Soil morphology adaptations to global warming in arid and semiarid ecosystems

H. Curtis Monger

Plant and Environmental Sciences, New Mexico State University, Las Cruces, NM, USA, Email cmonger@nmsu.edu

Abstract
As the aboveground goes, so goes the belowground. Or stated differently, as climate and vegetation change, soil morphology adapts to those changes. Two general categories of soil morphology adaptations are (1) vertical movement of horizons and (2) presence of constituents. Vertical movement of horizons most prominently includes the upward shift of argillic and calcic horizons as climates become drier (increased aridity) and their downward shift when climates become wetter. Presence of constituents includes the accumulation of organic carbon in A horizons during wetter climates and its loss during drier climates, in contrast to soluble salts that accumulate during arid periods but are flushed from the soil during wetter climates. Based on pedological observations during the last century and paleorecords, some soil morphology features are many times more labile than other features, ranging from diurnal soil gas and water dynamics to millennial-scale mineralogical transformations. Soils in arid and semiarid ecosystems cover approximately 46 % of the total ice-free land area and have received much attention because of their vulnerability to desertification. Change in climate, including warming temperatures, can set into motion changes to soil moisture that not only impact soil morphology, but also biotic processes, such as shrub invasion that has feedback loops to root structure, microbial activity, CO_2 fluctuations, and carbonate chemistry. Replacement of grass cover with woody shrubs also increases bare ground that sets into motion positive feedback loops that amplify erosion and favour further shrub advances. Such lateral migrations are, in turn, linked back to soil because the velocity of these migrations is dependent on the nature of soil-geomorphic templates. Because of their vast area and their sensitivity to increased warming, morphological change of arid and semiarid soils may be vast, only exceeded by changes in soils of tundra and boreal forests that experience warming.

Key Words
Arid and semiarid soil change, global warming, desertification, biotic change, pedogenic carbonates

Introduction
Vertical movement and the thickening or thinning of soil horizons is affected by the lateral movement of biomes across the soil surface driven by climate change. The rates at which these changes occur vary widely depending on properties of the soil and properties of the landscape. Soil properties like temperature and the chemistry of the soil atmosphere can vary hourly. Soil organic matter and soluble salt content may vary over a period of decades. Clay mineralogy and dissolution of framework minerals may vary on a time scale of thousands to millions of years (Birkeland 1999). Properties of the landscape that can affect the velocity of lateral biome migration include the physical and chemical properties of the soils as a substrate, as well as the influence of topography. The term *soil-geomorphic template*, has been used to account for the combined influences of soil, topography, and soil parent material on vegetation patterns and biome migration (Monger and Bestelmeyer 2006). Soil is a factor in biotic change because it is the substrate that provides water, nutrients, anchorage for plants, and habitat for burrowing animals. Topography is a factor in biotic change because it influences local microclimate by means of elevation, lateral redistribution of water, and slope orientation. Soil parent material is a factor in biotic change because it provides the lithic inheritance from the geologic landscape that gives rise to soils with different particle size distribution (i.e., available water holding capacity) and nutrient status. Numerous linkages and feedback-loops occur between the soil-geomorphic template, microclimate, vegetation, and animals. A perturbation in any of these factors can steer an ecosystem from one state to another. The integral relationship between the soil-geomorphic template and biotic change is an example of how biological and geological systems are coupled and co-evolve on the long-term (Quaternary landscape evolution) and short-term (human-induced desertification) time scales.

Methods
To quantify lateral movements of arid and semiarid ecosystems and understand the resulting soil changes, various remote sensing, GIS, soil morphology, carbon dioxide fluxes, and isotopes methods are required (Gile *et al.* 1966; Serna *et al.* 2006; Chopping *et al.* 2008; Monger *et al.* 2009).

Results

Soil organic carbon is a morphology feature that responds to climate change more quickly than other features (Figure 1). Pedogenic carbonate responds less rapidly, but like organic carbon, may have labile and recalcitrant end members not accounted for by measurements of carbonate using standard techniques (Philips *et al.* 1987; Monger *et al.* 1991). Clay content is least affected by climate and has a more gradual increase with time being generated by neoformation during wetter periods and dust accumulation during drier periods.

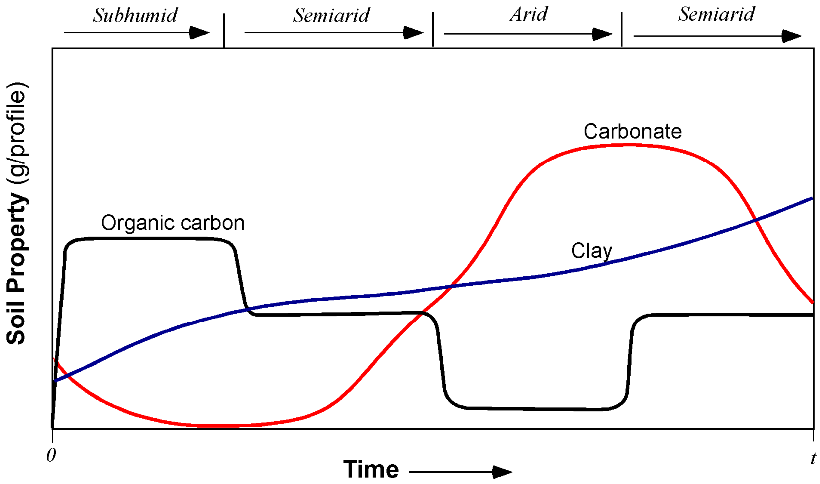

Figure 1. Hypothetical variations of three soil properties with time and climate change. Modified from Birkeland (1999).

