Soil erosion controls on biogeochemical cycling of carbon and nitrogen.

By: Asmeret Asefaw Berhe (*Life and Environmental Sciences Group, University of California, Merced*), Chelsea Arnold (*Environmental Systems Graduate Group, University of California, Merced*), Erin Stacy (*Sierra Nevada Research Institute, University of California, Merced*), Rebecca Lever (*Environmental Systems Graduate Group, University of California, Merced*), Emma McCorkle (*Environmental Systems Graduate Group, University of California, Merced*) & Samuel Negusse Araya (*Environmental Systems Graduate Group, University of California, Merced*)

Citation: Berhe, A. A., Arnold, C., Stacy, E., Lever, R., McCorkle, E. & Araya, S. N. (2014) Soil erosion controls on biogeochemical cycling of carbon and nitrogen. *Nature Education Knowledge* 5(8):2

The Earth's land surface is dominated by sloping landscapes. Every year, soil erosion laterally distributes on the order of 75 Gt of topsoil (Berhe et al. 2007). The coupled biogeochemical cycles of carbon (C) and nitrogen (N) are strongly influenced by soil erosion as it affects their fluxes in and out of the soil system, storage, distribution within the soil matrix, and residence time in soil. At the global scale, it is estimated that erosion can account for a net sink for atmospheric carbon dioxide (Stallard 1998).

Erosion of Soil Carbon and Nitrogen

Soil erosion has three distinct phases — detachment, transport, and deposition — which can have profound impacts on soil carbon (C) and nitrogen (N) dynamics. To initiate erosion, particles are detached from the soil through physical processes involving rain, wind, or burrowing of soil by meso- and macrofauna. Detachment exposes soil to lateral movement. During the detachment phase, soil **aggregates** are disrupted, exposing **organic** matter (OM, including C and N) that had been physically protected inside aggregates to loss by decomposition and transport in dissolved or particulate forms. During the lateral transport phase of soil erosion, more aggregates can be disrupted and constituent biochemical compounds dissolved. The transport phase renders organic matter and inorganic ions of nitrogen (nitrate, NO_3^-, and ammonium, NH_4^+) more accessible to microbes and leaching, thereby increasing their loss from the eroding landform positions of a given hillslope. Conversely, the mixing of mineral and organic matter during transport and the subsequent formation of new aggregates can slow down loss of C and N. To what extent C or N is lost from hillslope soil profiles through decomposition or total dissolved loss of eroded OM will depend on the type and intensity of the erosive processes, duration of transport, and the type of depositional environment in which the eroded material accumulates (Nadeu *et al*. 2012). In the final phase of deposition, eroded particles and dissolved constituents of runoff enter downhill (concave or flat) depositional landform positions, river systems, or other water bodies where C and N can be stored and protected from loss.

Erosion induces terrestrial sequestration of atmospheric carbon dioxide (CO_2) if at least some of the C eroded from slopes is replaced by production of fresh **photosynthate** and/or stored in more stable OM pools in depositional landform positions (Berhe *et al*. 2007, Harden *et al*. 1999, Stallard 1998). Over the last two decades, some studies argued that erosion leads to increased loss of OM from the soil system, suggesting that erosion is a net source of CO_2 to the atmosphere (for example, Bajracharya *et al*. 2000, Jacinthe & Lal 2001, Lal 2003, Lal 2005). However, numerous experimental and modeling studies have since verified the potential for erosion to induce a net CO_2 sink in the terrestrial biosphere if C balance (Figure 1) is computed at an appropriate watershed scale by taking into account the total amounts of C stored and exchanged to/from soil profiles in eroding versus depositional landform positions (Figure 2) (Berhe *et al*. 2007, Berhe *et al*. 2008, Van Oost *et al*. 2007).

