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Weathering, soil formation and initial ecosystem evolution on a glacier forefield: a case study from the Damma Glacier, Switzerland

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ABSTRACT

The understanding of biogeochemical processes at the interface between geosphere, hydrosphere and biosphere is of paramount importance for many questions related to global climate and environmental change at very different time and spatial scales. In addition, soils are the principal resource for food production and the understanding of soil formation processes and biological interactions within soils is indispensable for the development of sustainable land-use strategies. In this contribution we present a research initiative, the multidisciplinary 'BigLink' Project, aiming at a better understanding of the links between weathering, soil formation and ecosystem evolution and how these biosphere-geosphere interactions are influenced (and themselves influence) climate and environmental change.

Introduction

Global change has well recognized effects on climate, on nutrient fluxes for example, and on biodiversity, but its effects on weathering, soil formation and soil organic matter accumulation are less well understood. In the future, increased temperatures, changes in rainfall patterns and seasonal distribution, as well as atmospheric N and S deposition, are likely to increase the rates of weathering and influence biogeochemical processes in soils. A good understanding of the response of weathering and soil-forming processes to climate and environmental changes is important for the inclusion of climate-vegetation-soils feedbacks in global climate models, and for the long-term preservation of soil fertility. Furthermore, global warming also leads to the retreat of glaciers and permafrost in many parts of the world resulting in the exposure of pristine landmasses to atmospheric conditions

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and in changes in the hydrological cycle in entire watersheds.

In this contribution we will present the approach and first results of the Project BigLink: **Bi**osphere-**G**eosphere interactions: **Link**ing climate change, weathering, soil formation and ecosystem evolution. funded by the Competence Center Environment and Sustainability (CCES) of the ETH Domain, Switzerland, with contributions by ETH-Zürich, the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Swiss Federal Institute of Aquatic Science and Technology (EAWAG) and the Swiss National Science foundation. This project aims at a detailed multidisciplinary study of the initial phase of weathering to obtain a detailed picture of the processes occurring at the biosphere-hydrosphere-geosphere interface and to develop new geochemical tools to study weathering and soil-formation processes. A better knowledge of solute inputs, e.g. acid deposition on weathering rates, soil formation and erosion, and on ground and surface water chemistry, is thus fundamental for the evaluation of the influence of climate change on ecosystems. To unravel the complexities of weathering systems, collaborative interdisciplinary science is needed. Although many of these aspects have been studied individually, there is a lack of a comprehensive coordinated study of weathering which includes all biological, geochemical, mineralogical, hydrological and geological aspects, and upscaling from the micro- to the watershed scale. The long-term goal is to improve our understanding of basic processes and improve our ability to upscale to larger watersheds and to forecast changes in the hydrology and element fluxes of whole watersheds with changing climate.

Location of the investigation area

The research site at the terminus of the Damma glacier is located in the Central Alps, in the canton of Uri, Switzerland (N46º38.177' E008º27.677'), ~2100 m above sea level. The climate in this area is characterized by a short vegetation period, and ~2400 mm of precipitation per year. The front of NE exposed Damma glacier has retreated at an average rate of ~10 m per year since the beginning of systematic measurement in 1921. For our studies we established a grid for representative sampling of soil evolution along the chronosequence which are studied by all involved groups. In addition, we are monitoring meteorological conditions, as well as sampling the inputs and outputs from the catchment, by means of automated water-sampling stations.

