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Long-term base cation weathering rates in forested catchments of the Canadian Shield

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ABSTRACT

A number of methods exist for estimating mineral weathering rates. Yet, quantifying this crucial biogeochemical reaction in the field has always been a challenge because mineral weathering takes place in open systems whose initial state conditions are not well known and where material inputs and outputs vary in time and space. Here, using the soil profile mass balance method, we estimated long-term weathering rates of base cations (BCs) for a set of 21 watersheds, and we investigated the links between environmental variables and soil properties and the spatial variation in BC weathering rates in the study area. The watersheds are located in southern Quebec and vary with respect to hydro-climatic conditions, soil properties and forest cover. Average long-term estimates of annual BC weathering rates for the study area were 0.16, 0.10, 0.09 and 0.06 $kmol_c\ ha^{-1}\ year^{-1}$ for Ca, Mg, Na and K, respectively. Overall, redundancy analysis (RDA) indicated that soil surface area, percent deciduous canopy cover, elevation, as well as soil albite content were the most significant variables explaining together 56% of the total variation in BC weathering rates. Consistent with previous findings, our results showed that, beside soil properties, climate-related environmental variables played key roles in determining the variability of BC weathering rates in the study area. In the context of global climate change, more insights are needed for a better understanding of the effects of discrete climatic variables on BC weathering rates.

1. Introduction

Identifying the most important environmental factors that drive complex biogeochemical processes such as mineral weathering and relating them to the alteration mechanisms of soil minerals constitute a research frontier in the field of biogeochemistry. Meeting this challenge is essential for developing models capable of predicting mineral weathering rates as a function of projected future changes in environmental conditions. A crucial function of mineral weathering in terrestrial ecosystems is to provide essential plant nutrients, notably base cations (BCs). In addition, mineral weathering contributes to the chemical composition of surface waters (Marchetto et al., 1995; Houle et al., 2012a). By influencing atmospheric CO_2 concentration, silicate weathering also influences climate change at the geologic time scale (Berner and Lasaga, 1989).

Several methods have been used to quantify weathering rates in terrestrial ecosystems (Clayton, 1979; Velbel, 1985; Brimhall et al., 1991a, 1991b; Sverdrup and Warfvinge, 1993; Egli and Fitze, 2000). In this study, we have focused on long-term average estimates of BC weathering rates at pedogenic time scale that have been estimated according to the profile mass balance method (Brimhall et al., 1991b; Egli and Fitze, 2000). This method is based on the geochemical behavior of conservative elements such as Ti and Zr which are considered immobile during weathering processes (Cann, 1970; Floyd and Winchester, 1975). It takes into account pedogenic processes, including changes in soil chemical composition and volumetric soil expansion or contraction (Brimhall et al., 1991a, 1991b; Courchesne et al., 2002). The basic assumptions are that: 1) the actual chemical composition of the C horizon is identical to the composition of the initial parent material; 2) the total chemical composition of the parent material is uniform throughout its profile at the initiation of pedogenesis and; 3) additions of material to the soil surface through, for example, aeolian deposition, as well as losses of material through physical surface erosion are minimal, so that the present-day vertical variation in total chemical composition reflects the cumulative effects of mineral weathering in the soil profile over time. This estimation method has limitations because some assumptions notably those relative to the initial uniformity of the parent material and to the equivalence between the chemical composition of the unweathered parent material and the present C horizons cannot always be verified (Courchesne et al., 2002; Schaller et al., 2009). Despite these limitations, the soil profile mass balance has been considered a reliable method to estimate long-term weathering losses at pedogenic time scale (Ouimet, 2008), and was used in a number of studies

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(Kirkwood and Nesbitt, 1991; Taylor and Blum, 1995; Courchesne et al., 2002; Schaller et al., 2009).

There is a wide array of environmental factors and soil properties that are known to likely impact on BC weathering rates. These include topography, prevailing hydro-climatic conditions, vegetation type, biological activity in soils and the chemical (pH, organic matter), physical (surface area) and mineralogical properties of the soil and of the parent material (Holmqvist et al., 2003; Wilson, 2004; Gordon, 2005; Egli et al., 2006). For example, Egli et al. (2006) reported that variables such as water flux, temperature and vegetation could be crucial in determining the rate at which minerals weather in Alpine podzols of northern Italy. Apart from studies carried out along climo-sequences, it is often difficult to relate the variability of estimated BC weathering rates to environmental factors because of the limited number of sites investigated at one time in a given study. A notable exception is the work of Schaller et al. (2009) who determined long-term mineral weathering rates from 39 soil profiles at 13 distinct sites within the Hubbard Brook Experimental Forest, in the White Mountains (New Hampshire, USA). These authors detected a weak negative correlation between mineral weathering rates and site elevation in the region, which led them to hypothesize that the spatial variability in weathering rates could be associated to variations in temperature, precipitation or vegetation type along an elevational gradient. However, the relative importance of each of these variables on long-term mineral weathering rates was not quantified.