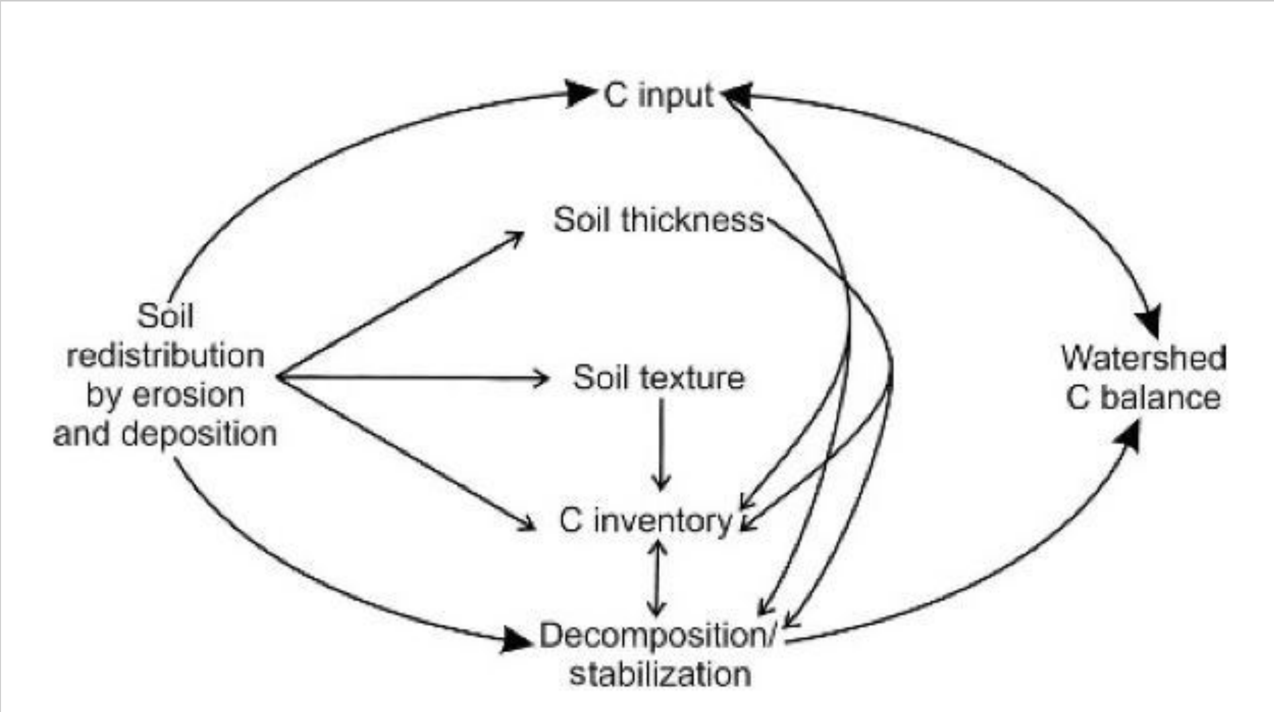

Figure 1: C balance.

Effect of lateral soil distribution by soil erosion on watershed carbon balance, as mediated by changes in C input to soil, soil thickness, soil texture, and organic matter stabilization and/or decomposition.

