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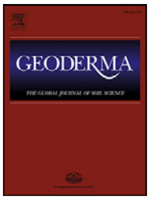

Review article

Soil formation rates on silicate parent material in alpine environments: Different approaches–different results?

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ABSTRACT

High-mountain soils develop in particularly sensitive environments. Consequently, deciphering and predicting what drives the rates of soil formation in such environments are a major challenge. In terms of soil production or formation from chemical weathering, the predominating perception for high-mountain soils and cold environments is often that the chemical weathering 'portion' of soil development is temperature-inhibited, often to the point of non-occurrence. Several concepts exist to determine long-term rates of soil formation and development. We present three different approaches: (1) quantification of soil formation from minimally eroded soils of known age using chronosequences (known surface age and soil thickness — SAST), (2) determination of soil residence times (SRT) and production rates through chemical weathering using (un)stable isotopes (e.g. $^{230}Th/^{234}U$ activity ratios), and (3) a steady state approach using cosmogenic isotopes (e.g. ^{10}Be).

For each method, data from different climate zones, and particularly from high-mountaINS (alpine environment), are compared. The SAST and steady state approach give quite similar results for alpine environments (European Alps and the Wind River Range (Rocky Mountains, USA)). Using the SRT approach, soil formation rates in mountain areas (but having a temperate climate) do not differ greatly from the SAST and steady state approaches. Independent of the chosen approach, the results seem moderately comparable. Soil formation rates in high-mountain areas (alpine climate) range from very low to extremely high values and show a clear decreasing tendency with time. Very young soils have up to 3–4 orders of magnitude higher rates of development than old soils (10^5 to 10^6 yr). This apparently is a result of kinetic limits on weathering in regions having young surfaces and supply limits to weathering on old surfaces.

Due to the requirement for chemical weathering to occur, soil production rates cannot be infinitely high. Consequently, a speed limit must exist. In the literature, this limit has been set at about 320 to 450 t/km^2/a. Our results from the SAST approach show, however, that in alpine areas soil formation easily reaches rates of up to 800–2000 t/km^2/a. These data are consistent with previous studies in mountain regions demonstrating that particularly young soils intensively weather, even under continuous seasonal snowpack and, thus, that the concept of 'temperature-controlled' soil development (soil-forming intervals) in alpine regions must be reconsidered.

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1. Introduction

As climate warming becomes a more obvious environmental factor, questions of how soils and landscapes have developed and what future scenarios may be possible are concerns of major scientific and socio-economic importance. This is especially important in high-mountain settings, where melting of permafrost and changing vegetation regimes lead to rapid and dramatic changes in soil formation and erosion (Haeberli, 2005; Haeberli et al., 2007). High mountain valleys experience active gravity-driven hillslope processes (Heimsath and McGlynn, 2008) — and this activity potentially increases when glaciers and permafrost retreat or frost periods decrease. Knowledge of the spatial and temporal dynamics of high mountain soil-development processes in a landscape context is therefore required; however, our current knowledge in this field is incomplete and fragmented. Predicting what drives the transition from 'non-soil' to a soil-mantled rocky landscape (or from bedrock or raw regolith to a 'developed' soil mantle) is, therefore, a significant challenge for models of landscape evolution and for 'critical zone' studies (Heimsath et al., 2012). The data needed to calculate weathering rates and the production of soil materials have recently become accessible through the use of cosmogenic or other nuclide techniques (e.g., Dosseto et al., 2008; Heimsath et al., 1997; Riebe et al., 2003). Likewise, evidence of material production or denudation is preserved in stream sediments or directly in soil profiles. Long-term total denudation rates can be measured at the catchment scale or single soil profile using (cosmogenic) nuclide measurements (e.g., Brown et al., 1995; Granger et al., 1996; von Blanckenburg, 2006). In combination with geochemical mass balance data from which dissolution losses are inferred from the rock-to-soil enrichment of insoluble elements, long-term chemical weathering rates can also be determined (Green et al., 2006; Norton and von Blanckenburg, 2010; Riebe et al., 2001, 2003, 2004a,b).

