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A mechanistic model to predict soil thickness in a valley area of Rio Grande do Sul, Brazil

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ABSTRACT

Soil thickness is an important soil characteristic changing over space and time. In this study, we used a mechanistic soil landscape models to predict soil thickness and show it under development over time. The study was conducted in an 8,118 ha area in Vale dos Vinhedos, Rio Grande do Sul State, Brazil. Different soil production functions (SPF) combined with a landscape evolution model (LEM) were explored. The SPF calculated the soil production rates and LEM calculated erosion and deposition patterns. We evaluated two types of model. Model 1 was used to predict the current soil thickness. The model equals the erosion estimations (by a LEM) to the soil production rate (by a SPF). Three types of SPF were tested, based on a spatial variation of soil moisture. A steady-state condition was assumed, considering soil production rates similar to erosion rates. The model simulated erosion events to 1 year, using a Digital Elevation Model (DEM). A soil survey with observed soil thickness was used to validate the different models. Model 2 used the soil thickness estimation from Model 1 to simulate the soil thickness changes up to 100 kyr, considering the balance between soil production rate and soil eroded or deposited. The soil thickness changes were evaluated in different landscape positions. In Model 1, the linear correlation between observed and predicted soil thickness varied between 0.25 and 0.49, with higher linear correlation in models using soil moisture data. The RMSE under different models varied between 34 cm and 37 cm. Overall, soil depth was more accurately predicted in the upland areas than in the valley bottom areas. Model 2 suggested that the soil thickness variation largely depended on the landscape position. The average soil thickness changed from initial 67 cm (0 Kyr) to 103 cm (100 kyr).

1. Introduction

Physically-based models of landscape-scale erosion and deposition have largely advanced in the last decades. Landscape Evolution Models (LEMs) can simulate elevation changes based on differences caused by erosion and deposition, and have been validated in a wide range of environments. LEMs have been widely used in the Earth Sciences (Willgoose, 2005) as an experimental tool to investigate processes of landscape evolution. LEMs can also be used to study the spatial distribution of soils and vegetation (Saco et al., 2007; Saco and Moreno-de las Heras, 2013; Pelletier et al., 2013; Yetemen et al., 2015).

There is an interaction process between soil and landscape. Soil texture, soil organic carbon and surface stone cover are properties that affect landscape evolution dynamics and the spatial variability and magnitude of erosion (Minasny et al., 2015). Conversely, landscape evolution influences soil development, as erosion or deposition changes the thickness across the landscape. In an eroding landscape, the bedrock-saprolite contact is closer to the surface, which in turn accelerates the soil production (Heimsath et al., 1997). The accelerated soil production could be due to the action of bioturbation, by the uprooting of bedrock material (e.g. Phillips and Marion, 2006), more intense chemical weathering as surface horizons are flushed by infiltrating rain-

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water (Maher, 2010), or more active physical weathering as a result of frost cracking (Anderson et al., 2013).

Few models have integrated landscape and soil formation and most studies work with a hypothetical landscape and validation of soil-landscape models with limited field data (Minasny et al., 2015). Saco et al. (2006) used the SIBERIA model, combined with a soil production rate, to evaluate the use of spatially varied soil moisture. Results were comparable to Heimsath et al. (1997) who showed an exponential decline in soil production rate with soil thickness. The LORICA model (Temme and Vanwalleghem, 2015) was built based on the landscape evolution LAPSUS and the soil formation MILESD (Vanwalleghem et al., 2013); it demonstrated soil landscape interactions, but the model was not validated with field data. Vanwalleghem et al. (2013) used MILESD on a test area within the Werrikimble National Park in NSW, Australia. The model included physical and chemical weathering, clay migration, neoformation, bioturbation and carbon cycling. The results showed the importance of the soil-forming processes interacting with erosion and deposition. The model predicted trends in total soil thickness along a *catena*, which were comparable to field observations. Soil thickness, texture and bulk density were predicted with errors in the order of 10%.

A convenient assumption in some studies (Nicótina et al., 2011; Heimsath et al., 1997) is that soil production and transport are in steady-state. Heimsath et al. (2001a, 2001b) notes that deviations from such steady-state lead to an incorrect modelling of the exposure history. Therefore, most studies have been carried out in diffusion-dominated convex ridges (noses), hereby avoiding places dominated by landslides or other perturbations such as tree falls. Little or no research has been carried out in complex landscapes that include actively eroding areas and bottom valleys, influenced by sediment deposition. In lower-lying areas soil thickness increases and soil production is expected to be low according to the assumed exponential dependency between soil production and depth.

The objectives of this study were to assess the potential of a combined soil and landscape evolution model to (i) predict soil thickness and (ii) to estimate the trends of soil thickness variation over time, under different landscape positions. Different models were developed and tested and the results were validated using measured soil thickness data in the region of Vale dos Vinhedos in Rio Grande do Sul State, Brazil. The study was conducted in two steps. Firstly, we evaluated four different combined soil production – landscape evolution models to predict soil thickness. In the second step, soil thickness evolution was analyzed, by using the predicted soil thickness as input in a LEM.

