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Assessment of variability and uncertainty of soil organic carbon in a mountainous boreal forest (Canadian Rocky Mountains, Alberta)

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ABSTRACT

Mountain environments are heterogeneous and dynamic geomorphic environments sensitive to land use and climate change. Heterogenic environmental conditions result in a large variability of mountain soil properties, and thus in large uncertainties of inventories of soil organic carbon (SOC). In this study we analyzed the variability of soil properties associated with the calculation of a SOC inventory in a mountain environment in the Canadian Rocky Mountains (Alberta). Therefore, we calculated the analytical uncertainty and spatial variability of SOC stocks using Gaussian error propagation and Taylor series expansion along seventeen 36 m long transects to identify major sources of uncertainty. SOC stocks in the upper 10 cm and 30 cm are 2.4 ± 0.7 kg C m^{-2} and 6.4 ± 5.6 kg C m^{-2}, respectively. The bulk densities generated the largest uncertainty associated with the analytical precision (10.0%). However, analytical uncertainties (ranging between 2.3 and 24.2%) are much smaller than the uncertainty introduced by the spatial variability, for instance of the coarse fraction (63.8%) and SOC concentration (40.1%). This study contributes to insufficiently considered analysis of uncertainties in SOC stocks and demonstrate the high potential of nested sampling approaches to identify sources of uncertainties of SOC stocks. To reduce the uncertainties associated with heterogeneous mountain environments, we propose to apply more sophisticated statistics (e.g. regression analysis considering frequency distributions of measured coarse fractions in different geomorphic environments) rather than simple mean per unit approaches, as frequently applied in regionalization studies of soil properties.

1. Introduction

Globally, soils are the largest terrestrial pool of carbon (C), storing approximately 1500 Pg C in the top 1 m (Batjes, 1996; Lal, 2004). Even small fluctuations of soil organic carbon (SOC) content due to changes in climate, land use or management practice, may result in a significant net exchange of C between the atmosphere and the pedosphere (IPCC, 2007; Mishra et al., 2009). Understanding the role of soil C in the global carbon cycle thus requires detailed knowledge on the fluxes, amounts, and spatial patterns of SOC. Therefore, accurate quantification of SOC storage and its spatial pattern is of fundamental importance to global climate change modeling (Zhao et al., 2005; Quinton et al., 2010).

There is considerable uncertainty if mountain ecosystems, which cover roughly 20% of the terrestrial Earth's surface, will act as a sink or source for future atmospheric CO_2 (Bockheim et al., 2000). Compared to soils at lower altitudes, very little is known about carbon storage in mountain soils, although these are especially vulnerable to climate change and constitute a substantial reservoir of organic C. Generally, lower temperatures and higher precipitation favor slow organic matter decomposition (Riedo et al., 2001; Djukic et al., 2010). Hence, small changes in temperature and precipitation may release large amounts of CO_2, due to increased microbial activity in a warmer and wetter climate compared to recent conditions (Theurillat et al., 1998).

Generally, SOC stock inventories rely on relationships between SOC and potential controlling factors such as elevation and temperature (e.g. Garcia-Pausas et al., 2007; Djukic et al., 2010), aspect and slope position (e.g. Homann et al., 1995; Perruchoud et al., 2000), bedrock material and texture (e.g. Banfield et al., 2002; Hoffmann et al., 2009), pH (e.g. Falloon and Smith, 2009), topography (e.g. Yoo et al., 2006), vegetation and stand age of the forest (e.g. Pregitzer and Euskirchen, 2004; Luyssaert et al., 2008), and both human and natural disturbances (e.g. Czimczik et al., 2005; Morgan et al., 2010). Relations between soil properties and environmental variables are scale dependent and are generally derived from local measurements of soil properties and regional datasets that cover areas up to several thousand square kilometers (e.g. digital elevation models, soil maps, geological maps, and vegetation maps).

All SOC stock assessments are associated with large uncertainties that may result from: i) the complex interactions between the environmental variables, ii) the limited representation of small-scale variability

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of soil properties and soil forming processes at the scale of the SOC inventories, and iii) analytical uncertainties associated with the determination of SOC concentration, bulk density, and soil texture (Freibauer et al., 2004; Goidts et al., 2009). This is particularly true for mountain environments, which are characterized by a large spatial variability of the soil-forming factors and soil properties. Within a few meters large differences of the SOC concentration (in the order of 5% to 20%) may be observed. This small-scale heterogeneity is generally not represented by regional datasets, such as geological maps, soil maps, or digital elevation models (DEM), which typically have a resolution of 10–50 m (Leifeld et al., 2005; Stutter et al., 2009). Consequently, improving SOC inventories requires identifying and reducing the sources of uncertainty that result from scale discrepancies between the operating soil-forming processes and the available regional datasets. First attempts have been made to quantify the uncertainty of regional SOC stock assessments in agricultural lowlands. For instance, Schwager and Mikhailova (2002) have illustrated the error propagation function for various sampling situations within one field and Goidts and van Wesemael (2007) presented a methodology to assess SOC stocks and their evolution at a regional scale in Belgium. In contrast to agricultural environments, little is known on the sources of uncertainty in mountain environments, where uncertainties are expected to be larger due to their pronounced topography. Major questions therefore remain regarding the relationship between topography and the spatial variability of SOC stocks, the identification of factors that significantly contribute to the uncertainty of SOC inventories, and the optimal sampling strategy for the SOC stock assessment in mountain terrain.

