A conceptual model for physical and chemical soil profile evolution

M.J. Kirkby

School of Geography, University of Leeds, UK

ARTICLE INFO

A B S T R A C T

A simplified soil model is presented for evolution of the mineral soil profile. The model provides a compromise between highly empirical models and highly mechanistic/geochemical models, and represents some of the main features of observed profiles, with features that can be identified with 'A', 'B' and 'C' horizons. The model is responsive to a range of global environments, which can be represented through climate and parent material parameters. In many cases there is an almost single-valued relationship between surface weathering and soil depth, allowing further simplification of the model, and allowing it to be included within a parsimonious landform evolution models. A key parameter and assumption of the model is the degree of weathering below which no further solution occurs, which limits the maximum extent of soil development. This is speculatively linked to CO_2 turnover rates and the degree of aridity.

1. Introduction: proposed model framework

Hydrological, biological, chemical and mechanical processes take place throughout the critical zone (Fig. 1), interacting at a wide range of temporal scales, and together driving evolution of the soil/regolith profile. Over time, weathering introduces material into the base of the profile, while geomorphic processes transport material downslope, progressively eroding the surface of the land. These processes interact, slower weathering, for example, producing coarser material that is eroded more slowly. Rates of production and removal may be out of balance for millions of years, leading to either indefinite accumulation of soil or stripping to parent material, but in many cases there is an approach to a quasi-equilibrium with a finite depth of soil.

In this paper, processes of soil formation have been simplified to provide a tentative theoretical framework, providing a conceptual model of soil profile evolution. This builds on, and expands, prior work (Carson and Kirkby, 1972; Kirkby, 1977, 1985a), and has been informed by the many and diverse soil evolution models in the literature (e.g. Minasny and McBratney, 1999, 2001; Finke and Hutson, 2008; Gabet and Mudd, 2009; Opolot and Finke, 2015). A number of simplifying assumptions have been made to keep the model relatively simple, particularly with respect to the geochemical evolution of the soil, although some can, in principle, be relaxed. A high priority has been to include as many significant interactions between the processes acting within the profile as possible, and particularly those between the evolving profile and soil hydrology. The necessary resulting simplifications have, hopefully, provided some gains in understanding but also consequential sacrifices in rigour.

Early concepts of soil development express the evolving balance of physical and chemical denudation (Carson and Kirkby, 1972, p. 265), leading either to an equilibrium in which the degree of weathering at the surface is a function of the balance between the two forms of denudation, or to indefinite deepening of the soil profile. The increase in soil depth is given by the difference between the rate of weathering and the rate of erosion, corrected for the degree of weathering of the surface material. The rudimentary model proposed by Minasny and McBratney (1999, 2001) takes account of a depth-dependent weathering rate and a surface-controlled erosion rate to develop the profile model, additionally taking account of changes in bulk density as weathering proceeds. Brimhall and Dietrich (1987) combine this approach with a much more sophisticated geochemical analysis to show how recalcitrant soil components (Fe and Al) may accumulate as hardpans or laterites as silica is preferentially removed due to its greater solubility.

Hoosbeek and Bryant (1994), Lebedeva et al. (2010) and Li et al. (2014) make use of similar advection-dispersion equations for the movement of solutes to those used by Kirkby (1985a) and Van Genuchten and Wierenga (1986), and estimate solute concentrations by appealing to chemical equilibrium between water and solid mineral phases.

Willgoose and his group (Cohen et al., 2009; Welivitiya et al., 2016) have focussed on the physical breakdown of material into progressively finer fractions, and the accumulation of an armour layer at the surface as water erosion winnows fines to progressively concentrate the coarser material. In the mARM3D model alternative depth-dependent weathering functions are combined with the comminution model to provide a valuable model for critical zones for which physical breakdown is the
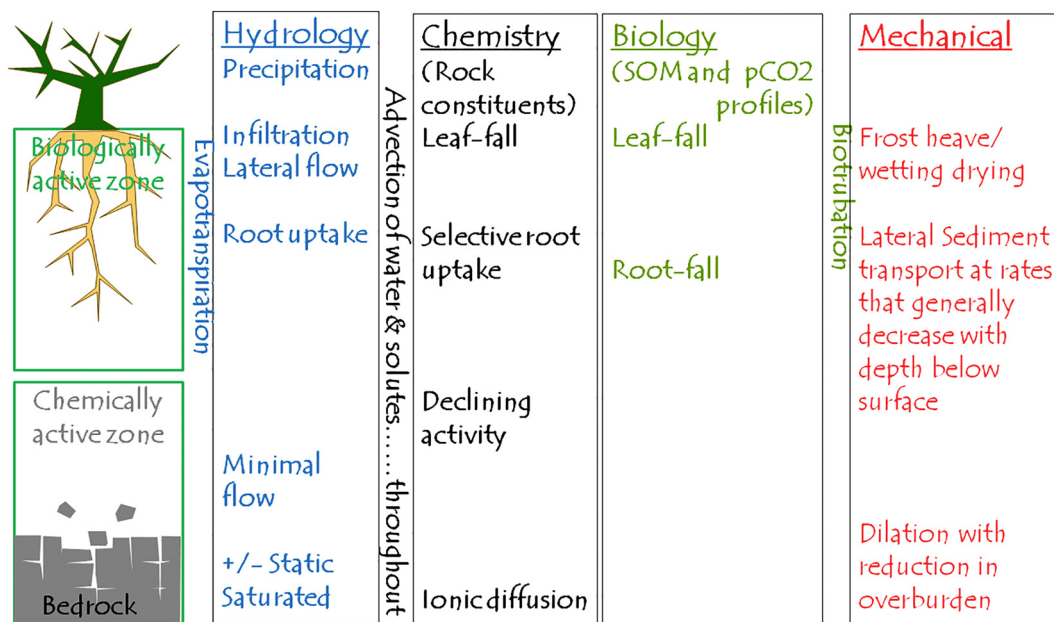
Fig. 1. Hydrological, chemical, biological and mechanical processes within the critical zone.

