Geoderma 211–212 (2013) 39–50

Contents lists available at ScienceDirect

Geoderma

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

Assessing forest soil base cation status and availability using lake and stream sediment geochemistry: A case study in Quebec (Canada)

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ARTICLE INFO

Article history:
Received 2 February 2013
Received in revised form 23 May 2013
Accepted 14 June 2013
Available online 30 July 2013

Keywords:
Forest soils
Base cations
Sediments
Geochemical concentration
Forest soil fertility
k-nearest neighbour method

ABSTRACT

Spatial information about forest soil base cations is important because of its implications for forest health and resilience to disturbance and management.

The relevance of using geochemical data from lake and stream sediments collected for mining prospection purposes was evaluated to assess on a relative basis the forest soil base cation status and availability across the Quebec (Canada) forest landbase, an area for which information on soil properties is scarce.

The relevance of the acid extraction of the fine fraction (<177 μm) method, used to determine element composition of sediments, was tested as an indicator of forest soil fertility and exchangeable base cation status. Values of element concentrations of sediments were then extrapolated spatially from their sampling points to the whole of the Quebec forest landbase, based on their geographical location and on the topographical features of their position using the *k*-nearest neighbour imputation method. The acid extraction used to determine the geochemical composition of sediments yielded concentrations of Ca, Mg and K that were well correlated with the observed exchangeable base cation concentrations, effective cationic exchange capacity and presence of clay-sized particles of soil samples. Also, spatial imputation of the geochemical signature of sediments to the forest landbase produced values that successfully represented variations in acid-extractable K and Mg in forest soils, as validated with two independent forest soil datasets, but it failed to capture variations in acid-extractable Ca concentrations. Nevertheless, the spatialized values broadly illustrated the gradient of forest soil exchangeable base cation reserves, soil clay content and site richness at a coarse scale across landscapes.

1. Introduction

The earliest days of forest science in Canada were largely devoted to forest soil classification: it was used to delineate forested areas deemed productive enough to be cleared and used for agricultural crop cultivation (Gélinas, 2010). Adequate information about soil resources has thus always played an important role in support of planning and decision-making about the functional use of land.

However, soil classification systems and survey methods have been developed chiefly for agricultural purposes, and not for forestry (Fisher and Binkley, 2000). Moreover, actual forest soil pit data are often sparse, especially in Canada which possesses a large and highly diverse forested landbase. Maps at the scale of 1:1 million for drainage, type and texture of parent material, and soil classification exist for the whole of Canada. Some provinces also have maps of surficial deposits at a finer scale, e.g. at 1:40,000 in Quebec. However, there is no detailed and standardized information about soil chemistry for the forest landbase. Nevertheless, demands for environmental services provided by forests, such as biomass production, carbon sequestration and maintenance of ground water quality, as well as environmental stresses on forests, e.g. climate change, acidic atmospheric deposition and ozone pollution, are increasing. Forest soils are central contributors to the capacity of forests to provide these services. Understanding and quantifying soil patterns in relation to ecosystem health are thus essential (Grunwald, 2009).

In particular, the capacity of forest soils to provide base cations such as potassium (K), calcium (Ca) and magnesium (Mg) is important because of its practical implications for forest health and productivity. Base cation decline in forests, especially Ca, has raised concerns regarding productivity and biodiversity of terrestrial as well as freshwater ecosystems across Canada (Huntington, 2000; Huntington et al., 2000; Jeziorski et al., 2008; Likens et al., 1996; Schaberg et al., 2001; St. Clair et al., 2008). Base cation status in soils has also been shown to influence tree growth (Baribault et al., 2010; Phu, 1975) and susceptibility to sugar maple dieback (Bailey et al., 2004; Bernier

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http://dx.doi.org/10.1016/j.geoderma.2013.06.006

and Brazeau, 1988a, 1988b; Hallett et al., 2006). In addition, base cation status has been identified as an important indicator of site sensitivity to intensive forest biomass harvesting (Thiffault et al., 2006, 2011). It is also an input in calculations of nutrient budgets (e.g. Akselsson et al., 2007) and modelling of critical loads of acidity (e.g. Grennfelt et al., 2001; Ouimet et al., 2006) for forest ecosystems. Information about forest soil base cation status and availability is needed to develop sensitivity/suitability maps that delineate, for example, risk areas for soil acidification or potential areas for intensive forest management.

Different methods have been developed to evaluate rates of release of base cations by mineral weathering in soils, which need large amounts of input data and produce a wide range of estimates, as shown by several comparative studies (e.g. Hodson and Langan, 1999; Kolka et al., 1996; Ouimet and Duchesne, 2005; Starr et al., 1998; Whitfield et al., 2006). This suggests that the uncertainty around estimates of weathering rates may hinder their relevance for practical applications (Klaminder et al., 2011).

