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Rates of sustainable forest harvest depend on rotation length and weathering of soil minerals

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ABSTRACT

Removals of forest biomass in the northeastern US may intensify over the coming decades due to increased demand for renewable energy. For forests to regenerate successfully following intensified harvests, the nutrients removed from the ecosystem in the harvested biomass (including N, P, Ca, Mg, and K) must be replenished through a combination of plant-available nutrients in the soil rooting zone, atmospheric inputs, weathering of primary minerals, biological N fixation, and fertilizer additions. Few previous studies (especially in North America) have measured soil nutrient pools beyond exchangeable cations, but over the long rotations common in this region, other pools which turn over more slowly are important. We constructed nutrient budgets at the rotation time scale for three harvest intensities and compared these with detailed soil data of exchangeable, organic, and primary mineral stocks of in soils sampled in 15 northern hardwood stands developed on granitic till soils in the White Mountain region of New Hampshire, USA. This comparison can be used to estimate how many times each stand might be harvested without diminishing productivity or requiring fertilization. Under 1990s rates of N deposition, N inputs exceeded removals except in the most intensive management scenario considered. Net losses of Ca, K, Mg, and P per rotation were potentially quite severe, depending on the assumptions used.

Biologically accelerated soil weathering may explain the lack of observed deficiencies in regenerating forests of the region. Sites differed widely in the long-term nutrient capital available to support additional removals before encountering limitations (e.g., a fourfold difference in available Ca, and a tenfold difference in weatherable Ca). Intensive short-rotation biomass removal could rapidly deplete soil nutrient capital, but traditional long rotations, even under intensive harvesting, are unlikely to induce nutrient depletion in the 21st century. Weatherable P may ultimately limit biomass production on granitic bedrock (in as few as 6 rotations). Understanding whether and how soil weathering rates respond to nutrient demand will be critical to determining long-term sustainability of repeated intensive harvesting over centuries.

1. Introduction

Deciduous forests in the northeastern United States have a long history of exploitation as a source of fuel and timber. New harvesting methods emerged in the 1970s, in which branches and low-value trees were chipped and sold as fuel rather than left on site. Studies of the increased nutrient removal associated with such harvests raised concern about the potential depletion of important nutrients, especially Ca, from forest soils (White, 1974, Johnson et al., 1988, Federer et al., 1989; Hornbeck et al., 1990; Adams et al., 2000). Interest in forest bioenergy has increased again recently (e.g. Malmsheimer et al., 2008; Richter et al., 2009), driven by energy price volatility and the goals of reducing net greenhouse gas emissions and dependence on imported energy.

Sustainable forestry comprises management practices that maintain the capacity of the forest to provide important ecosystem services in the future, including water quality, biodiversity, species composition, and forest productivity (Janowiak and Webster, 2010; Walker et al., 2010; Berger et al., 2013). Here we address potential productivity declines due to nutrient removal in stands harvested repeatedly. From this perspective, sustainability requires that removals of nutrients from ecosystems be balanced by inputs to plant-available pools (Sverdrup and Svensson, 2002; Flueck,

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2009). Though many forests in the northeastern USA remain productive after having been harvested and regrown twice or more, continued harvest removals and associated hydrologic losses of nutrients will eventually reduce net primary productivity unless ecosystem inputs increase above current estimates. Observations of nutrient availability and productivity in whole-tree harvested stands have yielded mixed results, at least for the relatively short time scales examined thus far (Thiffault et al., 2011). Though analogous forest systems elsewhere in the world are often fertilized to replace nutrients where biomass removals are high (e.g. northern Europe, Stupak et al., 2008), forest fertilization is not currently common in the northeastern USA.

Exchangeable nutrients have historically been considered the nutrient pool most available to plants and of greatest relevance in assessing productivity (Marschner, 1995). However, exchangeable pools contain only a small fraction of the nutrients required by a regrowing forest (e.g. Likens et al., 1994; Likens et al., 1998). Indeed, at decadal time scales, even forests undergoing vigorous biomass accumulation appear not to deplete exchangeable soil nutrient pools (Johnson et al., 1991, 1997; Bélanger et al., 2004). More relevant to longer-term productivity is the rate of supply of these nutrients from less available pools or sources external to the ecosystem, relative to the rate needed to support regrowth (Rastetter and Shaver, 1992; Craine, 2009).

