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Decoding potential effects of climate and vegetation change on mineral weathering in alpine soils: An experimental study in the Wind River Range (Wyoming, USA)

Christian Mavris [a,b,d], Gerhard Furrer [b], Dennis Dahms [c], Suzanne P. Anderson [d], Alex Blum [e], Jens Goetze [f], Aaron Wells [g], Markus Egli [h,*]

[a] Department of Earth Sciences, Natural History Museum, Cromwell Road, London SW7 5BD, UK
[b] Institute of Biogeochemistry and Pollutant Dynamics (IBP), ETH Zurich, CH-8092, Switzerland
[c] Department of Geography, University of Northern Iowa, Cedar Falls, USA
[d] INSTAAR and Department of Geography UCB-450, University of Colorado, Boulder, CO 80309, USA
[e] US Geological Survey, 3215 Marine Street, Boulder, CO 80303, USA
[f] Department of Mineralogy, TU Bergakademie Freiberg, D-09596 Freiberg, Germany
[g] ABR, Inc. Environmental Research and Services, P.O. Box 240268, Anchorage, AK 99524, USA
[h] Department of Geography, University of Zurich, CH-8057, Switzerland

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ABSTRACT

Climate change and a related increase in temperature, particularly in alpine areas, force both flora and fauna to adapt to the new conditions. These changes should in turn affect soil formation processes. The aim of this study was to identify possible consequences for soils in a dry-alpine region with respect to weathering of primary minerals and leaching of elements under expected vegetation and climate changes. To achieve this, a field empirical approach investigating an altitudinal sequence was used in combination with laboratory weathering experiments simulating several scenarios. The study sites are located in Sinks Canyon and Stough Basin of the Wind River Range, Wyoming, USA. The following sites (from moist to dry with increasing temperature along the sequence) were investigated: 10 soil profiles (Typic Haplocryoll) in a tundra ecotone, 10 soil profiles (Ustic Haplocryoll) in a pine-fir forest and 20 soil profiles (Ustic Argicryoll) in sagebrush. All soils developed on granitoid moraines. Soil mineralogy was analysed using cathodoluminescence and X-ray diffraction. This revealed that biotite and plagioclase were both weathered to smectite while plagioclase also weathered to kaolinite. Cooler, wetter, altitude-dependent conditions promoted weathering of primary minerals. Furthermore, the soils of the tundra and forest zone exhibited a higher acidity and more organic carbon.

In a series of wet laboratory batch experiments, materials from topsoils (A horizons) and subsoils (B horizons) in each ecotone were examined alone or in combination with other samples. In a first step, aqueous extracts of the topsoil samples were generated in batch reactors and analysed for the main ions. In a second and a third step the topsoil extracts were reacted with the subsoil samples of the same ecotone, and with the subsoil samples of the ecotones at higher altitude. The total duration of these batch experiments was 1800 h, and the solutes were measured using ICP-OES and ion chromatography. Dissolved Ca, Mg and K were mainly controlled by the chemical weathering of oligoclase, K-feldspar and biotite. With increasing altitude the total concentrations of Ca, Mg and K in the aqueous extracts decreased, the relative ionic contribution from K decreased, while the ionic contribution from Ca increased.

Climate change (warming, changed precipitation) potentially will reduce weathering intensity, soil acidity and the content of organic carbon. An altitudinal shift in vegetation due to climate change seems to affect the ionic composition of the soil solution. In the case of a shift from forest to sagebrush and tundra to forest or sagebrush, the relative contribution from K would increase at the expense of Ca. We hypothesise that K will play an important role in future biogeochemical cycles under the assumptions of climate warming and subsequent vegetation shifts to higher altitudes.

1. Introduction

Mountain ecosystems are, for several reasons, likely to be especially responsive to changing environmental conditions such as global

* Corresponding author.
E-mail address: markus.egli@geo.uzh.ch (M. Egli).

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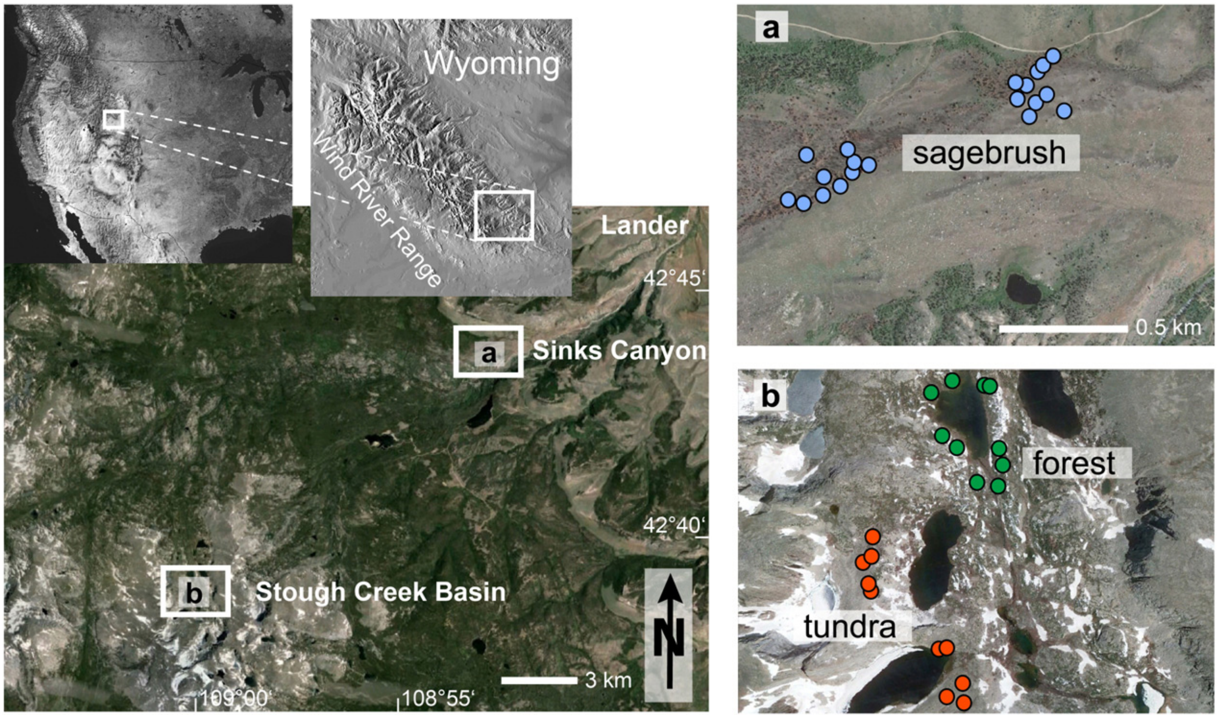