2. Materials and methods

2.1. Study area and soil data

The study was conducted in the Vale dos Vinhedos (Vineyard Valley) which is a wine production region in northeastern Rio Grande do Sul State (Fig. 3). The area covers 8118 ha ($29^0 08'15''$S to $29^0 14'26''$S, and $51^0 29'48''$W to $51^0 37'55''$W). The climate is classified as Cfb: subtropical with a mild summer, mean annual temperatures of 17.2 °C and 1736 mm annual rainfall (EMBRAPA, 2008). Extrusive rocks are the dominant lithology, mostly from the Mesozoic Era (IBGE, 1986).

The geology is part of Bacia do Paraná, Formação Serra Geral, and is divided in two units: Unit of Gramado, in lowlands and Unit of Caxias, in uplands. The Unit of Gramado has basalt as a predominant parent material. Rhyodacite is predominant in the Unit of Caxias. The rocks are from Cretaceous, with approximately 132 Myr, and resulted from a succession of volcanic flows.

The topography is formed by steep and jagged edges, by a drainage system with high capacity of vertical erosion. Some upland areas are preserved and are a testimony of older geology. The relief was carved by the drainage system, sectioning the sequential volcanic flows, and forming stepped structural terraces.

The geology map available is at a scale 1:750,000 (CPRM, 2006) and the DEM has 5mx5m resolution. The DEM was upscaled to 15 m grid cell size. Soil map (Flores et al., 2012) and land use map (Bonfatti et al., 2016) in scale 1:10,000 are available. A map with 13 landform classes was elaborated using the DEM and the software LandMapR (MacMillan, 2003). The soil database consists of 163 pedons, with 32 soil properties and elemental concentrations (Flores et al., 2012).

The average soil thickness (depth to bedrock) is 150 cm (range 25 to > 250 cm) and many soils are stony and rocky (average 4.5% of fragments > 20 mm in diameter). In the study area, Inceptisols cover about 44%, Ultisols 29% and Mollisols almost 15%. Mollisols are mostly present at lower elevations close to valley bottoms in the northern part of the study area. Soils in the western part of the study area, classified using the Brazilian Soil Classification System (SiBCS), are mainly Argissolos (Ultisols and Alfisols), Chernossolos (Mollisols), and Neossolos (Entisols and Mollisols). The eastern part has more rugged terrain and the dominant soils are Neossolos (Entisols) and Cambissolos (Inceptisols), with association of Argissolos (Ultisols and Alfisols), Latossolos (Oxisols) and Nitossolos (Oxisols and Ultisols) (Flores et al., 2012).

Forest (44%) and Vineyard (31%) are the dominant land use in the study area. Deciduous forest is the main vegetation in plateau rugged areas, and Araucaria forest in flatter areas (IBGE, 1986). A soil thickness map was produced by regression-kriging (Bonfatti et al., 2016) (Fig. 3).

2.2. The mass continuity equation

The basis of a LEM is the mass continuity equation (Carson and Kirkby, 1972; Dietrich et al., 1995; Heimsath et al., 2001b):

$$\rho_s \frac{\partial h}{\partial t} = \rho_r \frac{\partial e}{\partial t} - \nabla q_s \tag{1}$$

where h is the soil thickness, e is the elevation of the bedrock-soil interface, ρ_s is the soil density, ρ_r is the density of the rock, q_s is the flow of material and ∇ is the vector of partial derivatives.

In this equation, the variation in mass of soil thickness depends on the balance between the mass of soil produced (variation of bedrock elevation) minus the mass lost by erosion (or summed by deposition). Dividing by ρ_s, we adjusted the equation from mass to depth continuity (m):

$$\frac{\partial h}{\partial t} = \left(\frac{\rho_r}{\rho_s}\right)\frac{\partial e}{\partial t} - \frac{\nabla q_s}{\rho_s} \tag{2}$$

The parameter $\partial e/\partial t$ is equivalent to the soil production rate and the q_s is the erosion/deposition rate. If soil production is higher than erosion, the soil thickness h will increase over time, otherwise, the soil thickness will reduce. There is a feedback mechanism between erosion and soil production. The erosion will approximate the weathering front to the surface, accelerating the soil production. When the soil production rate is similar to the erosion rate, the system is in equilibrium (Pelletier and Rasmussen, 2009; Phillips, 2010), or in a steady-state soil thickness ($\partial h/\partial t = 0$). This assumption is convenient to modelling, but might not reflect the current reality. Other factors have great impacts in actual soil thickness, as anthropic influence or climate change. However, a steady-state is a useful assumption when considering long time periods.