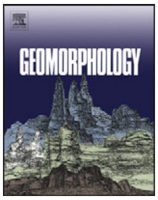
Geomorphology 204 (2014) 510–517

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph



The role of climate-driven chemical weathering on soil production

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ARTICLE INFO

Article history:
Received 11 February 2013
Received in revised form 21 August 2013
Accepted 25 August 2013
Available online 4 September 2013

Keywords:
Soil production function
Soil depth
Numerical modelling
Weathering limits

ABSTRACT

Climate plays an important role in controlling rates of weathering and weathered regolith production. Regolith production functions, however, seldom take climate parameters into account. Based on a climate-dependent weathered regolith production model, at low denudation rates, relative regolith thicknesses are less sensitive to changes in precipitation rates, while at high denudation rates, small changes in climatic parameters can result in complete stripping of hillslopes. This pattern is compounded by the long residence times and system response times associated with low denudation rates, and vice versa. As others have shown, the transition between regolith-mantled and bedrock slopes is dependent on the ratio of denudation to production. Here, we further suggest that this is itself a function of precipitation rate and temperature. We suggest that climatic parameters can be easily incorporated into existing soil production models and that such additions improve the predictive power of soil production models.

1. Introduction

1.1. Modelling soil formation for timescales spanning thousands of years

Hillslopes comprise the entire range of landscapes, from thick soil mantles to bare rock. Soil thickness on these slopes is a function of upbuilding and downwasting processes including incorporation of organic material, aeolian deposition and compaction among others (Johnson et al., 2005a,b). The mechanisms and rates of regolith production on hillslopes and the formation of soils have been addressed in numerical studies, mainly through the use of depth–decay functions where weathering rates decay exponentially with increasing soil thickness (e.g., Tucker and Slingerland, 1994; Heimsath et al., 1997; Tucker and Slingerland, 1997), or by hump-shaped functions (Humphreys and Wilkinson, 2007; Heimsath et al., 2009; Pelletier and Rasmussen, 2009; Gabet and Mudd, 2010) where weathering rates are at their maximum for a limited soil thickness, which is commonly 20–40 cm. Despite the wealth of soil production data, there has been little headway made towards integrating climate into soil production models. Pelletier and Rasmussen (2009) presented a climate-dependent weathering model based on effective energy and mass transfer (*EEMT*; Rasmussen and Tabor, 2007):

$$EEMT = 347,134e^{-1/2\left[\left(\frac{MAT-21.5}{-10.1}\right)^2+\left(\frac{MAP-4412}{1704}\right)^2\right]} \tag{1}$$

$$P_0 = \mathrm{a}e^{\mathrm{b}EEMT} \tag{2}$$

where *MAT* is the mean annual temperature in °C, *MAP* is the mean annual precipitation in mm yr^{-1}, a ($\mathrm{m\ ky}^{-1}$) and b ($\mathrm{m}^2\ \mathrm{kJ}^{-1}\ \mathrm{yr}^{-1}$) are empirically derived constants, and P_0 is the bedrock lowering rate ($\mathrm{m\ ky}^{-1}$). This model does a good job of predicting weathered regolith production rates in the tested settings (data from Riebe et al., 2004). The *EEMT* model is effective, but does not directly address primary mineral weathering. While soil production and weathering are not interchangeable, the weathering of primary minerals is a vital step in the production of most soils, especially for regions where inputs through colluvial, alluvial, or aeolian sources are lacking (Minasny et al., 2008). Mineral-specific weathering and regolith production models have been developed in the past few years (Ferrier and Kirchner, 2008; Lebedeva et al., 2010). These models have been instrumental in identifying the boundaries between supply limited and kinetically-limited weathering, but they do not explicitly include climate variables such as precipitation. Two recent papers (Dixon and von Blanckenburg, 2012; Heimsath et al., 2012) have come to slightly different conclusions with respect to the limits on soil production. Dixon and von Blanckenburg (2012) suggest a global maximum soil production rate (dependent on lithology) while Heimsath et al. (2012) build on the concept that the maximum

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http://dx.doi.org/10.1016/j.geomorph.2013.08.030

production rate is also dependent on erosion rates such that faster erosion rates yield faster regolith production rates. Important in these studies is the consideration that soil formation and weathering are ultimately linked for geomorphic time scales spanning thousands to hundred thousands of years, which we build on here.

In this paper, we use a climate-dependent model of regolith production that can be easily introduced into landscape evolution models. Our model is based on existing geomorphic transport laws (Dietrich et al., 2003) and weathering equations (White and Blum, 1995) operating on hillslopes, and includes precipitation, temperature, and erosion rate as independent variables. Dixon and von Blanckenburg (2012) defined regolith production as the chemical alteration of bedrock to form saprolite, and soil production as the disturbance of saprolite to create soil. We address the simplest case where soil is formed directly from bedrock weathering. Likewise, we consider a simple scenario in which soil thickness reaches a steady state related to weathering and erosion. While this assumption may not hold for all natural settings, some locations display relatively simple soil production functions which are dependent on soil thickness and potentially erosion rate (Heimsath et al., 1997). In this case, regolith production and soil production are equivalent. As such, soil production in this model is accomplished through the chemical alteration of primary silicate minerals. We note that processes such as bedrock cracking through physical processes, formation of weathering pathways, lithological heterogeneities and orientation of geological fabric are boundary conditions with important consequences for weathering rates. However, we explicitly focus on this simple end member scenario to explore the extent to which climate-controlled chemical alteration contributes to the formation of soils and weathering covers, how these mechanisms compete with surface erosion, and how hillslopes respond if thresholds in weathering and erosion ratios are reached.