The main aim of this study is to estimate the uncertainty and error sources of SOC stocks in the Kananaskis Valley in the Canadian Rocky Mountains (Alberta). We first estimate the site-scale variability (e.g. variability along 17 transects of 36 m length) of relevant soil properties (bulk density, coarse fraction and SOC concentration) and SOC stocks in the mountainous study site. Second, we analyze the relation of SOC stocks to environmental characteristics that influence soil formation and SOC storage (elevation, slope, aspect, soil texture, stand age, lithology, geomorphic environment). However, it is beyond the scope of this paper to discuss the relationship between soil properties and environmental characteristics in full detail. The low number of independent measurements, which is given by the number of transects, limits the application of more sophisticated regression analysis. Third, we analyze the unexplained variability caused by the limited resolution of the available data using a nested sampling approach. Therefore we quantify the variability within homogenous transects and analyze the propagation of analytical measurement errors and spatial differences based on Gaussian error propagation and Taylor series expansion (Taylor, 1997; Schrumpf et al., 2011). Finally, we identify the main sources of these uncertainties and provide implications for improving future sampling strategies in mountain environments.

2. Study site

The study site is located along Highway Hwy 40 within the Kananaskis River basin in south-western Alberta, about 110 km west of Calgary (Fig. 1). The Kananaskis basin stretches from 115°30′W to 114°14′W and 51°07′N to 50°05′N and is located within the Front Ranges of the Canadian Rocky Mountains. Elevations range from 1315 masl (at the outlet to the Bow River) to 3219 masl (Mt. Rae at Highwood Pass).

Mean annual precipitation in the Kananaskis valley (Meteorological Service of Canada, ID 3053600; elevation 1391 masl) varies between 442 and 960 mm (average of 630 mm), with a precipitation maximum during May and June and a minimum during December and January. Precipitation varies throughout the valley, increasing from east to west and about 20 mm for every 100 m of elevation gain.

The topography, which is characterized by NNW-SSE aligned ridges and valleys (Fig. 1), is strongly controlled by the orientation of thrust faults that are typical for the Rocky Mountain front ranges. The ridges are built up by Paleozoic carbonates, whereas the intervening valleys are formed of Mesozoic clastics. Thus, bedrock types of the studied slopes are either Devonian/Mississipian or Jurassic sandstones or siltstones. Predominant parent materials in the valleys are Triassic, Jurassic, Permian, and Upper Cretaceous shale and sandstones (McGregor, 1984).

Soil distribution and characteristics are strongly influenced by active geomorphic processes. Exposed, unweathered bedrock occurs frequently on slopes steeper than ~35°. The most prevalent source material for soils is colluvium veneer on slopes <35°. Colluvial slope deposits in the study area dominantly result from the weathering of bedrock, soil creep, rockfalls, and debris flow (McGregor, 1984).

Based on the FAO (2006) soil classification, dominant soils in the study area are Cambisols, Regosols, Gleysols and Histosols (Greenlee, 1980). Cambisols, which are the most common soil type in the area, occur on steep slopes where water penetration is low and thus weathering of the soil is restricted. Regosols occur throughout a wide range of ecological conditions and are very common in higher elevations. In water-saturated or near-saturated conditions in topographic depressions Gleysols and Histosols may occur. Generally, soil horizons are weakly developed through the high activity of geomorphic processes, which cause frequent distortion and the removal or burial of developed soils (Greenlee, 1980).

The vegetation of the study area is dominated by natural forest. The dominant tree species in the montane ecoregion (1000–1400 masl) are *Pinus contorta* var *latifolia*, *Picea glauca* (white spruce) and *Picea engelmanii*. Deciduous trees (*Populus tremuloides* = trembling aspen and *Populus balsamifera* = balsam poplar) cover less than 5% of the study area and are limited to the montane ecoregion. In the subalpine ecoregion (1400–2100 masl) dominant trees are *Picea engelmannii* (Engelmann spruce), *P. contorta* var *latifolia* (lodgepole pine) and *Abies lasiocarpa* (L.) Mill. (subalpine fir). The alpine ecoregion is located above the treeline, which is at approximately 2100–2400 masl (Macias-Fauria and Johnson, 2013).

Forest stand ages in the Kananaskis region are strongly controlled by the occurrence of forest fires that are predominantly lightning-caused and occur from July to the end of August. These fires are crown fires, characterized by high intensities and high rates of spread, which kill all trees and remove a large proportion of the organic layer (Fryer and Johnson, 1988). The fire return interval has varied over the last 300 years between ~90 to 150 years, in response to changing climates and fire suppression management (Johnson and Larsen, 1991; Macias and Johnson, 2006). Major forest fire during the last century occurred in 1936, 1925, 1920 and 1909 AD (Johnson and Wowchuk, 1993).

3. Material and methods

3.1. Sampling strategy

To analyze the SOC variability in the highly heterogeneous study area we used a two-level nested sampling approach (Zhang and McGrath, 2004; Zhang, 2007; Stutter et al., 2009). The relationship of soil properties and SOC stock with environmental conditions of the Kananaskis valley was established based on the selection of 17 sampling sites along Hwy 40, roughly a distance of 50 km (Fig. 1).

Each site was described by its topographical position, geology, vegetation, and climate based on regional datasets. The terrain inventory map (map-scale: 1:125 000) (Jackson, 1987) was used to stratify sites into the following geomorphic environments: colluvial slope deposits, moraine, glaciofluvial, alluvial fan, and floodplain. Topographical parameters (including elevation, slope, and aspect) were obtained from a digital elevation model with a raster size of 30 m. The DEM was interpolated from contour lines of the Canadian National Geographic database with a scale of 1:50 000. Geological information was taken from the geological map of the Rocky Mountain Foothills and the Front Ranges in Kananaskis Country (Geological Survey of Canada, map