However, the determination of 'soil production' or 'soil formation' is difficult and several approaches and concepts exist that lead to potentially different or possibly even contradictory results. In this paper we compare three approaches for estimating soil production/formation rates, with particular focus on mountain and alpine areas where soils have developed in silicate materials of glacial moraines. These approaches include i) the chronosequence approach (stable sites, known surface age, profile thickness), ii) soil residence time, and iii) steady state approach (for details see Section 3 below).

As the basic concepts behind each of these methods to determine rates of soil formation or production are distinctly different, it is useful to determine whether the results of these methods are also distinctly different — or not. In this paper we present and discuss these concepts by comparing published and new data from mountain sites having an alpine climate.

2. Soil formation and weathering

2.1. Principles

Landscapes are shaped by the uplift, deformation and breakdown of bedrock and the erosion, transport and deposition of sediment. According to Dietrich and Perron (2006), all landscapes must obey an equation for the conservation of mass:

$$\frac{\partial z}{\partial t} = U - I - \nabla q_s \tag{1}$$

in which z is the elevation of the ground surface, t is time, U is the uplift rate, I is the lowering of the bedrock surface, and q_s is the volume flux of stored sediment (soil, colluvium, alluvium, and so on) per unit width. It is broadly understood that tectonic forcings influence the pace and pattern of landscape evolution by their control on landscape relief and the physical and chemical processes that move sediment and dissolve bedrock (Dixon et al., 2012; West et al., 2005). An understanding of the tectonic processes (U) operating on the landscape as well as 'geomorphic transport laws' (I and q_s) is required to describe the rates of different transport, bedrock-to-soil conversion and erosion processes in terms of material properties, climatic influences and attributes of the topography and subsurface.

Soil formation (or production) depends mainly on the lithology (e.g. highly reactive minerals such as carbonates and sulphates vs. crystalline rocks), the development of organic matter (Conen et al., 2007), the rate of supply of fresh regolith through physical weathering and erosion, the age of exposure, and the character of the hydrological system. This harkens back to the fundamental concept of Dokuchaev (1883) and, in an extended form, of Jenny (1941) according to which soil formation is a function of the five (more or less) independent factors 'time', 'climate', 'topography', 'organisms' and 'parent material'. All these factors act together to influence the rate(s) and direction(s) of soil formation. In this work, we focus on soils developed on silicate parent materials.

The terms 'soil production', 'soil formation' and 'soil development' have been used with differing meanings in different texts, and have to be defined in a first step. For the purposes of this paper, we consider the terms 'soil formation' and 'soil development' to be synonymous. The term 'soil production' designates the gross production while 'soil development (or soil formation)' describes the net effect.

- *Soil formation* (soil development; see Shaw (1930), Jenny (1941), Phillips (1993), Minasny et al. (2008), Sommer et al. (2008)): Soil is viewed as an open system with additions and removals of materials to and from the profile, and translocation, transformation within the profile. Pedogenesis can be progressive or regressive. Progressive pedogenesis includes processes that promote differentiated profiles leading to a horizonization, leaching, developmental upbuilding, and soil deepening. Regressive pedogenesis (Minasny et al., 2008; Sommer et al., 2008) includes processes that promote rejuvenation processes, retardant upbuilding (impedance produced by surface-accreted materials), and surface removals (erosion). In terms of soil thickness, soil formation (and as a synonym soil development) refers to a change (usually an increase) of h (Fig. 1). Soil formation is therefore considered as a net change in mass balance of the soil compartment.
- *Soil production*: In general, soil production includes the transformation of the parent material into soil (due to chemical and physical weathering, mineral transformation) and the lowering of the bedrock (or parent material) — soil boundary (Heimsath et al., 1997). Ahnert (1967) and Heimsath et al. (1997) suggested that the rate of soil production ($\partial e / \partial t$) can be represented as an exponential decline with soil thickness, whereas other authors observed a humped function (e.g. Heimsath et al., 2009).

2.2. Vegetation

Living organisms are important for many of soil and landscape related processes. Over short timescales, the impact of living organisms is quite apparent: rock weathering, soil formation and erosion, slope stability or instability and river dynamics are directly influenced by biotic processes that mediate chemical reactions, dilate soil, disrupt the ground surface, and add strength with a weave of roots (Dietrich