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Phosphorus in accumulated harvest residues on skid trails

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ABSTRACT

Phosphorus is an essential yet scarce macronutrient, and as such forest nutrition often relies on cycling of P between biomass and soils through litterfall and roots. For technical and soil protection reasons, modern harvesting systems create thick brash mats on skid trails by depositing residues, thus concentrating P there. What portion of this redistributed P is immobilized, lost, or recycled could be significant to forest nutrition and management. However, open questions exist regarding the quantity and fate of P deposited on skid trials. The aim of this study was to determine how much P is redistributed to skid trails and what happens to that P. We modeled the amount of P deposited on a skid trail during a whole-tree thinning of an *Abies alba* Mill. stand, and quantified P stocks in the forest floor and mineral soil five years after the operation. An estimated 60% of harvested P from the encatchment was deposited on the skid trail. Five years after the harvest, forest floor P stocks in the skid trail dropped from an extrapolated 8.9 to 4.4 g m^{-2}. The difference of 4.5 g m^{-2} of P was not evident in mineral soil stocks, and loss through runoff or leaching would be minimal. With the greatest concentration of roots in the forest floor on the middle of the skid trail, mineralization and uptake of the missing P was the most likely explanation. This suggests that accumulated P on skid trails can be recycled through uptake by trees. Further testing in other stands and on which vegetation takes up accumulated P is still needed.

1. Introduction

Phosphorus is susceptible to mismanagement as it is scarce, an essential macronutrient, and is replenished slowly through weathering and limited atmospheric deposition (Walker and Syers, 1976; Newman, 1995; Föllmi, 1996). Given these properties, cycling of P between soil and biomass through litterfall and roots is necessary to maintain forest nutrient stocks (Attiwill and Adams, 1993; Fox et al., 2011). Harvesting interferes with this continuous exchange of P by removing biomass (Tiessen et al., 2011). Yet how much P is exported by a harvesting system depends not only on the quantity of biomass extracted, but also on the P concentrations of that biomass. Fractions such as branches, leaves, and roots are relatively rich in P, and thus harvesting systems that extract larger quantities of these fractions risk depleting a stand's nutrient stock (Kimmins, 1977; Achat et al., 2015). Illustrative examples of this include depleted P stocks in agriculture (Flueck, 2009), intensive plantation forestry (Tiessen et al., 2011), and 'whole-tree harvesting' (WTH) spurred by ever increasing demand for woody biomass (Richter et al., 2009; Thiffault et al., 2011; Helmisaari et al., 2014).

However, economic efficiency and protection of soil and water also govern the selection of harvesting systems, not only yield and nutrient stocks. Mechanized felling and forwarding offer substantial gains in cost effectiveness yet risk critical damage to soils (Cambi et al., 2015). Such traffic is now increasingly restricted to skid trail networks used over multiple rotations (von Wilpert and Schäffer, 2006). In those systems, which are common in Central Europe, harvested stems are processed on the skid trail, thus creating semi-protective brash mats (Hutchings et al., 2002; Han et al., 2009) and maintaining an orderly work area. This accumulation of harvest residues concentrates nutrients — including P — on compacted skid trails.

To what extent this redistribution of P affects stand nutrient stocks is unknown. Wall (2008) reported that removing residues did not matter to soil P pools. Yanai (1998) also deemed the portion of stand P stocks in biomass fractions that constitute harvest residues insignificant in relation to total P in the mineral soil, yet found that P removal during harvesting was huge in relation to P stored in the forest floor. Likewise Laiho and Prescott (2004) showed that coarse woody debris could retain P for decades. And, curiously, shifts in soil P stocks following harvesting have

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been observed predominately in larger, 'slowly-cycling' pools (Richter et al., 2006). Even then, there are four possibilities as to what happens to the accumulated P: it is (1) not mineralized and retained in the residues, (2) mineralized and lost through runoff or leaching, (3) mineralized and immobilized in mineral soil, or (4) mineralized and taken up by vegetation.

Processing on skid trails could simulate systems where residues and P are either left on-site in the stand or moved off-site — retention and export of P, respectively. Understanding how concentrating harvest residues on skid trails affects P stocks lies in answering the following questions:

1. How much P is redistributed to skid trails?
2. What happens to that P?

In this study we address Questions 1 and 2 by (i) quantifying the P input from harvest residues and (ii) quantifying P stocks in a stand and skid trail's forest floor and mineral soil. Changes within these pools of P have implications for harvest residue management.

2. Materials and methods

2.1. Study site

Litter and soil samples originated from a one hectare, thirty year-old, planted silver fir (*Abies alba* Mill.) stand on the Schönberg, a 650 m foothill west of the Back Forest, Germany (7°47′ 44″ E, 47°56′ 30″ N). Though few in number, additional species in decreasing count include larch (*Larix decidua* Mill.), beech (*Fagus sylvatica* L.), oak (*Quercus* sp.), and spruce (*Picea abies* [L.] Karst.). Average yearly temperature is 9°C with 15–16 °C during the vegetation period, and yearly precipitation is 900–1000 mm (Bogenrieder, 2006). The soil is a Luvic Stagnosol (Endoclayic, Humic) (WRB, 2014) with silt-loam to silty clay textures derived from superficially decalcified loess-loam of the Quaternary period (Genser, 2006). The French military presence in Germany used the surroundings as a training area till the 1990s, though almost no visible traces of such activity remain.