dominant process. These models have also been coupled with landscape evolution models to generate downslope catenas as the landform as a whole evolves.

Other soil profile models have made a much more detailed analysis of chemical processes, generally using kinetic equations to describe rates of solution and solution products for different constituent minerals. Examples of such models are the WITCH model (Goddéris et al., 2006) and the SoilGen model (Opolot and Finke, 2015). These models also explicitly incorporate carbon cycling to provide relevant levels of CO_2 partial pressure in the soil, linking to RothC or ASPECTS to provide carbon cycling and outgassing. They also include some hydrology, allowing them to respond to the external environment. Due to their relative complexity, however, they are more difficult to couple with landscape evolution.

Vanwalleghem et al. (2013) have created a model explicitly for coupling with landscape evolution (MILESD), dividing the soil profile and parent material into four layers to model movement of solutes and clay between layers, bounded by depth-dependent weathering of parent material and diffusive sediment transport at the surface. Carbon cycling and bioturbation are also significantly incorporated in exchanges between the upper layers. This approach represents an advance on previous work through integration of hydrology and weathering into a simple and unified model structure that is compatible with landscape evolution models.

Because of the complexity of the processes operating in soils, and their interaction with surface sediment processes, all models represent compromises, emphasising some aspects and over-simplifying others. The present proposal provides no resolution from this dilemma, but offers an alternative approach which has some strengths, and allows further exploration of some internal linkages. Nevertheless it is recognised that carbon cycling is currently not included, and that changes in bulk have been assumed to be negligible, with loss of substance balanced by a corresponding reduction in density, an assumption that is, in some contexts, demonstrably false.

Here we make a number of major assumptions in order to simplify and generalise some of the processes involved in soil profile development. The first, and most important of these, is to combine all chemical constituents into a single term which expresses the degree of weathering, and is defined below. It is implicit in this assumption that weathering is a largely congruent process, so that, for a given parent material and physical environment there is an almost one-to-one relationship between degree of weathering and chemical composition, so that, for example, there is a single-valued relationship between degree of weathering and solute concentration. This relationship is analogous to the commonly used approximation that, at a site, there is a single-valued relationship between soil moisture storage and flow rate.

The second major assumption is that modifications in the rates of other processes can also be simply related to degree of weathering. This dependence has been applied implicitly to grain size distribution, and explicitly to the rate of surface sediment erosion (or as one control on the rate of sediment transport in a landscape context). The functional form of these relationships has usually been expressed here as a power law, with exponents reflecting qualitative rather than quantitative forms. The third assumption made is that solute concentrations in soil water are, on the time scales of profile development, in chemical equilibrium with the solid phase, so that concentrations are the product of a solubility that is the mass-weighted concentration of mineral solubilities in the weathered solid phase at a given degree of weathering, again expressible as a single valued function of the current local degree of weathering. This assumption reflects experimental work on silicates (Garrels and Christ, 1965; Bricker et al., 1968; Robinson and Stokes, 1959), suggesting that equilibration occurs over periods of about 100 h for silica, and somewhat longer for alumina: all periods that are short compared to the time scale for profile evolution. The fourth major assumption is that there is no change in volume as the soil weathers. This assumption has been used in a number of previous models (e.g. Lebedeva et al., 2010) and is visibly supported by the presence of intact structures within saprolite, for at least some parent materials, but is not universally applicable, for example in limestones and podsols. The fifth major assumption is that, for a given environment and parent material, there is a maximum degree of weathering beyond which no further soil development occurs. This assumption is speculative, but is essential to the model. It is discussed briefly in the conclusions below.

Ignoring, initially, the organic horizons, a simple way to characterize the changing properties of the profile is by referring to the total loss of substance at any level, based on an analysis of all constituent minerals. If a hypothetical constituent that is assumed to be totally insoluble is increased in abundance by k times at some level in the profile relative to its abundance in the parent material, then the proportion, p, of rock substance at that level $1/k$. In many cases, simple soil