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Carbon storage and nutrient mobilization from soil minerals by deep roots and rhizospheres

Ingeborg Callesen [a,*], Robert Harrison [b], Inge Stupak [a], Jeff Hatten [c], Karsten Raulund-Rasmussen [a], James Boyle [c], Nicholas Clarke [d], Darlene Zabowski [b]

[a] *Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark*
[b] *School of Environmental & Forest Sciences, University of Washington, United States*
[c] *College of Forestry, Oregon State University, United States*
[d] *Norwegian Institute of Bioeconomy Research, Aas, Norway*

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ABSTRACT

Roots mobilize nutrients via deep soil penetration and rhizosphere processes inducing weathering of primary minerals. These processes contribute to C transfer to soils and to tree nutrition. Assessments of these characteristics and processes of root systems are important for understanding long-term supplies of nutrient elements essential for forest growth and resilience. Research and techniques have significantly advanced since Olof Tamm's 1934 "base mineral index" for Swedish forest soils, and the basic nutrient budget estimates for whole-tree harvesting systems of the 1970s. Recent research in areas that include some of the world's most productive and intensively managed forests, including Brazil and the USA, has shown that root systems are often several meters in depth, and often extend deeper than soil is sampled. Large amounts of carbon are also sometimes stored at depth. Other recent studies on potential release of nutrients due to chemical weathering indicate the importance of root access to deep soil layers. Nutrient release profiles clearly indicate depletion in the top layers and a much higher potential in B and C horizons. Reviewing potential sustainability of nutrient supplies for biomass harvesting and other intensive forest management systems will advance understanding of these important ecosystem properties, processes and services relevant for management.

1. Introduction

1.1. Biogeochemical consequences of utilizing forest biomass resources

Box 1

> ‘‘X had marked time in the limestone ledge since the Paleozoic seas covered the land. Time, to an atom locked in a rock, does not pass.
>
> The break came when a bur-oak root nosed down a crack and began prying and sucking. In the flash of a century the rock decayed, and X was pulled out and up into the world of living things. He helped build a flower, which became an acorn, which fattened a deer, which fed an Indian, all in a single year. From his berth in the Indian's bones, X joined again in chase and flight, feast and famine, hope and fear. He felt these things as changes in the little chemical pushes and pulls that tug timelessly at every atom. When the Indian took his leave of the prairie, X moldered briefly underground, only to embark on a second trip through the bloodstream of the land." (Leopold, Aldo 1949).
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> Reference: Leopold, Aldo 1949. ''Odyssey" in A Sand County Almanac and Sketches Here and There. Oxford University Press. New York, New York.

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* Corresponding author.
E-mail addresses: ica@ign.ku.dk (I. Callesen), robh@uw.edu (R. Harrison), ism@ign.ku.dk (I. Stupak), Jeff.Hatten@oregonstate.edu (J. Hatten), krr@ign.ku.dk (K. Raulund-Rasmussen), forsol40@comcast.net (J. Boyle), nicholas.clarke@nibio.no (N. Clarke), zabow@u.washington.edu (D. Zabowski).

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The effects of biomass harvesting on nutrient supplies and carbon storage in soils are important to consider in management of forests for long-term productivity and other ecosystem services. The issue is complicated because forest harvesting is increasingly intensified to meet demands for bioenergy feedstock. Intensified practices include removal of logging residues or whole trees, which significantly increases removal of nutrients from a forest ecosystem's internal cycling (Raulund-Rasmussen et al., 2008). Intensified harvest practices may also lead to decreased inputs of organic matter to soils and in the long term they might cause a decrease in soil carbon pools.

Policies, regulations, and guidelines have been put in place by various jurisdictions to ensure and guide sustainable forest management, and sometimes intensified forest biomass harvesting specifically (Stupak et al., 2007, 2008, 2013; Titus et al., 2013). In order to maintain ecological functions, it is generally considered a good practice to avoid intensive harvesting on sensitive sites, while on other sites a certain amount of harvesting residues should be left in the forest, or residues should be left over the summer to shed nutrient-rich plant parts before removal (Stupak et al., 2008; Vance et al., 2014). This approach requires a quantitative mapping of sites that are sensitive to nutrient depletion. Processes developing such policies, regulations and guidelines are to some extent based on rigorous science studies, but subjective expert assessments may be necessary to fill in knowledge gaps. Ultimately, all available knowledge is subjected to priorities and balancing of tradeoffs by decision makers. The outcome may have significant consequences for the forest sector and the associated industries, and ultimately for the rural districts where these industries operate. It is thus important, also from a societal point of view, that political decisions are based on best available knowledge. Estimates of soil nutrient supplies and carbon stores should thus reflect the actual ecosystem processes for the whole ecosystem, and for the particular site in question.