Fig. 1. Overview of the WRR sampling areas, located in the U.S. state of Wyoming (inset): (a) Sinks Canyon (20 sagebrush sites), and (b) Stough Creek Basin (10 forest and 10 tundra sites).

warming, acid deposition and atmospheric nutrient inputs (Theurillat et al., 1998; Arn, 2002; Hosein et al., 2004; Seastedt et al., 2004). Ecosystems in turn affect soil-forming processes (Amundson et al., 2007), particularly through their impact on chemical weathering rates. The rates of chemical weathering reactions and their dependencies on environmental factors are of fundamental interest for understanding soil systems and their inter-relations with surrounding environments.

Dissolution of most primary rock-forming minerals is limited by slow kinetics at the mineral–water interfaces (Stumm and Morgan, 1996). Mineral dissolution rates depend on *extrinsic* factors such as T, pH, Eh, and exudates from microbes and plant roots, as well as on *intrinsic* factors such as mineral-surface properties and the presence of weathering products. Acidity and the availability of ligands promote dissolution reactions for primary minerals and govern their transformations into secondary minerals (Furrer et al., 1990; Wehrli et al., 1990; Sverdrup and Warfvinge, 1993; Mavris et al., 2010). Erosion provides materials with an easily weatherable surface and consequently is a primary intrinsic influence in the soil system. Chemical weathering and physical erosion are coupled to the degree that mineral weathering rates depend on the availability of fresh mineral surfaces with high reactivity (White et al., 1999; Jacobson and Blum, 2003; Riebe et al., 2004; Dixon and von Blanckenburg, 2012; Heimsath et al., 2012; Heimsath, 2014; Larsen et al., 2014).

One obvious expression of environmental change due to climatic warming is the altitudinal shift of vegetation and related ecological associations (Di Pasquale et al., 2008; Berthel et al., 2012; Solàr, 2013). Muhs et al. (2001) concluded that weathering rates are influenced primarily by a combination of precipitation, temperature and parent rock material; however, higher temperatures do not necessarily lead to increased weathering rates in alpine regions (Egli et al., 2003b). The empirical effects of the climate factor on weathering rates, mineral formation, and transformation remain equivocal and are still a matter of debate (e.g., Óskarsson et al., 2012; Lybrand and Rasmussen, 2014). While some demonstrate that temperature is the dominant variable exerting control on the extent of weathering (e.g., Óskarsson et al., 2012), others emphasise or hypothesise the particular role of water availability in the soils and biological processes (e.g., White and Blum, 1995; White et al., 1999; Dixon et al., 2009; Williams et al., 2010; Brantley et al., 2011; Rasmussen et al., 2011). Patterns of weathering processes in alpine environments are strongly linked to biological and microclimatic factors (Egli et al., 2010). Climate warming can give rise to short-term changes in the distribution of vegetation and may induce soil chemical and mineralogical changes within a relatively short period of time (Zanelli et al., 2006, 2007).

Investigations in dry alpine regions concerning the effects of climate change on mineral weathering are mostly lacking. Sagebrush steppe

Table 1
Characteristics of the field sites.

Ecotone	Vegetation	Elevation m asl	MAT[a] °C	MAP[a] mm/yr	Soils (Soil Taxonomy; Soil Survey Staff, 2014)	Parent material
Sagebrush	Mountain big sagebrush/bluebunch wheatgrass; with *Artemisia tridentata* var. *vaseyana*/, *Elymus spicatus*, *Elymus spicatus–Poa secunda*	2400	+2.7	400	Ustic Argicryoll	Granitic till
Forest	Douglas-fir with Rocky Mountain maple whitebark pine/grouse whortleberry; *Pinus albicaulis*/*Vaccinium scoparium* h.t. as dominant species	3200	−2.1	700–800	Ustic Haplocryoll	Granitic till
Tundra	Blackroot sedge, Alpine Turf; with *Geum rossii* var. *turbinatum* as the dominant species	3350	−3.0	800–900	Typic Haplocryoll	Granitic till

[a] Data source: Massatti (2007), Dahms et al. (2012), PRISM Climate Group (2014).