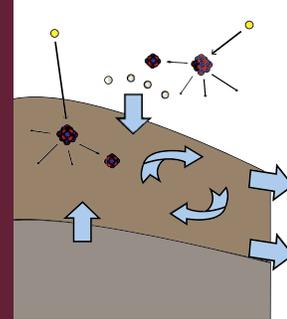


# Tracing and Pacing Soil Across Slopes

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**The conversion of rock to soil prepares Earth's surface for erosion by wind, water, gravity, and life. Together these agents wear down hills and mountains even as the land rises up under the stress of tectonic forces in the crust. Meanwhile, weathering liberates nutrients from minerals and disaggregates rock into regolith, generating hospitable substrates for life. Over the last two decades, geochemists, geomorphologists, and soil scientists have increasingly used cosmogenic nuclides to quantify how fast soils are made, modified, and finally swept away in hilly and mountainous landscapes around the world. These studies are revolutionizing our understanding of soils and their role in feedbacks that shape Earth's surface, influence overlying ecosystems, and modulate climate over millions of years.**

**KEYWORDS:** landscape evolution, pedogenesis, soil sustainability, critical zone, cosmogenic nuclides

## INTRODUCTION

Soil is produced and maintained by weathering of underlying rock, delivery of dust from the atmosphere, and cycling of carbon and nutrients in the biosphere. Because soil is typically rich in carbon, nutrients, and plant-available water, it serves as a vital substrate for life at the interface of air and rock. Yet some of the same chemical, physical, and biological processes that generate soil also help sweep it away from the surface, either in solution as a chemical flux or as a solid, physical flux. This chemical and physical erosion wears landscapes down, counteracting the tectonic upheaval of hills and mountains via the agents of wind, water, gravity, and life. Thus, Earth's land surface evolves over time as it delivers nutrients to ecosystems and sheds sediment and solutes into streams and the oceans. Over human lifetimes, a balance between the production and erosion of soil on slopes is vital to sustaining overlying ecosystems and the services they provide. Over geologic timescales, the delivery of soil-derived solutes to the oceans modulates Earth's climate by drawing down atmospheric CO<sub>2</sub>. Hence, the processes that generate, modify, and erode soil are central to the interplay of climate, tectonics, erosion, and life over a wide range of spatiotemporal scales.

Understanding the role of soil in this interplay remains a fundamental challenge (Brantley et al. 2007). Enormous progress towards this goal has been made over the 20 or so years since cosmogenic nuclide methods were introduced as tools for gauging rates of soil weathering and transport

across landscapes. Here we review major advances and widely used techniques in this rapidly growing area of research.

## THE SOIL SYSTEM

Soil is a key component of the *critical zone*—the place where air, rock, water, and life all meet (Brantley et al. 2007). Hence, the study of soil intersects many disciplines, including biogeochemistry, hydrology, geomorphology, low-temperature geochemistry, and soil science. Yet the term *soil* has meanings that vary from one discipline to the next. Here we

adopt definitions used widely by geomorphologists in studies of eroding upland landscapes (Fig. 1): “regolith” is the blanket of weathered material atop coherent rock; “soil” is the mobile surface layer of the regolith; and “saprolite” is the underlying layer of chemically altered regolith that is physically intact enough to retain the fabric of the parent rock (Fig. 2).

The production and transport of soil are readily expressed in terms of conservation of mass on slopes (Fig. 1). The mass and thus thickness of soil reflect the competition between the creation of soil, referred to here as “production,” and the removal of soil, referred to here as “erosion,” which may be physical or chemical. The sum of all components of erosion is often termed “denudation.” Both saprolite and soil can experience chemical losses (Anderson et al. 2002), but physical erosion is restricted to soil by definition (because saprolite is physically intact). Soil is produced by biophysical processes that disrupt underlying saprolite or rock and entrain it into the flow of soil downslope. This bottom-up physical conveyor of Earth materials is aided by chemical processes that alter primary minerals, remove mass in solution (White et al. 1998), and weaken underlying saprolite (Dixon et al. 2009). Deposition of solids and solutes at the surface by wind and rain also contributes to soil production (Derry and Chadwick 2007). Each pathway of production and removal shown in FIGURE 1 has been explored quantitatively with cosmogenic nuclides, as elaborated below.