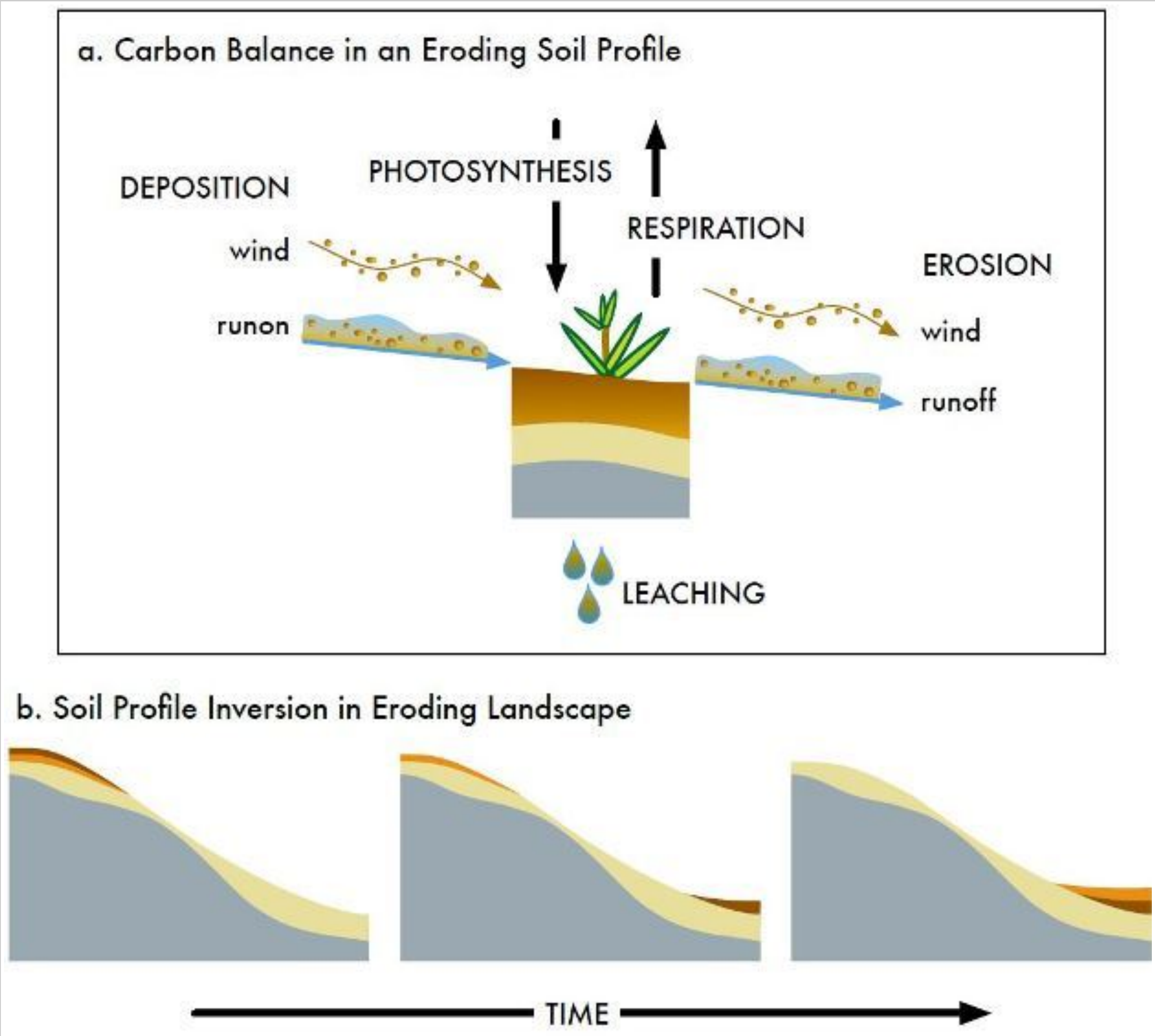

Figure 2: Depositional landform positions.

Organic matter dynamics in eroding landscapes that experience lateral transport of topsoil and associated OM from divergent slopes to convergent and flat depositional landform positions. (a) carbon balance in an eroding soil profile and (b) implication of soil erosion for soil profile development and burial of OM in topsoil of eroding profiles in depositional positions over time. Soil on the ridge-top experiences high rates of **erosion** during centuries of cultivation, exposing subsoil material. At lower landform positions in the hillslope, deep soils are formed with partial deposition of A- and B-horizon material that eroded from upslope positions.

In some agricultural landscapes, anthropogenically accelerated rates of erosion can lead to rapid and significant loss of up to 22% C over 50 years (Doetterl *et al*. 2012). But at the same time that C is lost from eroding hillslopes, enhanced rates of plant productivity in depositional positions, along with physical and chemical stabilization of OM in these landform positions, is likely to result in higher stocks of OM in depositional environments post-erosion and terrestrial sedimentation (Berhe *et al*. 2012). Deposition of eroded material is likely to preserve the deposited OM for a few decades or centuries (Van Oost *et al*. 2012).

