norway spruce (Kortesmaa et al., 2017). These procedures combined are more likely to cause greater direct effects on forest soil structure and indirect effects on soil

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processes, such as on the biogeochemical cycles, than either of these practices alone. Studies conducted in Finland have reported soil mixing and redistribution of soil organic matter (SOM) within the soil profile during 1–5 years (Kataja-aho et al., 2012) and 11–12 years (Kaarakka et al., 2016) after stump harvesting. A recent study by Persson et al. (2017) showed a tendency for changes in surface soil carbon (C) pools (organic layer + 0–10 cm mineral soil) 20–30 years after stump harvesting when compared to mounding, but observed no effect on soil C mineralization rate or soil nitrogen (N) transformations or pools.

Karlsson and Tamminen (2013) found no treatment effect on soil C and N pools 30 years after stump harvesting, whereas they reported an increase in tree seedling growth and natural regeneration. Stump harvesting causes heavy traffic at the logging site, as logging equipment is hauled to and from the stand, thus potentially resulting in more soil disturbance. Berg et al. (2015) reported a disturbed area of on average 6 m^2 per harvested stump. Bigger stumps come with an added yield from a bioenergy perspective, however, the average soil area disturbed increases exponentially with increasing stump size (Berg et al., 2015). Previous studies have reported that stump harvesting exposes a large surface area of mineral soil thus resulting in a larger area disturbed compared to site preparation (Kataja-aho et al., 2011a, 2012; Strömgren and Mjöfors, 2012; Saksa, 2013; Tarvainen et al., 2015). Stump harvesting also inevitably reduces the remaining stump and root biomass in the stand (Eräjää et al., 2010; Hyvönen et al., 2016).

Carbon neutrality of intensified forest biomass harvesting has been questioned in recent research (Repo et al., 2011; Schulze et al., 2012; Zanchi et al., 2012; Repo et al., 2015). Forest biomass removal results in direct and instant (i.e. combustion), as well as indirect and delayed C emissions (i.e. loss of decomposing biomass) from the harvested stand. In other words, carbon allocated to woody biomass will be released immediately instead of being retained in the ecosystem. Thus, the choice of the forest biomass partitioning used for bioenergy purposes greatly affects the magnitude and timing of potential C losses (Repo et al., 2011, 2012, 2015). Northern temperate and boreal forests are characterized by long stand rotation times (over 70 years) and relatively slow tree growth, which is in part limited by low N availability on mineral soils (Högberg et al., 2017). Stump and large diameter coarse roots are the largest coarse woody debris (CWD) component in a managed boreal forest, as other types of CWD are extracted in forestry operations (Eräjää et al., 2010; Palviainen et al., 2010; Rabinowitch-Jokinen and Vanha-Majamaa, 2010). Stumps and coarse roots decompose slowly, thus in a managed forest stand they serve as long-term C and N pools and as sources of nutrients (Melin et al., 2009; Hellsten et al., 2013; Palviainen and Finér, 2015). Therefore including stump-root systems in soil C and nutrient budgets of the whole stand would greatly improve the accuracy of these budgets/estimates (Sucre and Fox, 2009). Stump harvesting equivalents root harvesting as coarse roots and fine coarse roots represent the largest fraction removed in stump harvesting (Hyvönen et al., 2016). In the context of this article, stump-root system refers to the stump, coarse roots (diameter > 35 mm) and fine coarse roots (diameter = 5–35 mm) (Fig. 1).

Only a handful of studies have attempted to estimate the biomass and N removals associated with stump and coarse root removal (Hakkila, 1975; Augusto et al., 2015; Palviainen and Finér, 2015) due to the arduous nature of sampling entire stump-root systems. In Finland, a biomass study compiled from data from over 400 conifer stump-root systems estimated that stumps and coarse roots (diameter ≥ 5 cm) comprised 26–34% and 68% of the entire stump-root system biomass in a mature Norway spruce stand, respectively (Hakkila, 1975).