1.2. Rates of soil formation

Soil mantled slopes are formed in those landscapes where hillslope transport rates are slower than the weathering rates of bedrock. The resulting hillslopes display smooth curvatures, and the unconsolidated material is often transferred in the downslope direction by diffusive style processes, such as soil creep (e.g., Roering et al., 1999). In contrast, in landscapes where hillslope transport rates or fluvial incision rates exceed the upper limit of bedrock weathering rates, bedrock becomes exposed on hillslopes. These landscapes transport material to streams by episodic mass failure such as rock avalanches and landsliding. These mechanisms have been associated with large variations in denudation rates. Diffusive soil creep typically occurs at rates below 0.2 mm yr^{-1} (Binnie et al., 2007; DiBiase et al., 2010; Norton et al., 2010), while stochastic mass wasting is associated with order of magnitude faster denudation rates (Binnie et al., 2007; DiBiase et al., 2010; Norton et al., 2010; Savi et al., in press). Erosion rates on soil-covered hillslopes have been measured using in situ produced cosmogenic ^{10}Be, ^{26}Al, and ^{21}Ne concentrations in bedrock sampled under soils of different depths. The rates range from ~0.06–0.38 mm yr^{-1} for the central European Alps (Norton et al., 2008, 2010), ~0.08–0.37 mm yr^{-1} in the western United States (Heimsath et al., 1997, 2001a, 2005), 0.05–0.14 in western Australia (Heimsath et al., 2000, 2001b), ca. 0.2 and 0.05 mm yr^{-1} for soil-mantled hillslopes in northern Peru and northern Chile, respectively (Kober et al., 2006; Abbühl et al., 2010), and to 0.03 mm yr^{-1} in the Appalachian Mountains (Matmon et al., 2002). Cosmogenic nuclide-derived denudation rates in these settings average over ~10^4–10^5 yr timescales, which is long enough to integrate diffusive processes on soil mantled hillslopes. Episodic erosion rates are typically an order of magnitude faster, measuring 1–3 mm yr^{-1} in the western United States (Binnie et al., 2007), >3 mm yr^{-1} in the Swiss Alps (Norton et al., 2010), and 2–4 mm yr^{-1} in the Italian Alps (Savi et al., in press). These rates average over ~10^3 years, similar to the reoccurrence intervals for stochastic mass failure. Accordingly, the presence or absence of a soil cover on hillslopes is a key indicator of long-term erosion rates, and for the interpretation of possible erosional mechanisms in a landscape.

2. Modelling approach

2.1. Regolith production on hillslopes

We are primarily interested here in modelling the production of regolith on hillslopes under variable climate parameters. We explicitly determine regolith production rates and thicknesses assuming the system approaches a steady state. In particular, in the absence of profile collapse or inflation, mass balance on the hillslope requires that;

$$\frac{dH}{dt} = SPR - D \tag{3}$$

where H is the soil depth (L), SPR is the soil production rate (L T^{-1}), and D is the total denudation rate (L T^{-1}) — see Tucker and Hancock (2010) for a complete review of continuity of mass equations.

The denudation rate term is more fully expressed as the sum of the physical erosion rate and chemical weathering rate. However, the combined denudation term has the advantage of being directly quantifiable at the hillslope to catchment scale. In particular, cosmogenic nuclide-derived denudation rates are available for catchments around the world (see von Blanckenburg (2006) for review), and therefore make a convenient model input. The implications of this assumption are discussed below.

The remaining term on the right side of Eq. (3) is regolith production. Measurements of weathered regolith production rates are less common. Where they have been measured or estimated, rates tend to be between ~10^{-4} and 10^{-5} m yr^{-1} (Heimsath et al., 1997, 2000, 2001a,b; Bierman and Nichols, 2004; Heimsath et al., 2005; Norton et al., 2008, 2010) depending on lithology and climate. This production rate is also dependent on the thickness of regolith, and is commonly modelled using an exponential depth dependent function (e.g., Ahnert, 1967):

$$SPR = SPR_{\max} e^{-\alpha H} \tag{4}$$

where $SPR_{\max}$ is the maximum soil production rate under zero regolith cover (L T^{-1}), and α is a rate constant (L^{-1}) (Table 1). The parameters $SPR_{\max}$ and α have been determined by Heimsath et al. (1997, 2000, 2001a,b, 2005) to range between ~5×10^{-5} and 3.7×10^{-4} m yr^{-1} and 1.7 and 4 m^{-1}, respectively, for a range of granitic and quartz-bearing sedimentary rocks. The value of α for granitic rocks is typically ~2 m^{-1} (Heimsath et al., 2000, 2005).

While the exponential production function has been shown to perform well in some landscapes (e.g., Heimsath et al., 1997, 2000, 2001a,b, 2005), a "humped" regolith production function has also been observed in nature (Heimsath et al., 2009). The hump-shaped function exhibits a maximum production rate under a thin soil cover (Carson and Kirkby, 1972; Ahnert, 1976; Anderson, 2002). Here, we use the approach of Anderson (2002) and Pelletier and

Table 1
Model inputs.

a_0	0.42	Best fit to Riebe et al. (2004)
E_a	77 kJ mol^{-1}	White and Blum (1995)
α	3 m^{-1}	Best fit to Riebe et al. (2004)
T_0	278.15 K	White and Blum (1995)