Earth-Science Reviews 150 (2015) 102–120

Contents lists available at ScienceDirect

Earth-Science Reviews

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

Resolving the integral connection between pedogenesis and landscape evolution

Budiman Minasny [a,*], Peter Finke [b], Uta Stockmann [a], Tom Vanwalleghem [c], Alex B. McBratney [a]

[a] The University of Sydney, New South Wales, Australia
[b] Ghent University, Belgium
[c] University of Cordoba, Spain

ARTICLE INFO

Article history:
Received 22 December 2014
Received in revised form 25 June 2015
Accepted 4 July 2015
Available online 12 July 2015

Keywords:
Soil weathering
Landscape evolution
Geomorphology
Soil erosion
Pedogenesis

ABSTRACT

Soil is central in the terrestrial ecosystem, linking and providing feedback responses to the other components, i.e., water, atmosphere, and vegetation. However, the role of soil in landscape evolution is usually not well acknowledged. In modeling landscape evolution, soil is only treated as a residue of weathering that is transported and redistributed along the hillslope. Weathering is considered as a process that produces clays and generates unconsolidated materials available for erosion. While pedology has been debating the form of qualitative factorial models for 75 years; models for soil water, heat, solute, gas and chemical reactions in a profile have matured. As soils are distributed continuously in three dimensions across landscapes, the profile models need to consider lateral fluxes. This review outlines the role of soil in landscape modeling. First, we review the role of soil in the current landscape evolution models. We then review data and models on soil weathering rates and transport processes. We discuss soil profile models that simulate soil formation processes, and combined soil–landscape evolution models. Finally we discuss how the models can be tested and validated in the real world and suggest how both soil scientists and landscape modelers can work together to address the grand challenges in modeling earth surface processes.

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* Corresponding author.
E-mail address: budiman.minasny@sydney.edu.au (B. Minasny).

http://dx.doi.org/10.1016/j.earscirev.2015.07.004
0012-8252/

1. Introduction

Soil is the key component of the critical zone, linking and providing feedback responses to the other components (i.e., water, atmosphere, and vegetation). The role of soil in shaping the landscape is of the utmost importance, yet its role in earth science is underappreciated. As an example, the theme of the European Geosciences Union General Assembly in 2014 has been "The Face of the Earth", however, soil was not one of the main topics specifically represented at the meeting: Rocks of the Earth, Waters of the Earth, Life of the Earth, Atmosphere of the Earth, and Space and the Earth. While soil is mentioned briefly in 'Rocks', 'Water', and 'Life' lectures, only background information is given. Earth will not support life and its diversity if it was only shaped by rock, water and atmosphere. The influence of life on topography can only be dealt with when we consider soil processes (Dietrich and Perron, 2006; Brantley et al., 2011; Amundson et al., 2015).

Soil shapes the landscape directly. Variations in erodibility as caused by differences in soil texture and soil organic carbon (SOC) content in the course of soil formation will influence the spatial variation and magnitude of erosion processes (van Noordwijk et al., 1997; Van Oost et al., 2007). Variations in hydraulic properties as caused by spatially variable development of soil structure, texture and soil organic carbon will influence patterns of surface runoff and subsurface flow and thus of mass redistribution across the landscape. Spatially varying soil development will lead to variations in edaphic factors such as water and nutrient availability or their excess, which will induce heterogeneity of the natural vegetation and its biomass production and subsequently cause heterogeneity of organic matter inputs to the soil (Amundson et al., 2015). The main drivers for developing soil heterogeneity are initial variations in parent material properties, topography, biota and apparent random events (for instance tree falls). Soil also shapes the landscape in indirect ways. Humans use soil preferentially based on their assumed and experienced suitability for various purposes. Thus, humans are the agents but soil is the trigger. This will lead to heterogeneous land use, which will form heterogeneous landscapes.

This review outlines the role of soil in landscape modeling. Within this work we will demonstrate the role of soil in landscape evolution models and show the importance of landscape processes in soil genesis modeling. We will first review the role of soil in landscape evolution models, and then outline the major processes that produce soil, the weathering from bedrock, and soil carbon evolution. Then we will review models and processes that describe the development of a soil profile. Subsequently we will examine soil transport models and landscape models that include soil evolution. Finally we will discuss how we can validate and verify the model. We will then suggest how both soil and landscape evolution models can be coupled together to address the grand challenges in modeling earth surface processes.

2. The Grand Challenges

Not that long ago, the US National Research Council (NRC, 2010) identified nine Grand Challenges in Earth Surface Processes, and the importance of soil and its genesis is highlighted in at least two of them. The first is related to the question: How does the biogeochemical reactor of the Earth's surface respond to and shape landscapes from local to global scales?

"The weathering and eroding landscape varies both chemically and physically over space with strong patterns that reflect topography, lithology, biota, and climate; these changes occur over time in ways that we cannot yet predict quantitatively. Importantly, such bedrock weathering processes contribute to landscape evolution, influence biogeochemical fluxes, and impact regional climate. As landscapes evolve, biota play an active role in retaining some of the soluble elements, serving to anchor existing soil on hillsides and to accelerate soil formation."

The second challenge is: What are the transport laws that resulted in the evolution of the Earth's surface? It highlights "the need for a mechanistic understanding of processes that link climate, hydrology, geology, biota, land use, topography, and erosion rates. To tackle this challenge we need to discover, quantify, test, and apply laws that define the rates of processes shaping the Earth's surface."

While soil is central to both of these challenges, soil itself is not fully acknowledged. This indeed is still a challenge for soil and landscape scientists that can only be addressed and answered with quantitative mechanistic modeling of soil formation in the landscape. The first challenge is a direct challenge for soil scientists. While progress has been made in the last decade, soil scientists are still focussed on the factorial-type models (Lin, 2011). In another front, digital soil mapping approaches employ empirical relationships to predict the spatial distribution of soil properties (McBratney et al., 2003; Adhikari et al., 2014). They are limited, however, by the observations and the nature of the empirical relationships. Thus, there is a need to use pedological knowledge to quantitatively relate soil properties to the environmental drivers that form the soil. While parts of the soil physical and chemical processes can be modeled very well, such as water transport, soil carbon dynamics and chemical speciation, progress in modeling the development of soil as a whole is still scarce (Samouëlian and Cornu, 2008). This topic of measurement and modeling of soil weathering and soil profile evolution will be discussed in Sections 4 and 6 of this review.

The second challenge is mostly addressed by geomorphologists or landscape evolution modelers. In landscape evolution models, the driving mechanism for landform evolution is driven by topography and processes related to water (Fig. 1a) (Braun et al., 2014). The earth's topographic diversity is associated with the movement of tectonic plates, differences in rock density, and climatic variations. In tectonically active areas, landscapes are shaped by river erosion, whereby incision at the bottom of channels generates slopes, a process which destabilizes hillsides and causes mass movement by gravity-driven processes. The sediment resulting from these gravity-driven processes is then deposited in the river channel, which then acts as the main transport agent toward lower elevations (Goren et al., 2014). River processes control landscape dynamics over large length scales, whereas hillslope processes control the dynamics over smaller length scales (Goren et al., 2014). We will discuss this in Sections 3 and 7.

However, in geomorphology, soil is mainly treated as a residue of weathering that is transported and redistributed along the hillslope. Weathering is considered as a process that produces clays and generates