Temporal and Spatial Patterns of Soil, and Associated C and N Erosion

The biogeochemical implications of soil erosion partly depend on the travel distance of topsoil and dissolved soil constituents, and whether erosion is a continuous or episodic process for a given ecosystem. Large, episodic events may bury large amounts of organic-rich material below the surface, decreasing its decomposition rates relative to what would have occurred had the material remained on hillslopes or on the top part of the depositional landform position's soil profiles. The distance that eroded sediments travel is a function of the type of erosion, the degree of disturbance experienced by the soils, and the connectivity to water channels. Most material mobilized by overland or **sheet erosion** is deposited nearby in a matter of seconds or minutes during a storm, often resulting in a rapid input of C and N into the deposited area and potentially altering the **nutrient** cycles in both source and deposition areas. Sediment that reaches a water channel or is eroded in that channel can travel much further over longer time periods. Overall, sediment export out of the eroding watersheds decreases as basin size increases, and most (70–90%) of the sediment is deposited within the source watershed or nearby watersheds (Stallard 1998).

In the absence of anthropogenic disturbances such as tillage, estimates of long-term erosion rates around the world suggest that mass transport is highly episodic. **Cosmogenic nuclides** from rocks, for example, yield long-term estimates of ~0.02–0.06 mm soil eroded annually. By contrast, disturbances such as fire or intensive agriculture mobilize large amounts of sediment and associated **nutrients** within a very short period of time. For example, in 2002, a single severe storm in the Sierra Nevada Mountains near south Lake Tahoe removed 10 mm of topsoil in just a few hours from a forested hillslope that had been burned by wildfire several weeks before (Carroll *et al*. 2007).

Intensively cultivated lands are also highly susceptible to erosion, especially where the need for higher yields overrides the implementation of recommended soil and water conservation techniques (Table 1). The rate of soil erosion in intensively cultivated agricultural systems is estimated to be an order of magnitude higher than natural rates of erosion. Rates of agriculture-induced erosion are influenced by varying site characteristics, but are estimated to range from an average of 0.13 ± 0.02 mm/yr for conservation agriculture to 3.94 ± 0.321 mm/yr for conventional agriculture(Montgomery 2007).

Rates of soil erosion	sample size, n	median, mm/yr	mean, mm/yr	standard error, mm/yr
Conventional agriculture	448	1.537	3.939	0.321
Conservation agriculture	47	0.082	0.124	0.022
Native vegetation	65	0.013	0.053	0.016
Geological	925	0.029	0.173	0.029

Soil production	188	0.017	0.036	0.004

Table 1: Rates of soil erosion for land under conventional agriculture, conservation agriculture, and native vegetation compared to typical rates of soil production and geologic rates of soil erosion, from Montgomery (2007).

The magnitude of topsoil and associated C and N erosion is further controlled by factors such as slope, vegetation, precipitation, and parent material. These factors determine the structural stability and hydraulic conductivity of soil as well as the magnitude of erosion that is likely to result from different types of disturbances. The type of parent material of a given soil influences the composition of the soil, its susceptibility to erosion, its effectiveness as a plant and microbial growth medium, and its potential to stabilize soil C and N against losses (Berhe & Kleber 2013, Cerda 1999). At any given time, the amount of topsoil eroded is greater for soils on moderate slopes compared with those on very steep slopes, partly because soils on moderate slopes are thicker than those on steep slopes, where most of the soil mass is eroded soon after it is formed (Alewell *et al*. 2008). Erosion can also reduce soil C and N stocks by reducing the rate of input associated with new photosynthetic productivity and biological N fixation, and through lateral redistribution of C and N from topsoil of eroding positions (Gregorich *et al*. 1998). The combined result of these processes is that in steep slope positions, especially ones that are continuously cultivated, erosion is the dominant loss mechanism for C and N (Gregorich *et al*. 1998).