The effects of environmental factors on mineral weathering rates have been tested under laboratory (Welch and Ullman, 2000) and field (White and Blum, 1995; Brady et al., 1999; Riebe et al., 2004) conditions. Yet, these studies investigated the effects of individual environmental factors, but did not consider their interactions and their simultaneous, synergetic or antagonistic, effects on mineral weathering rates (Gordon, 2005). Moreover, evidence from field research indicated that the presence of confounding factors often impedes our capacity to isolate and quantify the controls exerted by a discrete environmental factor on mineral weathering rates (Riebe et al., 2004). In this context, the objectives of this study were: i) to quantitatively estimate the long-term weathering rates of the cations Ca, Mg, Na and K in the soils of a series of 21 forested watersheds located in southern Quebec; and ii) to partition the impact of a range of environmental factors and soil properties acting simultaneously on the long-term weathering rates of Ca, Mg, Na and K. Working with a large number of field sites offers the opportunity to assess the in situ relationships between BC weathering rates with environmental conditions and soil properties and to investigate their simultaneous effects using multivariate statistical techniques.

2. Materials and methods

2.1. Study area and sampling sites

The weathering rates of base cations were estimated for 21 watersheds that are part of the Quebec lakes network (Houle et al., 2004). The watersheds were selected as to cover a wide range of geological, pedological and hydro-bioclimatic properties. They are located on the Canadian Shield, within a ~90,000 km^2 area in southern Quebec that is parallel to the St. Lawrence River and bordered by the Ottawa and Saguenay rivers (Fig. 1). In this area, the Canadian Shield is composed of bedrocks formed during the Precambrian era, which consists mainly of igneous (granite, syenite, anorthosite) and metamorphic (gneiss, granitic gneiss, paragneiss, marble) rocks (Lachance et al., 1985). The soils are classified as Podzols in the Canadian system of soil classification (Soil Classification Working Group, 1998) and belong to the Spodosol order of the Soil Taxonomy (Soil Survey Staff., 2014).

The 21 watersheds are forested and free of major direct human activity. They are distributed along a southwest–northeast bioclimatic

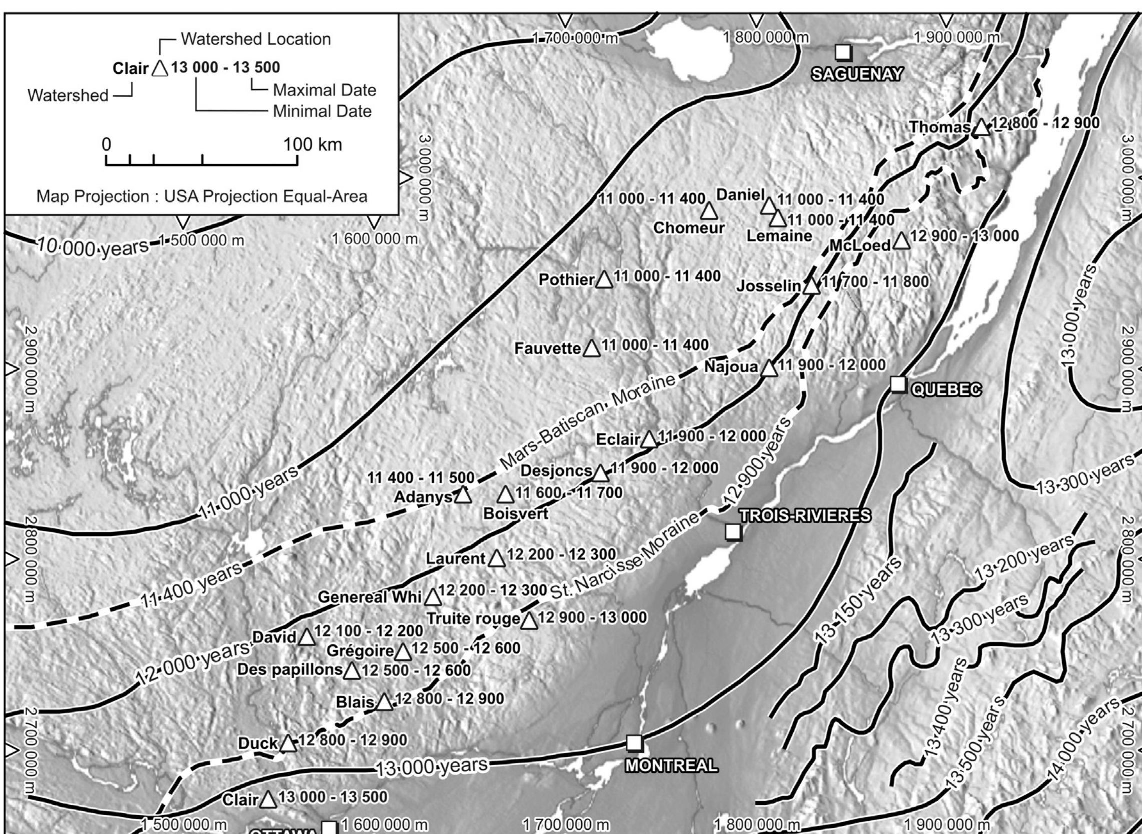

Fig. 1. Location of the watersheds in southern Quebec. The maximum and minimum numbers of years since the retreat of the Laurentian Ice Sheet are shown. The Saint-Narcisse morainic complex and the Mars-Batiscan moraine together with the main and late Younger Dryas isochrones of the Laurentide Ice Sheet ice margin are from Occhietti (2007).