However, relative methods may be employed to qualify and rank soils across landscapes based on their base cation potential availability, e.g. by establishing relationships with other soil features that are more readily available, such as soil texture, cationic exchange capacity (CEC) and pH (Callesen et al., 2005). These methods often necessitate some knowledge of the mineralogical or elemental content of the parent material, as soils with similar morphological characteristics such as texture can show a large range of mineralogical characteristics (Arocena and Sanborn, 1999) and base cation release capability (Callesen et al., 2005), although a simple texture-based model has shown some potential (Koseva et al., 2010). Site-specific determination of mineralogical or elemental composition of forest soils is expensive and time-consuming, especially in regional applications that require covering the variation across landscapes. Geological maps may be used as proxies for estimating soil mineralogy and geochemistry. However, forest soils in recently glaciated areas across the circumboreal zone are often disconnected from the underlying bedrock, since the origin of the surficial deposit may not be local and rather may be dependent on the glacial and post-glacial movements and on the degree of weathering to which the material has been subjected (Akselsson et al., 2006; Phillips, 2010; Veillette, 2004).

In Canada, although data from forest soils per se are few, data from mining prospection and exploration are abundant. One such database is SIGEOM (Système d'Information GEOMinière; Geomining Information System; website: http://sigeom.mrnf.gouv.qc.ca/signet/classes/I1102_indexAccueil) in the province of Quebec. It contains geochemical information from tens of thousands of sediment samples collected in small lakes and streams across the province, although very unevenly distributed. For SIGEOM, the fine fraction (<177 μm) of the sediment samples was extracted using a solution of nitric acid and analysed by atomic absorption spectrometry for various elements of interest for mining prospection and geochemical mapping. Sediment samples have been widely used for regional, multi-element geochemical surveys (Grunsky, 2010). Sediment sampling is considered the most cost-effective approach to reconnaissance geochemical mapping across the Precambrian Shield and Appalachian regions of Canada (Davenport et al., 1997). The value of such geochemical databases for studying environmental issues, such as delineating high-risk areas for contamination of groundwater (Tarvainen and Paukola, 1998), has also been assessed. The geochemical signature of lake and stream sediments has been shown to be related to some extent to that of the surrounding surficial deposits (Mäkinen, 2005; Rencz et al., 2002) from which forest soils develop. Sediment composition has also been shown to be strongly affected by surficial features and processes such as the presence of clay minerals and adsorption of metals, and to a lesser extent by the lithologies (Bellehumeur et al., 1994). However, there is no systematic information on the relationships between the geochemical composition of lake and stream sediments and forest soils. If such relationships exist, then one could take advantage of the availability and spatial distribution of data from SIGEOM and similar databases from other jurisdictions, and use them to estimate the chemistry and base cation availability of forest soils across large areas, thus compensating for the scarcity of forest soil pit data.

The aim of this study was to gauge the usefulness of geochemical data of lake and stream sediments in assessing the forest soil base cation status and availability. This was performed by comparing the SIGEOM geochemical data and methodology with data from mineral horizons (to a 30 cm depth) of forest soils collected in permanent forest inventory plots located across the forest landbase of Quebec.

The research questions were two-fold:

1) When applied to soil material, does the extraction method used on sediment samples give a relevant indicator of soil base cation status and availability within a soil profile?
   Geochemical signatures are often determined on the fine fraction of samples (<177 μm or less) because this fraction yields higher concentrations and higher variability. This makes it easier to prepare stable regional maps because all analytical results are well above detection limits and regional variation is high compared with analytical error (e.g. Reimann et al., 1998). However, in soil science, the <2 mm fraction is typically used to characterize chemistry, thus producing results that are comparable to accumulated soil data in the world. It is also believed that this fraction represents accurately the total soil volume (Tan, 1996). Element extractions used in geochemical studies, like *aqua regia* (i.e. HCl–HNO_3 extraction) or the nitric acid method used in SIGEOM, also differ from extraction methods traditionally used by forest soil scientists to assess soil nutritional status (e.g. $BaCl_2$ or other salt solution extraction for exchangeable cations; Hendershot et al., 2007). It is thus unclear how geochemical data compare with frequently used forest soil quality indicators, such as pH and cationic exchange capacity and exchangeable cations (Schoenholtz et al., 2000).
2) Can the data from the sediment samples be spatialized in order to provide an indicator of forest soil base cation status and availability across landscapes?
   Production of meaningful maps depends on using the appropriate techniques to generalize point data across landscapes (Lima et al., 2008). Sediment samples in the SIGEOM database were collected in lakes and streams, and sampling was based on an irregular sampling grid. It is thus necessary to spatialize the data from their medium to the surrounding landbase, and impute values to swathes of the forested area from which no data is available.

2. Material and methods

2.1. Sources of data

2.1.1. Geochemical database SIGEOM

The SIGEOM database contains data from over 70,000 sediment samples collected in small lakes and streams across the forest landbase of Quebec in the 1970's and 1980's (Fig. 1a). Samples were sieved to <177 μm (80 mesh) and subjected to the acid extraction method SEAP-S-B-81. In the methods reported by Gagné (1990), sediments are heated to 550 °C for 1 h, and then treated with nitric acid (2 M) for 1 h. Concentrations of a suite of elements are then determined on the extracts by inductively coupled atomic plasma emission spectrometry (ICP-AES). For this study, concentrations of the base cations Ca, Mg, K were taken from the database.

2.1.2. Forest soil databases

Two forest soil databases that provided standardized and comparable information, and for which it was possible to control the quality,