In Norway spruce roots, wood density increases from stump to roots, as the growth near the stump is faster and growth rings are thus larger (Hakkila, 1975). Harvested woody biomass also almost always includes the bark and finer roots which have a higher proportion of bark than coarse roots (Hakkila, 1975). Bark contains more nutrients than root wood (Hellsten et al., 2013), which contributes to thinner coarse roots having a higher concentration of nutrients. Fine, absorptive roots break

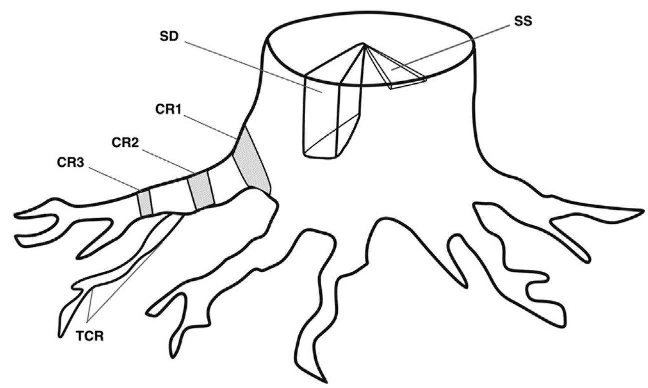

Fig. 1. Illustration of the sampling of the stump-root system. Stump sector (SS) and stump disc (SD) samples were collected in longitudinal and vertical direction, respectively. Coarse root discs (CR1–CR7) (diameter > 35 mm) were collected from the coarse roots in the direction of root in 30 cm intervals. Thin coarse roots (TCR) (diameter = 5–35 mm) were sampled in their entirety (i.e. the whole root was collected). Image is not to scale. Modified from Vaittinen, 2008.

easily at stump harvesting and therefore a part of them remains in the soil after harvesting. Nevertheless, if fine roots are removed with the stumps a substantial nutrient loss is likely (Hellsten et al., 2013) which in turn may potentially contribute to a growth loss in the next tree generation (Weatherall et al., 2006).

The aim of this study was to estimate the extent of soil surface disturbance caused by stump harvesting and how much biomass is removed from a stand in stump harvesting. More specifically, we wanted to quantify how much C and N is removed from the soil with the stumps and coarse roots that are pulled along with the main stump and assess the long-term impacts of stumps harvesting on soil C and N pools. Finally, we wanted to assess whether the disturbance effects of stump harvesting on soil surface persist over time.

2. Materials and methods

2.1. Experimental design

2.1.1. Soil surface disturbance

Three clear-cut Norway spruce sites (site is synonomous to stand in the context of this experiment), located in central and southern Finland, were studied. All the sites were located in the boreal vegetation zone, in the humid continental region (Table 1). The sites differed in time since harvesting: Haukilahti was clear-cut in 2001, Karkkila in 2007 and Hyvinkää in 2010. In 2014, 4, 7 and 13 years after final harvesting, six (5 m × 5 m, 25 m^2) experimental plots were established at each experimental site; three plots where mounding was carried out and three where stumps had been harvested in addition to mounding. Altogether 18 experimental plots were established (n = 3 per site). Experimental plots were located at a distance of at least five meters from other experimental plots and the edges of the whole site. Stony boulder areas and major forest machine paths were avoided and due to the lack of visible tracks on the experimental plots, wheel ruts were not included in the disturbance classification. The experimental plots were located in a 4 × 4 km area in Haukilahti and 300–600 m apart in Hyvinkää and Karkkila. Each 25 m^2 experimental plot was further divided into 25 separate one square meter frames, in which the soil disturbance class was determined using a 24 mm cylinder soil corer. Three disturbance classes were identified: (i) undisturbed, (ii) mound created in site preparation and (iii) excavation/stump pit (Table 2). The percent cover of each disturbance class (%) was estimated within each one meter frame (totaling to 100%).

All the experimental sites had been planted with Norway spruce seedlings the year following clear-cutting.

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