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Strong negative impacts of whole tree harvesting in pine stands on poor, sandy soils: A long-term nutrient budget modelling approach

P. Vangansbeke [a,b,*], A. De Schrijver [a], P. De Frenne [a], A. Verstraeten [c], L. Gorissen [b], K. Verheyen [a]

[a] Forest & Nature Lab, Ghent University, Geraardsbergsesteenweg 267, BE-9090 Melle-Gontrode, Belgium
[b] Flemish Institute for Technological Research (VITO), Boeretang 200, BE-2400 Mol, Belgium
[c] Research Institute for Nature and Forest (INBO), Kliniekstraat 25, BE-1070 Brussels, Belgium

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ABSTRACT

Global environmental changes such as climate change, overexploitation and human population growth increase the interest in woody biomass from forests as a resource for green energy, chemistry and materials. Whole Tree Harvesting (WTH) can provide additional woody biomass, mainly for bioenergy, by harvesting parts of the crown not harvested under conventional Stem-Only Harvesting (SOH). However, WTH also increases nutrient export, potentially depleting soil nutrients and threatening future stand productivity. Here we assess the impacts of WTH in Corsican pine stands (*Pinus nigra* ssp. *Laricio* var. *Corsicana* Loud.) with a rotation period of 48 years on poor, sandy soils in Belgium. We performed a detailed nutrient budget assessment before and after thinnings and clear-cuts under scenarios of WTH and modelled the long-term changes in ecosystem nutrients under both WTH and SOH. Our results demonstrate a strong immediate impact of WTH on aboveground nutrient stocks (mainly in clear-cuts). In clear-cuts with WTH, half of the base cations (calcium, potassium, magnesium) in the trees and forest floor were exported. The amount of available cations in the soil is not sufficient to immediately compensate for this export. Only one fourth of the amount exported were available for biota in the top 50 cm of the soil. We also modelled long-term development of ecosystem nutrients (available nutrients in the soil and nutrients in trees and forest floor) and found that the available soil calcium, potassium and phosphorus stocks are insufficiently replenished by deposition and weathering to sustain WTH on the long term. We found no indications of potential depletion of ecosystem cations and phosphorus for the next ten rotation periods under SOH management. Our results thus support a less intensive management in pine stands on poor, sandy soils, for instance, by adopting SOH and/or longer rotation periods.

1. Introduction

The use of woody biomass for bioenergy has increased by almost 80% in the 27 European Union member states between 1990 and 2008 (Eurostat, 2011). As a result of the EU 20-20 objectives, demand for woody biomass is expected to keep rising and even double by 2030 (Mantau et al., 2010). At the moment, more than two-thirds of harvested woody biomass originates from forestry (Mantau et al., 2010). Simultaneously, the demand for wood for materials is increasing (Mantau et al., 2010). On the one hand, this accelerating demand resulted in increased import of woody biomass, in western Europe mostly as pellets imported from North-America (Sikkema et al., 2010). The increased demand has also stimulated interest in production of wood chips and pellets in western Europe. Biomass in European forests is mainly produced as stem wood (52%); the remainder are logging residues (26%) and stumps (21%) (Mantau et al., 2010). The main source of biomass for bioenergy from forests originates from leftovers such as crown wood and smaller trees from early thinnings. Stump extraction is currently economically unfeasible in several European regions (including Belgium) with a very low forest cover (e.g., costs mentioned in Berch et al. (2012) largely exceed the current market prices). Stem wood, on the other hand, is primarily used for material purposes and in Belgium kept away from the energy market by legislation (Vangansbeke et al., 2015b).

Enhanced utilization and harvest of whole trees raises questions about the sustainability of this practice and the impact on ecosystem services delivered by forests (Schulze et al., 2012). For example, the additional harvest of biomass in forests on top of the harvest of logs might negatively affect forest biodiversity of

* Corresponding author at: Forest & Nature Lab, Geraardsbergsesteenweg 267, 9090 Melle-Gontrode, Belgium.
E-mail address: Pieter.Vangansbeke@UGent.be (P. Vangansbeke).

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saproxylics, small mammals and birds and the functioning of associated aquatic ecosystems by increasing acidifying potential and reducing stream productivity (Berger et al., 2013). Also soil microbial properties and activity and related soil productivity and functioning can be influenced (Smaill et al., 2008b). During Whole Tree Harvesting (WTH) more nutrients are exported from the forest than under Stem-Only Harvesting (SOH) (Achat et al., 2015). The additional export could be significant, despite the lower crown biomass compared to stem biomass, because the nutrient concentrations in these tree parts are much higher than in logs (Neirynck et al., 1998). Jorgensen et al. (1975) found that the export of N, P and K under WTH, including the larger roots, was about three times bigger than under SOH in a 16 year old pine plantation. Depending on the forest and soil type, WTH might have a negative impact on the soil fertility of a stand (Jorgensen et al., 1975; Olsson et al., 1996a) and its future productivity (Johnson, 1994; Walmsley et al., 2009; Wall, 2012). A harvesting regime can be considered unsustainable when the ratio between the imports (mainly through deposition and weathering) and exports (mainly through harvest, leaching and run-off) of nutrients is smaller than 0.9, and if the remaining ecosystem nutrient stock is not sufficient for the next ten rotation periods (Göttlein et al., 2007). The ecosystem nutrient stock exists of the nutrients in trees, forest floor and the available soil nutrients (Fig. 1).

Studying the effects of contrasting harvesting scenarios on soil nutrient development can be performed (1) by empirically comparing pre- and post-harvest nutrient stocks, (2) by modelling the long-term impact or (3) by quantifying growth reductions in the stand. Here we give a short literature overview of different studies on the impact of WTH on nutrient status of forest stands.