The stand was most recently thinned in December 2009 with felling and delimbing by harvester on skid trails, and extraction via a forwarder (equivalent to "Stem[Wood + Bark] + Branches + Foliage" in Achat et al., 2015). Crucially, this thinning was the first mechanized forest operation in the stand, meaning biomass found on skid trails were not relics from harvests before 2009. The sampling was in spring 2014, thus allowing debris to decompose and its associated nutrients cycle into other pools.

2.2. Field design

A 60 by 20 m harvesting encatchment was established as the sampling area and was centered on a skid trail with no stand boundary effects and representative coverage of vegetation, debris, and bare mineral soil. Three transects crossed the chosen skid trail. Each transect was one meter in width and extended ten meters to both sides to cover the harvesting encatchment. They were placed to cover the variation in slope, drainage, and accumulated biomass. To compare samples by the same degree of disturbance, each transect was stratified into four categories adjusted after Schäffer et al. (2009) as seen in Fig. 1: "Center Bulge", "Wheel Track", "Side Bulge", and "Stand" (as control). It was assumed the level of disturbance and thus effects were equivalent per stratum regardless of lateral orientation (left or right side) on the skid trail.

2.2.1. Biomass

In the sample area, woody biomass thinned in 2009 was estimated from an inventory of the stumps left from that thinning. We measured all stump diameters within the study plot; stump height (where the diameter was calipered) was on average 15 cm above ground level. On all remaining trees we measured total height and diameters at stump height, diameter at breast height (Dbh, 1.3 m), and 7 m above ground (upper diameter). Altogether we tallied 134 trees on the plot (equivalent to a stem density of 1117 trees ha^{-1}). Based on these measurements we fitted regression equations with stump-height as predictor for Dbh, total height, and upper diameter. We subsequently used these equations with the stump data to reconstruct the unobserved dimensions of the harvested trees. From these estimated tree attributes we calculated volume and biomass of the trees using a function library[1] commonly applied to forest inventories in Germany (Kublin, 2003).

Additionally we felled eight silver firs (*A. alba*) representing the range of dimensions in order to calculate P concentrations. For each of the eight we recorded tree height, stem diameter every 2 m, whorl positions, and their location within the crown. At each whorl the number of branches were counted, and branch base diameters were measured on a subsample. At first, we distinguished (i) the stem with a minimum diameter of 7 cm (including bark), and (ii) the crown, which included the upper part of the stem with a diameter less than 7 cm as well as all green and dry branches. The stem was subdivided into *wood* and *bark*. Within the crown, green branches were separated into *wood* (including bark) and *needles*. Altogether we distinguished seven compartments for biomass calculations: (i) stem wood ($\geqslant$7 cm with bark); (ii) stem bark; (iii) stem (wood and bark) with diameter <7 cm; (iv) dry branches (wood and bark); (v) green branches (wood and bark) with diameter >10 mm; (vi) green branches (wood and bark) with diameters $\leqslant$10 mm; (vii) *needles*. Samples representing different compartments were taken for laboratory analysis: green and dry branches for representative mixed samples were selected from the crown (with needles separated later), and three rounds were cut at stem base, middle, and upper crown.

2.2.2. Forest floor

Forest floor samples came from an aggregation of three 900 cm^2 sample spots per stratum. Each spot was cut out with a saber saw (Bosch PSA 18 LI). As each stratum except the *Center Bulge* was split within the transect, each side had at least one spot while the third was assigned randomly. Sampling spots were located in the middle of each stratum as marked in Fig. 1 to remain as independent as possible from other strata (spots extended between both points in the *Center Bulge*). Additionally, placement of sampling spots attempted to capture representative amounts of litter and debris within each stratum.

2.2.3. Mineral soil

Soil rings (200 cm^3) at depth steps 0–5, 5–10, and 15–20 cm were taken at two points per stratum (each 'x' in Fig. 1). These points were located in the same manner as the litter sampling: points were split evenly by side and placed as independently from other strata as possible. With regards to the *Center Bulge*, it is assumed the points are independent from each other when about 50 cm apart.

2.3. Laboratory analysis

Biomass and forest floor samples were subdivided into fractions (Table 1) before drying at 40 °C. Each of those fractions except roots were chipped with a garden shredder, homogenized, and subsampled. Each soil ring was likewise dried at 40 °C, sieved

[1] Freely available from the FVA, Baden-Württemberg (in German): <http://www.fva-bw.de/indexjs.html?http://www.fva-bw.de/forschung/bui/bdatpro.html> (last accessed July 24, 2015)