Implications of Soil Erosion for Persistence of C and N in Soil

Soil erosion affects both the rate of inputs and persistence (residence time) of C and N in the soil system. Erosion affects production of new photosynthate and consequently input of C into soil due to its effect on soil fertility. The redistribution of topsoil and associated nutrients due to soil erosion changes the spatial distribution and rates of plant productivity in eroding watersheds. Typically, erosion leads to reduced rates of plant productivity in slopes (especially when production is not augmented by supplements such as fertilizers and irrigation water) and higher rates of productivity in downslope depositional environments (Parfitt *et al*. 2013), where most of the topsoil and associated nutrients and OM eroded from the slopes is deposited (Stallard 1998). Reduction in **net primary productivity** and input of residue to soil further affects the long-term susceptibility of the topsoil and associated C and N to loss by soil erosion. **Erosivity** (i.e., the type, temporal distribution, and intensity) of precipitation controls how much material is detached and how far it is transported (Alewell *et al*. 2008). Above-ground vegetation serves to slow down the kinetic energy of rain drops, which reduces the impact of precipitation; with lower energy, fewer soil aggregates are disrupted and less particulate matter is detached for erosional transport. Soil is stabilized by formation of aggregates and peds, which are held together by plant roots, **fungal hyphae**, and **mycorrhizal associations** that microorganisms form with plant roots. Mulching, composting, and other means of recycling biomass increase the stock of OM in soil along with formation of micro- and macro-aggregates that increase the water- and nutrient-holding capacity of soils. This in turn, facilitates higher productivity of vegetation in a positive feedback loop (Kosmas *et al*. 2000).

Erosion can also affect the physical and chemical mechanisms that stabilize C and N, and slow down their losses from the soil system. Eroded OM that is deposited on land is physically stabilized by burial, aggregation, and/or high water content, which restrict the activity of aerobic microorganisms and reduce its rate of decomposition, compared with points higher on the slope (Berhe *et al*. 2012). However, erosion-induced reduction in CO_2 loss from soil may not always occur with reduction in efflux of all **greenhouse gases** from the soil system. In depositional landform positions that remain waterlogged for long periods of times, the eroded material deposited may also experience anaerobiosis — which can increase the rate of methane production — and **denitrification** (compared with the slope profiles), which leads to higher rates of efflux of methane (CH_4) and oxides of nitrogen (Schlesinger 1997). On the other hand, deposition in a lake or the ocean is expected to lead to lower rates of oxidative decomposition compared with the slopes where eroded soil OM originated.

The balance between decreased decomposition rates (reduced C emissions) and higher **methanogenesis** (increased C emissions) is likely to be temporally and spatially heterogeneous. On the other hand, exposure of subsoil material on slopes by erosion creates opportunity for mineral-OM associations in the clay-rich subsoil profiles, facilitating stabilization of both C and N in the eroding slopes. In the lower-lying depositional environments, selective transport and deposition of smaller, lighter, and reactive soil minerals and OM also creates the possibility for additional physical and chemical mineral-OM associations through direct bonding of organic functional groups with surfaces of minerals through electrostatic attractions, ligand exchange reactions, and/or complexation, leading to reductions in the rates of C and N loss from the depositional soil profiles (Berhe & Kleber 2013).

Exposure of physically protected OM during the detachment or transport phases of soil erosion can serve to increase decomposition of other soil OM by prompting the soil microbial community to use the energy created from the fresh OM to decompose the older OM that was previously present in the soil — a process known as priming (Kuzyakov 2010). This increased decomposition of OM and **mineralization** of organic N in soil is driven by the microbes' need for energy substrates and nutrients (including C and N), which ensures the coupling of these two **biogeochemical cycles** (Batlle-Aguilar *et al*. 2011). Erosion can also lead to elevated concentrations of C, N, and other nutrient elements in sediment and downstream water bodies, which can significantly alter the ecology and biogeochemical cycling in those aquatic systems (Miller *et al*. 2005).

Implication of Anticipated Changes in Climate

Over the next 50-100 years, Earth's average temperature is projected to rise an average of 1.5 to 4.8° C, leading to an intensification of the hydrologic cycle (IPCC 2013). Changes in vegetation cover and in the amount and intensity of rainfall are among the major controls that will determine how climate change will affect soil C and N erosion. Of these two, vegetation cover, which is affected by biomass production, is more difficult to predict because of the complex ecosystem interactions and functional traits of the different types of biomass (Nearing *et al*. 2004, Nearing *et al*. 2005). Change in land use, specifically intensification of agricultural production at the expense of forests and/or perennial pastures, is projected to increase rates of soil erosion

(O'Neal *et al*. 2005).