Early research techniques to study forest nutrient supplies include Olof Tamm's 1934 “base mineral index” for Swedish forest soils (Tamm, 1934), developed to assess the fraction of nutrient-bearing, reactive minerals in the fine earth fraction. In the 1960s, more holistic ecosystem approaches emerged and input–output nutrient budgets were established to estimate the impact of whole-tree harvesting systems on continued nutrient supplies (e.g. Boyle et al., 1973). Sampling of soils for evaluation of nutrient supplies and carbon stores in such studies has often been done only for the upper 15–20 cm of soils. Newer weathering estimates based on modeling results consider soil volume to the depth of 50 or 100 cm (Futter et al., 2012). These sampling depths are most often used in forest soils and ecosystem research. Numerous studies have shown, however, that tree roots penetrate to depths far below 100 cm, depending especially on climate and soil variables that affect the soil water balance (Jackson et al., 1996; Schenk and Jackson, 2005; Stone and Kalisz, 1991); these deep roots may contribute significantly to trees' nutrient supplies and carbon storage at depth (Richter and Markewitz, 1995). Nutrient leaching may be over-estimated if based on soil water concentrations and fluxes at depths that do not capture the uptake by deeper roots.

Our central thesis for this paper is that deep roots and deep soil layers may contribute significantly to nutrient supplies and soil carbon storage capacity of temperate and boreal forest ecosystems. We build our arguments around our own scientific work and results from the literature.

1.2. Assessments of soil organic carbon stocks and stock changes

Life processes in deep soil horizons are important for two reasons: access to pools of water and nutrient resources and deep carbon stocks (Harper and Tibbett, 2013; Rumpel and Kögel-Knabner, 2011; Zabowski et al., 2011; Whitney and Zabowski, 2004). Deep water and nutrient resources can contribute to tree growth, and, as a consequence, carbon sequestration in the forest ecosystem. Root distribution profiles show that 95% of all fine roots are located within 100 cm from the mineral soil surface in moist temperate and boreal forest ecosystems (Hansen et al., 2003; Rosengren et al., 2006; Köstler et al., 1968). Therefore a pragmatic ‘effective rooting depth’ is sometimes used. This is where much forest soils and ecosystem research has been carried out.

Assessments of soil organic carbon (SOC) currently include a number of approaches aimed at either directly or indirectly measuring or modeling SOC change over time. SOC is the largest pool of terrestrial C (Post et al., 1982; Scharlemann et al., 2014), estimated at 65–78 Pg to 100 cm depth for the continental USA (West et al., 2010; Kern, 1994). In the case of forest land, about 15 Pg is found in vegetation versus 25 Pg in forest soils. Logically, larger C pools would mean that soil monitoring would receive the largest efforts in evaluating climate change impacts on C balance in forests, but in much literature SOC receives little attention compared to trees.

Studies of deep soils have often shown large amounts of carbon at depth, although the results are variable. Fig. 1 shows the significance of soil C at depths not often sampled, and implies the likely presence of at least some roots, as roots are a likely mechanism for carbon accumulation in soil at depth. For instance, in 22 soil profiles sampled in this Pacific Northwest, USA study, sampling to 20 cm resulted in an average of 58.7 Mg C/ha, while extending sampling depth to 50 cm increased soil carbon estimates to 113, and to 300 cm to 202 Mg C/ha, increases of 92 and 260 percent, respectively.

Soil formation usually begins with parent materials with negligible amounts of SOC (Brady and Weil, 2010). Soil organic carbon is widely thought to change at a slower rate than aboveground biomass carbon. Soil organic carbon is also difficult to measure directly, so modeling efforts are often used to estimate SOC in assessments of potential soil change (IPCC, 2006; Ogle and Paustian, 2005; Ogle et al., 2010; Smith et al., 2000; Schimel et al., 2001; West et al., 2008). Through photosynthesis plant growth produces organic matter that can be input to the soil. Microbial decomposition of organic matter together with leaching can result in rapid changes, either increases or losses, in SOC. SOC change is influenced by factors such as vegetation pattern, climate and soil properties (Richter et al., 1999). Generally subsurface SOC is considered a relatively stable pool. Early evidence offered for the stability of subsoil C results from studies identifying average residence times of hundreds or thousands of years (Oades, 1988; Jenkinson et al., 1992; Sollins et al., 1996; Baldock et al., 1997; Paul et al., 1997; Schöning and Kögel-Knabner, 2006). Little direct evidence has been provided showing that SOC stabilized under previous conditions will remain stable with changing conditions, such as with climate change, and some studies have shown that previously stable SOC may be rapidly mobilized to CO_2 (Fontaine et al., 2007; Fang et al., 2005).

Ideally, land managers could have an accurate procedure to inform them how a particular management strategy would change SOC losses or sequestration in the whole soil profile over time. Two examples of programs that sample soils over time are the Forest Inventory and Analysis program (FIA) of the U.S. Forest Service (Gillespie, 1999), and the Rapid C Assessment (USDA, 2013), which includes all vegetated areas. The FIA protocol calls for soil to be sampled to a maximum depth of 20 cm, so its utility in monitoring whole-profile SOC over time is very limited (Waltman et al., 2010; Jandl et al., 2014). The Rapid C Assessment system (USDA, 2013; Wills et al., 2013) samples soil profiles to 100 cm depth. It is currently uncertain what depth is required to truly understand SOC and potential changes in SOC (Harrison et al., 2011). Fig. 1

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