Weathering and soil-formation processes

Weathering and soil-forming processes have been the subject of extensive research for decades. For recent reviews see Brantley (2003) and Amundson (2003). However, although extensive laboratory and field studies exist, many processes are still poorly understood. For example, although the mechanisms and rates of mineral dissolution have been studied extensively, there are still large discrepancies between dissolution rates observed in the laboratory and in the field. The reasons are related e.g. to different surface areas of minerals in the field, the formation of secondary precipitates, macropore flow, the development of weathering rinds, or transport limitation due to the physical properties of the soil (e.g. White *et al.*, 1996). White and Brantley (2003) further suggested that extrinsic controls, like climate, have an additional influence on the dissolution rate observed in the field compared to rates derived in the laboratory. One major problem for a better understanding of weathering processes is the upscaling from laboratory- and mineral grain-size rates to field scales due in part to the hydrological complexity of natural systems (Brantley, 2003). Another important problem is the possibility to have spatially and temporally resolved sampling of a high variable natural system. In particular, plants and microorganisms can increase the rate of weathering of minerals by taking up ions from the soil solution, removing the dissolution products of minerals, and through the exudation of protons, low molecular weight organic acids, or siderophores, leading to ligand-promoted mineral dissolution (Marschner, 1995; Hinsinger *et al.*, 2001). Thus, to improve the understanding of processes influencing weathering rates, it is important to study in detail biological activity in the field, in particular the evolution of micro-organisms and plants, and their importance in mobilization of elements, as well as in the buildup of organic carbon in the soil. One of the key aspects of our project is a detailed study of microbial and plant communities along the chronosequence as well as the analysis of exudates in order to determine their role in weathering. In addition, new isotope tracers for the study of chemical weathering are being developed and tested in the glacial forefield of the Damma glacier. By developing new isotope tracers that are a direct probe for small-scale processes that take place in soils, we expect to provide a deeper understanding of the processes underlying initial soil formation, nutrient mobilization and uptake by organisms (plants, microorganisms) influencing chemical weathering.

Soil-organic carbon dynamics and ecosystem evolution

An improved knowledge of organic matter turnover rates in soils is very important for the quantification of soils as sources and/or sinks of atmospheric CO_2 and other greenhouse gases. The response of soil organic matter (SOM) decomposition to the predicted climate warming is hotly debated (see Davidson and Janssens, 2006, for a recent review). In addition, SOM is an important source of energy for heterotrophic soil organisms, and thus its resistance to biodegradation is of paramount importance to soil development and ecosystem evolution.

Chronosequences of several thousands of years and ^{14}C dating of SOM indicate that rates of net C accumulation in soils are greatest during the initial phase of soil formation (Schlesinger, 1990). Subsequently the C accumulation rates decrease with time and reach a steady state after thousands of years (Perruchoud and Fischlin, 1995; Michalzik *et al.*, 2003). Consequently, the C sink in soils is greatest during the first decades to centuries of soil genesis. However, many soil studies have been carried out with much older soils that have developed for thousands of years, and little is known of what is happening during the very initial phase. One of the main factors limiting our knowledge of organic matter cycling in soils is its complexity, which ranges from fresh fragments of various organisms to recalcitrant phases derived from millennia of biogeochemical processes in the soils. Many physical and chemical extraction methods have been used to characterize pools of organic matter with different reactivity, whereby the very different methodologies make it difficult to obtain conclusive answers. These methods have revealed many important features of carbon turnover, but important knowledge gaps remain. A relatively new approach in the study of organic carbon origin and turnover rates is the ^{14}C analysis of specific organic compounds separated either by gas chromatography (Eglington *et al.*, 1996) or by HPLC (Smittenberg *et al.*, 2002). These methods have mainly been applied to the study of marine sediments, although some successful applications have shown the potential of this method for SOM studies (e.g. Rethemeyer *et al.*, 2005).

Previous studies at the Damma glacier (Sigler and Zeyer, 2002) and from other sites have shown that the soil microbial community changes drastically along the chronosequence of deglaciation. In addition, it is known that carbon and nutrient pools, as well as vegetation composition change drastically with time after deglaciation (Chapin *et al.*, 1994). However, there are only very few studies which have attempted to link the evolution of microbial populations and that of plants at the same site. At the classic Glacier Bay site in Alaska, along a deglaciation gradient of 200 y a successional shift is observed from a vegetation of algae, lichens and mosses at the very early stages of soil development, to vegetation with abundant N_2-fixing plants in later stages, and vegetation without N_2-fixers in the oldest stages. A similar pattern seems to exist at the Damma Glacier Forefield, and we are investigating the relationship between the below-ground microbial populations and the evolution of the plants above ground.

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