Forest Ecology and Management 343 (2015) 144–156

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Base cation budgets under residue removal in temperate maritime plantation forests

James Johnson [a,*], Julian Aherne [b], Thomas Cummins [a]

[a] UCD School of Agriculture and Food Science, University College Dublin, Belfield, Dublin 4, Ireland
[b] Environmental Resource Studies, Trent University, Peterborough, Ontario K9J 7B8, Canada

ARTICLE INFO

Article history:
Received 27 October 2014
Received in revised form 21 January 2015
Accepted 22 January 2015
Available online 23 February 2015

Keywords:
Whole-tree harvest
Mineral-weathering
Atmospheric deposition
Calcium
Magnesium
Potassium

ABSTRACT

The removal of harvest residues—branches, treetops and needles—has the potential to impact the long-term sustainability of forest soils. In this study we used mass balance calculations to predict the impact of harvesting on ecosystem balances of calcium (Ca), magnesium (Mg), potassium (K) as well as on soil acidification (ANC_{le}) for forests in Ireland. Balances were determined for three harvesting scenarios: stem-only harvest (SOH), stem plus branch harvest (SBH) and whole-tree harvest (WTH). The study was carried out at forty sites—selected on a grid across the country. The sites were plantations of Sitka spruce (*Picea sitchensis* (Bong.) Carr), Norway spruce (*Picea abies* (L.) Karst.) and provenances of lodgepole pine (*Pinus contorta* (Dougl. var. *latifolia*)). Flux calculations were based on site measurements of standing biomass and soil properties as well as regional maps of atmospheric deposition. Under SOH and SBH, inputs were predicted to be sufficient to meet outputs for Ca, Mg and K budgets. Atmospheric deposition was the most important input to Ca and Mg balances. For K, inputs from mineral weathering were as important as deposition. Under WTH, Ca output was greater than input at 19 of the 40 study sites. However, the difference was small relative to the size of soil Ca pools; at these sites, exchangeable pools could support WTH removal for a median of 220 years. Magnesium and K removal under WTH was supported by inputs in deposition and weathering. For soil acidification budgets (ANC_{le}), base cation (BC) removal in harvesting under all scenarios was much greater than that BC generated by weathering, suggesting that soils will become acidified over the long term. There was considerable uncertainty around the calculation of fluxes. For Ca balances, confidence intervals spanned positive and negative values at many sites such that it was not possible to predict the balance of Ca budgets. In addition, uncertainty in flux calculations was particularly important for K budget because soil exchangeable pools were small and could be depleted within one to two rotations.

1. Introduction

In many areas forest harvesting now includes the removal of logging residues consisting of branches, foliage, treetops (also termed brash or slash) in addition to tree stems (McKay et al., 2003; Stupak et al., 2007; Walmsley and Godbold, 2010; Poudel et al., 2012). This material is being exploited as a source of energy to reduce dependency on fossil fuels. In some jurisdictions this is being driven by legislation, e.g., the European directive on the promotion of energy from renewable sources (DIRECTIVE, 2009/28/EC) requires that EU countries must produce, 20% of their energy by renewable sources by 2020. Whole-tree harvesting (WTH)—defined as the removal of stems as well as branches, treetops and needles (Thiffault et al., 2011; Akselsson et al., 2007) increases nutrient removal in comparison to conventional stem-only harvest (SOH). This has important implications for the biogeochemical cycling of elements with sedimentary cycles such as phosphorus (P), calcium (Ca), magnesium (Mg) and potassium (K), which depend on weathering to replace losses (Bormann and Likens, 1967). In addition, soil exchangeable Ca, Mg and K along with Na constitute base cations (BC), which buffer acidification processes. Many temperate and boreal forests are located on acid soils with low mineral weathering rates (Kolka et al., 1996; Ouimet and Duchesne, 2005; Futter et al., 2012; Vadeboncoeur et al., 2014), which may limit the long-term sustainability of base cation removal in harvesting.

The impacts of increased harvest removal on nutrient availability and soil chemistry can be assessed using different approaches including experimental field trials (Proe and Dutch, 1994; Walmsley et al., 2009), nutrient budgets (Watmough et al., 2005; Duchesne and Houle, 2008) and ecosystem modeling (Akselsson

* Corresponding author. Tel.: +353 86 1614924.
E-mail address: jim.johnson@ucd.ie (J. Johnson).

http://dx.doi.org/10.1016/j.foreco.2015.01.022
0378-1127/

et al., 2007; Aherne et al., 2012). Ecosystem nutrient budgets are calculated as the difference between inputs (atmospheric deposition and mineral weathering) and outputs (biomass removal and leaching losses) over the period of a forest rotation(s). As such they can be used as a means to assess depletion or accumulation of soil nutrients over the long term and potentially have the benefit of being able to characterize nutrient depletion before it actually occurs. (Ranger and Turpault, 1999). They can also been used to assess the impact of acidic deposition in comparison to biomass removal (Farrell et al., 2001; Joki-Heiskala et al., 2003; Aherne et al., 2012). In many cases, Ca leaching losses are of concern due to acidic deposition. For example, modeling studies from Sweden and Finland have indicated that base cations would be depleted even under SOH due to large leaching losses arising from acidic deposition (Joki-Heiskala et al., 2003; Akselsson et al., 2007). Similarly in eastern North America, input–output budgets have demonstrated large Ca leaching losses due to acidic deposition such that any harvesting would result in depletion of soil Ca (Federer et al., 1989; Watmough et al., 2005). In contrast, Duchesne and Houle (2008) demonstrated that K was the element of most concern at a boreal forest in Quebec. In this case, acidic deposition was low and uptake in biomass was the main pathway by which K was lost. Budget studies have also demonstrated the potential for nutrient depletion in plantation forests. In a Sitka spruce plantation in the UK, Stevens et al. (1995) indicated that for WTH to be sustainable nearly all Ca deposition would need to be retained as Ca weathering was negligible. Meanwhile, Ranger and Turpault (1999) showed that conventional harvesting could lead to depletion of Ca, Mg and K in Douglas fir plantations in France.