Rising temperatures can theoretically increase biomass production by increasing the number of Growing Degree Days for plants (O'Neal *et al*. 2005). Higher productivity generally results in slower soil erosion rates as vegetation cover protects against soil erosion. However, in cases where the temperatures rise too much,, temperature stress can have the reverse effect and decrease biomass, increasing soil erosion (Nearing *et al*. 2004). Higher temperatures can also enhance rates of residue decomposition–thereby increasing atmospheric CO_2 concentration and soil N availability — as long as other factors do not limit the activity of decomposing microorganisms (Davidson & Janssens 2006). In turn, the increase in atmospheric CO_2 concentration can have a fertilizing effect on biomass production, while at the same time suppressing transpiration from plant leaves by enhancing **stomatal resistance**, which increases the water-use efficiency of plants. Rising temperatures can also increase rates of evaporation (and **evapotranspiration**) from the terrestrial ecosystem, leading to changes in the rates of infiltration and runoff (O'Neal *et al*. 2005).

The frequency of extreme precipitation events is predicted to increase, as is the time between large events (Knapp *et al*. 2008). This could increase the frequency and magnitude of rainfall-driven erosion events. Based on simulation studies, it is expected that the global rate of erosion will grow by 1.7% for each 1% change in total amount and intensity of rainfall (Pruski & Nearing 2002). In addition, periods of prolonged drought, which is expected in some areas, can lead to large fire events, which would accelerate the rate of soil erosion in fire-affected upland ecosystems (Pierce 2004). Fire and burning of biomass lead to the removal of the litter layer or soil O-horizon, which is responsible for some soil stabilization (i.e., keeping natural erosion levels lower) (Morgan 2009). Fire also may create a hydrophobic (water-repelling) layer within the soil, which may speed the movement of material downslope, especially with large or high-intensity rainfall events (Morgan 2009). In combination, these two aspects of climate change are likely to change erosion rates worldwide.

Conclusion

Lateral distribution of topsoil and associated C and N with soil erosion can affect fluxes, stocks, and persistence of C and N in the soil system. Even though erosion induces a net terrestrial sink for atmospheric CO_2, this is not a reason to relax erosion-prevention measures. Minimizing rates of anthropogenically accelerated erosion is critical to protecting our natural soil resource and maintaining its multiple ecological roles, including carbon sequestration.

Glossary

aggregates: a soil structural unit made up soil mineral and organic constituents that are held together by reactive minerals such as iron oxides, organic compounds such as polysaccharides, and/or plant roots and fungal hyphae (see definition below).

biogeochemical cycles: the pathways for movement and transformations of chemical elements or molecules within or among the biotic and abiotic components of the Earth System as a result of biological, physical, geological, and chemical processes.

cosmogenic nuclides: are isotopes created when cosmic rays of very high energy interact with the nucleus of an atom in the solar system leading to cosmic ray spallation.

denitrification: is a microbially facilitated process in the nitrogen cycle that converts nitrate (NO_3^-) to dinitrogen (N_2), generally proceeding through the formation of a sequence of intermediate compounds such that $NO_3^- \rightarrow NO_2^- \rightarrow NO + N_2O \rightarrow N_2$.

erosion: the process by which topsoil material is moved about the surface of the earth by the action of water, wind, gravity driven diffusive transport, glacial ice, etc.

erosivity: the ability of any agent of erosion (wind, water, or gravity) to laterally transport soil material.

evapotranspiration: the sum of the movement of water from soil, plants and water bodies to the atmosphere through the processes of evaporation and transpiration.

fungal hyphae: typically long and branched threadlike filamentous structures that form the mycelium of a fungus.

greenhouse gas: a gas in the atmosphere that has the capacity to absorb and radiate energy in the infrared partition of the electromagnetic spectrum, and thereby leading to warming of the atmosphere and the earth's surface. Some common greenhouses gases include carbon dioxide, methane, nitrous oxide, tropospheric ozone, chlorofluorocarbons, and water vapor.

methanogenesis: is the process of formation of methane from the decomposition of organic matter by a group of microbes known as methanogens that are in the domain Archaea.

mineralization: is the process responsible for production of mineral or inorganic substances. In soil science and biogeochemistry mineralization can refer to the conversation of organic compounds such as carbohydrates to carbon dioxide, or the conversion of organic forms of nitrogen to ammonium and nitrate.