Nutrients enter forest ecosystems via atmospheric deposition and the weathering of geologic substrates. Nitrogen is not present in many parent materials but is also fixed microbially from the atmosphere. In regions of granitic parent material, base cations (Ca, Mg, K) are weathered primarily from silicate minerals, while the most important source of P is the accessory mineral apatite ($Ca_5(PO_4)_3(F,Cl,OH)$). Apatite can also be an important source of Ca in granitic soils (Blum et al., 2002; Nezat et al., 2004), because it weathers more rapidly than silicate minerals (Allen and Hajek, 1989). Long-term weathering rates have been estimated from soil profiles in the White Mountain region (Nezat et al., 2004; Schaller et al., 2010). Weathering rate estimates are inherently variable and difficult to compare across methods and locations (Klaminder et al., 2011; Futter et al., 2012). However, weathering rates that are required to close ecosystem budgets (Likens et al., 1996, 1998; Hyman et al., 1998) are sometimes an order of magnitude greater than measured long-term rates estimated from the degree of depletion of soil profiles relative to their parent material. This discrepancy is a common finding when comparing estimates of weathering by different methods in similar soils (Table 1), despite the expectation that current rates should be lower than long-term means due to the decline in weathering rate as soils age (Taylor and Blum, 1995). This discrepancy has been attributed to elevated acid deposition (Langan et al., 1995), but hydrologic Ca losses cannot be fully explained by observed acidic inputs (Hamburg et al., 2003). Rooting-zone soil weathering rates are difficult to assess at the watershed scale, where net fluxes are small relative to the large dynamic stocks, uncertainties are often large (Likens and Bormann, 1995; Yanai et al., 2012), soils vary over short spatial scales, and significant chemical contributions to streamflow may occur below the rooting zone.

Another potential explanation for high apparent weathering rates is that soil weathering may be accelerated when there is increased biotic demand (Hamburg et al., 2003). The removal of large amounts of biomass over the past ~150 years is a significant new disturbance in forests of the region. Wind, ice damage, and infrequent fires have been the dominant forms of disturbance over the past 10,000 years, and generally leave most nutrient capital on site. Regrowing forests may shift resource allocation towards the acquisition of nutrients other than N, such as P (Rastetter et al., 2013). Ectomycorrhizal fungi are known to weather primary minerals (such as apatite) by etching mineral surfaces with organic acid exudates under conditions where the weathering products (such as P) are limiting (Landeweert et al., 2001; Hoffland et al., 2004; Van Scholl et al., 2008). Greatly elevated rates of apparent mineral weathering have been observed in aggrading pine mesocosms (Bormann et al., 1998; Balogh-Brunstad et al., 2008), and may occur in rapidly aggrading forest stands as well (Hamburg et al., 2003; Bélanger et al., 2004).

1.1. Research approach and objectives

Analyses of the sustainability of forestry practices typically compare management-induced nutrient losses to nutrient inputs via atmospheric deposition and weathering (e.g. Sverdrup and Svensson, 2002; Duchesne and Houle, 2008). Building on work by Federer et al. (1989), we extend this approach by comparing net nutrient loss per rotation to nutrient stocks, under a range of assumptions about harvest intensity and nutrient availability. Specifically, we ask:

1. What is the net nutrient balance per rotation under various harvesting scenarios?
2. How much variation exists in nutrient stocks (exchangeable, organically bound, and apatite) among stands that are ostensibly similar in species composition and soil type?
3. Assuming that exchangeable and organically bound nutrients can be depleted over multiple rotations, which nutrient eventually becomes limiting (i.e. is exhausted first) under each harvesting scenario?
4. If apatite in the rooting zone is considered available, how many additional rotations would be possible?

The first question relates directly to "strong" definitions of sustainability, whereby resource stocks must be maintained at current levels over time (e.g. Goodland and Daly, 1996; Flueck, 2009). The second question seeks to characterize variation in soil nutrient stocks at spatial scales relevant to management decisions, in order to avoid depleting ecosystems beyond critical thresholds. The third and fourth questions stem from the observation that ecosystems may continue to function normally despite some level of stock depletion.

Our approach necessarily involves many assumptions about (1) the magnitude of fluxes that are difficult to estimate across a variable landscape and (2) how fluxes will change over time with increasing nutrient stress. When simplifying assumptions must be made, we have chosen those that likely lead to an overestimation bias of the number of rotations that can be sustainably harvested in the northern hardwood region.

2. Methods

2.1. Study sites

We sampled soils in 15 deciduous forest stands of varying age in the White Mountain region of central New Hampshire (Fig. 1; Table 2). Dominant species included American beech (*Fagus grandifolia* Ehrh.), sugar maple (*Acer saccharum* Marsh.), and yellow birch (*Betula alleghaniensis* Britton) in mature stands, and white birch (*Betula papyrifera* Marsh.), red maple (*Acer rubrum* L.), and pin cherry (*Prunus pensylvanica* L. f.) in younger stands. One site (B1) was a former pasture dominated by red spruce (*Picea rubens* Sarg.) mixed with northern hardwoods, and the area sampled at the Hubbard Brook Experimental Forest (HBEF) has red spruce and balsam fir (*Abies balsamea* L.) at higher elevations. Soils were primarily well or moderately drained, coarse-loamy, mixed-frigid typic Haplorthods developed on glacial till parent material derived from granitoid and high-grade metamorphic silicate rocks.