Soil morphology changes are also affected by erosion. In many arid and semiarid soils erosion has stripped away the A and B horizons of the soils and exposed underlying calcic horizons. Since the calcic horizons are brought into the shallow, more intense weathering zone of increased biologic activity above the depth where pedogenic carbonate normally forms, the possibility arises that such exhumed carbonates are active sources of CO_2 emissions (Serna *et al.* 2006). To address this possibility, the hypothesis was tested that soils with exhumed calcic horizons will emit more CO_2 than neighboring non-eroded soils by (1) comparing the amount of CO_2 released from the soil types and (2) by measuring the isotopic composition ($\delta^{13}C$) of CO_2. Two years of data revealed that the amount of CO_2 was not statistical different at the $\alpha = 0.05$ level. Moreover, the isotopic analysis of CO_2 did not match the isotopic values of pedogenic carbonate, nor were there any statistical differences ($\alpha = 0.05$) in $\delta^{13}C$ of CO_2 between the eroded versus non-eroded soil types. It was conclude, therefore, that exhumed calcic horizons are not actively emitting CO_2 at a rate significantly greater than adjacent soils, and thus carbon stored in calcic horizons can be considered a recalcitrant reservoir within the decadal timeframe pertinent to carbon sequestration policies.

Deeper wetting fronts in the Pleistocene also affect soil morphology and are probably responsible for vertical, karst-like pipes that cross-cut petrocalcic and calcic horizons. Similarly, carbonate filaments in B horizons overlying petrocalcic and calcic horizons in soils of Pleistocene age are probably the result of an upward shift in the depth of wetting during subsequent drier climates based on depths of carbonates in soils of Holocene age and radiocarbon dates of the carbonate crystals themselves. Other evidence for climatically driven shifts in carbonate depth includes engulfment of argillic horizons by calcic horizons as the depth of wetting shifts upward with increasing aridiy, and micromorphologic evidence of episodic deposition of carbonates, opal, and clay in argillic horizons and duripans.

Lateral movement of biomes can be determined by historical records and paleoenvironmental evidence. Carbon isotopes are particularly useful for understanding biome migration in arid and semiarid climates having C_4 grasslands and C_3 shrublands at multiple scales. (1) At the broadest scale, the *biome scale (hundreds to millions of km^2)*, an isotopic record interpreted as C_3 vegetation replacing C_4 grasslands may indicate invading C_3 woody shrubs instead of expanding C_3 forests (a common interpretation). (2) At the *landscape scale (several tens of m^2 to hundreds of km^2)*, the accuracy of scaling up paleoclimatic interpretations to a regional level is a function of the landform containing the isotopic record. (3) At the *soil profile scale (cm^2 to m^2),* soil profiles with multiple generations of carbonate mixed together have a lower-resolution paleoecologic record than stacked soil profiles separated by C horizons. (4) At the *rhizosphere scale (µm^2 to cm^2)*, carbonate formed on roots lack the 14-17‰ enrichment observed at broader scales, revealing different fractionation processes at different scales. Carbon isotopes also help explain recent bioclimatic migrations. For example, modern studies based on survey records and vegetation reveal that shrub invasion has been greater on the rocky piedmont slopes (bajadas) than in adjacent alluvial flat zones that receive runon water, similar to the patterns in the stratigraphic record. Lateral movement of biomes driven by climate change can also be accelerated by land management. In managed ecosystems, over-grazing, for example, can perturb this system by selective herbivory and seed dispersal, thus reducing ground cover and increasing erosion (Figure 2).

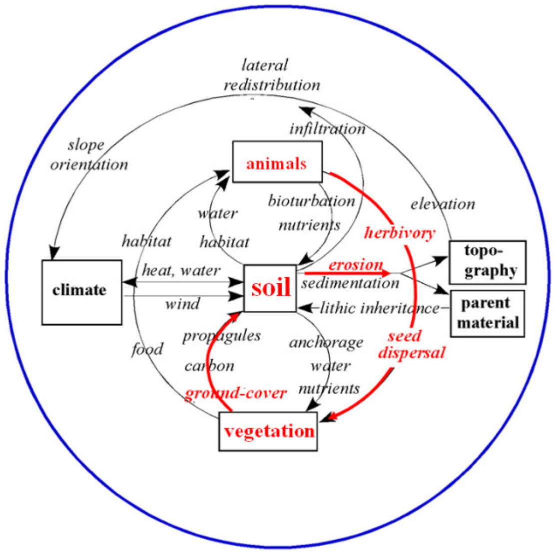

Figure 2. Model showing the links in the soil-geomorphic-biotic change system. Red text and arrows illustrate the paths involved when the system adapts to a perturbation caused by overgrazing. Figure modified from Monger and Bestelmeyer (2006).

Conclusion

Soil morphology, being the product of the five soil forming factors, responds to climatic and ecological changes. As such, it serves as a record of past changes. Some morphological features, however, are more sensitive to aboveground changes than other features. Because soils in arid and semiarid climates are vulnerable to desertification, it is important to understand the feedback loops of these dryland soils to aboveground ecosystems. Of particular importance is how soil-geomorphic templates influence the encroachment of woody shrubs into grasslands because this is the major biome migration occurring across vast areas of the World's arid and semiarid landscapes. These migrations are driven by increased aridity caused by warming, lower amounts of rainfall, and land management. Soil morphology is an integral part of this larger system.

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