mycorrhizal associations: a symbiotic association of fungi with roots of vascular plants that serves to facilitate the exchange of sugars, water and nutrients between the plants and microbes.

net primary production (NPP): the amount of plant biomass produced per unit area typically over a year or growing season. NPP is the difference between the total amount of plant biomass produced by the process of photosynthesis and cellular respiration.

nutrient: is an element or ion that supplies nutrition to living organisms, for example nitrogen, phosphorous, and potassium that are critical for plants to complete their growth cycles and undertake other physiological functions.

organic: a class of chemical compounds with a carbon backbone, includes compounds derived from living or dead organisms.

peds: large aggregates (see definition of aggregates above).

photosynthate: a carbohydrate or biomass produced by the process of photosynthesis. Where photosynthesis is the process responsible for synthesis of organic compounds (that is, carbohydrates) from the combination of carbon dioxide, water, and sunlight as a source of energy. The process of photosynthesis is carried out with the aid of nutrients in the environment, and chlorophyll and associated pigments.

sheet-erosion: a form of soil erosion where a thin film of water transports topsoil material evenly from the surface of soil.

stomatal resistance: the resistance of passage of carbon dioxide entering a leaf or water vapor leaving a leaf through the stomata on plant leaves.

References and Recommended Reading

Alewell, C., Meusburger, K., Brodbeck, M. & Banninger, D. Methods to describe and predict soil erosion in mountain regions. *Landscape and Urban Planning* **88**, 46-53 (2008) doi:10.1016/j.landurbplan.2008.08.007.

Bajracharya, R. M., Lal, R. & Kimble, J. M. Erosion effects on carbon dioxide concentration and carbon flux from an Ohio Alfisol. *Soil Science Society of America Journal* **64**, 694-700 (2000).

Batlle-Aguilar, J., Brovelli, A., Porporato, A. & Barry, D. A. Modelling soil carbon and nitrogen cycles during land use change. A review. *Agron Sustain Dev* **31**, 251-274 (2011) doi:Doi 10.1051/Agro/2010007.

Berhe, A. A. & Kleber, M. Erosion, deposition, and the persistence of soil organic matter: mechanistic considerations and problems with terminology. *Earth Surface Processes and Landforms* (2013) doi: 10.1002/esp.3408.

Berhe, A. A., Harte, J., Harden, J. W. & Torn, M. S. The significance of erosion-induced terrestrial carbon sink. *BioScience* **57**, 337-346 (2007).

Berhe, A. A., Harden, J. W., Torn, M. S. & Harte, J. Linking soil organic matter dynamics and erosion-induced terrestrial carbon sequestration at different landform positions. *Journal of Geophysical Research-Biogeosciences* **113**, G4 (2008) doi: 10.1029/2008jg000751, doi:10.1029/2008jg000751.

Berhe, A. A. *et al*. Persistence of soil organic matter in eroding vs. depositional landform positions. *Journal Of Geophysical Research-Biogeosciences* **117**, G02019 (2012) doi:10.1029/2011JG001790.

Brady, N. & Weil, R. *Nature and Properties of Soils*. 14th ed. Pearson Higher Education (Prentice Hall), 2008.

Carroll, E. M. *et al*. Spatial analysis of a large magnitude erosion event following a Sierran Wildfire. *Journal of environmental quality* **36**, 1105-1105 (2007).

Cerda, A. Parent material and vegetation affect soil erosion in eastern Spain. *Soil Science Society of America Journal*, 362-368 (1999).

Davidson, E. & Janssens, I. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature* (2006).

Doetterl, S., Van Oost, K. & Six, J. Towards constraining the magnitude of global agricultural sediment and soil organic carbon fluxes. *Earth Surface Processes And Landforms* **37**, 642-655 (2012) doi:10.1002/esp.3198.

Gregorich, E., Greer, K., Anderson, D. & Liang, B. Carbon distribution and losses: erosion and deposition effects. *Soil Till Res* **47**, 291–302 (1998).