In Ireland, the area of forest cover has expanded rapidly since the 1950's. The area of forests is now 11%, compared with 1% in 1900. This expansion has been achieved through the development of commercial plantations supported by the state. Initially government policy was to afforest areas considered unsuitable for agriculture. As a result, large areas of planting occurred on wet, nutrient poor soils in exposed areas, including large areas of peatlands. Since the 1980s and 1990s planting has taken place on a wider range of soil types with the introduction of grant aid to landowners (Farrelly et al., 2009). Plantations consist primarily of fast-growing conifers (>70%). Sitka spruce (*Picea sitchensis* (Bong.) Carr) is the main species, accounting for more than 50% of forest area, followed by provenances of lodgepole pine (*Pinus contorta*) (10%), birch (*Betula*) (4.7%) and Norway spruce (*Picea abies* (L.) Karst) (4.1%) (NFI, 2007). Lodgepole pine is often used as a pioneer species to facilitate the establishment of more nutrient-demanding species such as Sitka spruce in subsequent rotations (Carey and Hendrick, 1986). On organic soils phosphorus applications are sometimes necessary required to establish the crop (Carey, 2006). The conifer species used grow rapidly in Ireland's mild temperate climate where the growing season is long (Farrelly et al., 2009). As a result, rotation lengths in plantations are short, generally less than 50 years (NFI, 2007).

To date, harvesting has consisted of stem-only removal with harvest residues left on site. However, this material is being examined as a source of biomass for energy and may be removed in future (Anon, 2007). The combination of increased nutrient removal and nutrient poor soils means that the availability of Ca, Mg and K could be impacted by harvest residue removal. For example, harvesting experiments at two Sitka spruce stands in Ireland, reported that residue removal would increase K export by over 40% (Carey and O'Brien, 1979; Carey, 1980). In the UK, there have been reports of reduced growth in second rotation Sitka spruce on sites where WTH took place in comparison to SOH (Walmsley et al., 2009; Vanguelova et al., 2010). Vanguelova et al. (2010) also reported reduced soil base saturation and K foliar nutrition in second rotation Sitka spruce.

In this study we assessed the potential impact of residue removal on the soil pools of Ca, Mg, K as well as on soil acidity in plantation forests in Ireland. Phosphorus may have been applied to organic sites in the study and hence will not be addressed here. We used a mass balance approach, consisting of modeled input and output fluxes to calculate nutrient balances. Three harvesting intensities were assessed: stem-only harvest (SOH), stem plus branch harvest (SBH) and stem plus crown removal (WTH) on soil Ca, Mg, K pools by calculating long-term input–output balances at a network of forest sites.

The usefulness of input–output budgets depends on accurately quantifying major input and output fluxes, which in practice can be difficult to achieve. For example, a number of authors have highlighted the difficulty in quantifying mineral weathering rates (Hodson et al., 1997; Futter et al., 2012). Uncertainty arises due to the method used as well as spatial variability in soil characteristics. It is important to acknowledge the uncertainty in input–output budgets as it provides a level of confidence around budget outcomes for decision makers and helps to identify knowledge gaps that need to be addressed (Oenema et al., 2003; Ammann et al., 2009). As a result, we quantified uncertainties around deposition, weathering and biomass removal in order to provide a level of confidence around input–output balances.

2. Material and methods

2.1. Site description

Input–output balances were determined for 40 sites (Fig. 1) that were part of a monitoring network to assess the impacts of air pollution on forests in Europe—Council Regulation (EEC) No 3528/86 and associated with the International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) operating under the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP). Details of the ICP Forest monitoring network, including hypotheses and objectives are described by de Vries et al. (2000) and de Vries et al. (2003). The sites were 4 'Level II' and 36 'Level I' sites. Level II sites were chosen as examples of the most common tree species and soil types in Ireland while Level I sites were selected at intersection points of a 16 km × 16 km grid across the country. At Level II plots, collection of bulk precipitation, throughfall as well as forest floor and soil water chemistry took place during the period 1989–2010. At Level I sites annual assessments of crown condition and health have taken place (ICP Forests, 2011). The sites were even aged stands of Sitka spruce ($n = 27$) Norway spruce ($n = 3$) and lodgepole pine ($n = 10$), ranging in age from 12 to 55 years (median 34 years). Site altitude ranged from 31 to 470 m. Long-term average rainfall at the sites was estimated to be between 800 and 2300 mm per year based on national rainfall maps (Walsh, 2012a). Annual average air temperatures in Ireland are generally between 9 and 10 °C. Highest temperatures occur in the summer with seasonal maxima between 18 and 20 °C. Air temperatures seldom go below zero and very little precipitation falls as snow (Walsh, 2012a).

Between 2006 and 2008 soil surveys were carried out at 35 Level I and 2 Level II sites as part of the BioSoil study (Neville and Bastrup-Birk, 2006)—a demonstration project co-funded under the EU 'Forest Focus' forest monitoring program (EC regulation 2152/2003). Each site was augered to choose a suitable location for a representative soil pit. Five bulk density samples were taken using a 100 cm^3 ring at fixed depths: 0–10 cm, 10–20 cm, 20–40 cm and 40–80 cm, where 0 cm represents the upper surface of the natural soil whether organic or mineral. At Level I sites, the forest floor was sampled using a 25 × 25 cm metal frame at 5 points. At these points additional soil samples were taken and composited