A first type of WTH nutrient studies focused on the empirical identification of immediate or long-term effects of harvesting intensity on nutrient stocks. For example, Klockow et al. (2013) studied the effect of slash and live-tree retention in *Populus tremuloides* dominated forests in the USA. They found that a lower harvesting intensity (i.e., SOH vs. two intermediate scenarios retaining some slash on the stand vs. WTH) positively influenced the total nutrient stocks of the stand. Most remarkably, this study mentioned a slash retention of almost 50% under WTH due to harvest losses (Klockow et al., 2013). Olsson et al. (1996b) found a significant effect of harvesting intensity (SOH vs. WTH) on base saturation, especially in the litter layer (L, F and H layer), 16 years after harvest in spruce and pine stands in Sweden. Phillips and Watmough (2012) found a decrease in available soil stocks of calcium (Ca) and potassium (K), by making a detailed nutrient budget before and after stem-only selection cutting in sugar maple stands (*Acer saccharum* Marsh.) in Ontario, Canada. Jorgensen et al. (1975) found a significant decrease in available soil nutrient pools when WTH was applied instead of SOH. Vanguelova et al., 2010 found an increase

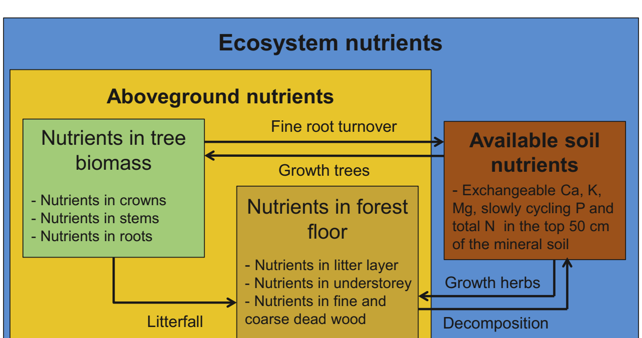

Fig. 1. Overview of the different stocks of ecosystem nutrients and the internal fluxes between these stocks.

in acidity and a decrease of available soil K and phosphorus (P) stocks under WTH in comparison to SOH in Sitka spruce stands in the UK after 28 years and Smaill et al. (2008b) detected a significantly lower biomass and nitrogen content of the litter layer under WTH compared to SOH, 8–16 year after harvest in pine stands in New Zealand. On the other hand, some studies reported little significant differences in nutrient stocks between stands after WTH and SOH. Wall and Hytonen (2011), for example, studied Norway spruce stands 30 years after SOH and WTH, with needles left on site, in Finland. They found no significant differences between the stands in stocks in forest floor and concentration in foliage of nitrogen (N), magnesium (Mg), P, Ca and K. Wilhelm et al. (2013) compared nutrient budgets and fluxes before and after harvest for 3 harvesting intensities (WTH and treatments leaving most of the crown in the stand) in oak dominated stands on poor, sandy soils in Wisconsin, USA. Only little differences were detected between the treatments in the first 2 years after harvest. In general, these empirical studies offer excellent insights into the immediate impact of different harvest regimes and can be used to test results from modelling work. However, this type of studies does not directly evaluate the long-term perspective of possible soil depletion.

A second type of studies used models to estimate the long-term impact of different harvesting intensities on nutrient stocks. Aherne et al. (2012), for instance, modelled the soil nutrient status under different harvesting intensities and under projected climate change scenarios for Scots pine (*Pinus sylvestris*), birch (*Betula pendula*) and Norway spruce (*Picea abies*) on contrasting soils in Finland. According to the model, WTH (with crowns, excluding stumps) in pine stands increased the removal of biomass by only 24%. Yet, the removal of base cations more than tripled and nitrogen was removed six times more than under SOH. Palviainen and Finér (2012) developed equations to estimate the nutrient content of crowns and stems based on the stand volume for pine, spruce and birch in Fennoscandia. Based on these equations they modelled nutrient exports under SOH and WTH for thinnings and clear-cuts. Generally they found negative nutrient balances under WTH for most nutrients and most tree species. The study of Phillips and Watmough (2012) estimated the long term impact of a stem only selection harvest by starting from an empirical dataset on the impact of harvesting and modelling the nutrient import by leaching and atmospheric depositions and the nutrient export by leaching. They found a net loss and a high long-term risk of depletion for bioavailable K and mainly Ca. Zanchi et al. (2014) modelled responses of spruce stands to increased biomass extraction (by residue removal, intensifying thinnings and shortening rotation periods) in southern Sweden. By assuming a fixed harvest loss of 40% of the foliage under all scenarios, they found significant changes in aboveground and belowground stocks and fluxes of carbon. In sum, modelling studies give an interesting overview of impact on a larger space and time scale. Moreover, a well performing model, tested on field data, such as the NuBalM model for nitrogen and biomass pools in pine stands, has the potential of being a useful management tool (Smaill et al., 2011). The drawback is that the data is mostly not empirically generated and sometimes lacking terrain validity, e.g., poorly accounting for the fact that only part of the crowns are exported and that significant harvest losses occur on site.

A third kind of studies directly assessed the impact of different harvesting intensities on future productivity of forest stands. Egnell (2011) found a significant decrease of productivity over 31 years in planted spruce after WTH in northern Sweden. Fleming et al. (2014) compared total aboveground biomass 15 years after harvest in pine stands in Ontario, Canada. The aboveground biomass decreased significantly under WTH with removal of the forest floor. Stands under SOH had a higher aboveground biomass than stands under WTH, but this difference was not