Harden, J. W. *et al.* Dynamic replacement and loss of soil carbon on eroding cropland. *Global Biogeochemical Cycles* **13**, 885–901 (1999).

IPCC. Climate Change 2013: The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers. (2013).

Jacinthe, P. & Lal, R. A mass balance approach to assess carbon dioxide evolution during erosional events. *Land Degrad Dev* **12**, 329–339 (2001).

Knapp, A. K. *et al.* Consequences of more extreme precipitation regimes for terrestrial ecosystems. *BioScience* **58**, 811 (2008) doi:10.1641/B580908.

Kosmas, C., Danalatos, N. G. & Gerontidis, S. The effect of land parameters on vegetation performance and degree of erosion under Mediterranean conditions. *Catena* **40**, 3–17 (2000).

Kuzyakov, Y. Priming effects: Interactions between living and dead organic matter. *Soil Biology and Biochemistry* **42**, 1363–1371 (2010) doi:10.1016/j.soilbio.2010.04.003.

Lal, R. Soil erosion and the global carbon budget. *Environment International* **29**, 437–450 (2003).

Lal, R. Soil erosion and carbon dynamics. *Soil and Tillage Research* **81**, 137–142 (2005).

Miller, W. *et al.* Inconspicuous nutrient laden surface runoff from mature forest Sierran watersheds. *Water, Air, and Soil Pollution* **163**, 3–17 (2005).

Montgomery, D. R. Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences* **104**, 13268–13272 (2007) doi:10.1073/pnas.0611508104.

Morgan, R. P. C. *Soil erosion and conservation*. Wiley-Blackwell, 2009.

Nadeu, E., Berhe, A. A., De Vente, J. & Boix-Fayos, C. Erosion, deposition and replacement of soil organic carbon in Mediterranean catchments: a geomorphological, isotopic and land use change approach. *Biogeosciences* **9**, 1099–1111 (2012) doi:1010.5194/bg-1099-1099-2012, doi:10.5194/bg-9-1099-2012.

Nearing, M., Pruski, F. & ONeal, M. Expected climate change impacts on soil erosion rates: A review. *Journal Of Soil And Water Conservation* **59**, 43–50 (2004).

Nearing, M. *et al.* Modeling response of soil erosion and runoff to changes in precipitation and cover. *Catena* **61**, 131–154 (2005) doi:10.1016/j.catena.2005.03.007.

O'Neal, M. R., Nearing, M. A., Vining, R. C., Southworth, J. & Pfeifer, R. A. Climate change impacts on soil erosion in Midwest United States with changes in crop management. *Catena* **61**, 165–184 (2005) doi: 10.1016/j.catena.2005.03.003.

O'Neal, M. R., Nearing, M. A., Vining, R. C., Southworth, J. & Pfeifer, R. A. Climate change impacts on soil erosion in Midwest United States with changes in crop management. *Catena* **61**, 165–184 (2005).

Parfitt, R. L. *et al.* Influence of erosion and deposition on carbon and nitrogen accumulation in resampled steepland soils under pasture in New Zealand. *Geoderma* **192**, 154–159 (2013) doi:10.1016/j.geoderma.2012.08.006.

Pierce, J. L., G.A. Meyer, A.J. Jull. Fire-induced erosion and millennial-scale climate change in northern ponderosa pine forests. *Nature* **432**, 84–87 (2004).

Pruski, F. & Nearing, M. Runoff and soil-loss responses to changes in precipitation: A computer simulation study. *Journal Of Soil And Water Conservation* **57**, 7–16 (2002).

Quinton, J. N., Govers, G., Van Oost, K. & Bardgett, R. D. The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geosci* **3**, 311–314 (2010).

Schlesinger, W. H. *Biogeochemistry: an analysis of global change*. 588 Academic Press, 1997.

Stallard, R. Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial. *Global Biogeochemical Cycles* **12**, 231–257 (1998).

Van Oost, K. *et al*. Legacy of human-induced C erosion and burial on soil-atmosphere C exchange. *Proceedings of the National Academy of Sciences* **109**, 19492–19497 (2012).

Van Oost, K. *et al*. The impact of agricultural soil erosion on the global carbon cycle. *Science* **318**, 626–629 (2007).