## COSMOGENIC NUCLIDES IN SOILS

Earth is constantly bombarded by high-energy particles radiated in the shockwaves of supernovae. These particles, primarily protons, are colloquially termed cosmic rays. They interact with the upper atmosphere, producing a cascade of radiation that produces cosmogenic nuclides

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as it passes through matter (Dunai and Lifton 2014 this issue). Commonly measured cosmogenic nuclides in Earth materials include  $^3\text{He}$ ,  $^7\text{Be}$ ,  $^{10}\text{Be}$ ,  $^{14}\text{C}$ ,  $^{21}\text{Ne}$ ,  $^{26}\text{Al}$ , and  $^{36}\text{Cl}$ . The abundance of these nuclides can be used to infer the near-surface residence time of minerals that contain them. Studies of soils have focused in particular on  $^{10}\text{Be}$ , in part because it is produced at predictable rates both in the atmosphere and in quartz grains near Earth's surface. Thus the fallout of  $^{10}\text{Be}$  onto soils from the atmosphere ("meteoric"  $^{10}\text{Be}$ ) and the buildup of  $^{10}\text{Be}$  in quartz ("in situ-produced"  $^{10}\text{Be}$ ) serve as cosmogenic clocks that record the time spent near the surface by Earth materials.

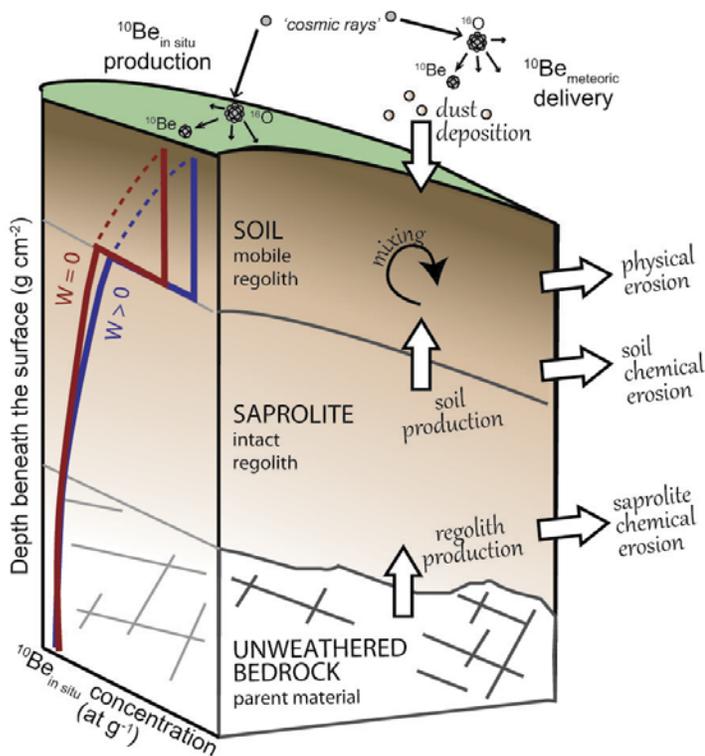
To understand how these cosmogenic clocks work, it may help to adopt the perspective of a mineral grain in rock. From this point of view, mass loss due to erosion at the surface causes the mineral to rise up and become exposed to cosmic radiation that produces cosmogenic nuclides within the mineral (the in situ variety). Meanwhile, nuclides produced in the atmosphere (the meteoric variety) fall to Earth's surface and attach to reactive surfaces as they filter through regolith. Thus,  $^{10}\text{Be}$  concentrations in soils at the

landscape surface reflect the integrated accumulation over all underlying depths as erosion exhumes Earth materials to the surface (Fig. 1). Minerals that rise more quickly due to faster erosion are exposed to cosmic radiation and fallout more briefly, leading to lower nuclide concentrations. Qualitatively, samples with higher nuclide concentrations imply slower erosion rates. More rigorously, nuclide concentrations in eroding regolith are used to quantify rates of multiple geomorphic processes using mathematical formulae.

The accumulation of meteoric and in situ-produced  $^{10}\text{Be}$  are typically modeled and measured separately because of differences in how they accumulate in soil. The concentration of meteoric  $^{10}\text{Be}$  can yield a non-eroding soil's age if the atmospheric flux is known. If the surface is eroding in steady state, the physical erosion rate can instead be calculated from the measured inventory and the known or inferred flux of meteoric  $^{10}\text{Be}$  to the soil (Monaghan et al. 1992). The principles behind the buildup of in situ-produced and meteoric  $^{10}\text{Be}$  are similar, but with important distinctions. When measuring the in situ variety, care must be taken to remove the meteoric variety (which is more abundant and found on reactive surfaces of soils). For this reason, in situ  $^{10}\text{Be}$  is typically measured in the mineral quartz, which is highly resistant to chemical weathering and thus readily purified via selective dissolution.

Nuclide production in quartz is fastest at Earth's surface and decreases exponentially with depth due to attenuation of cosmic radiation as it passes through matter. Exhumation of quartz from depth can be modeled with a differential equation that can be solved for the steady-state erosion rate, which encompasses mass losses due to both physical and chemical processes. In situ-produced  $^{10}\text{Be}$  concentrations and inferred erosion rates are averaged over the time required to erode just the top few meters of the landscape. For typical erosion rates in hills and mountains (i.e. 0.05–0.5 mm  $\text{y}^{-1}$ ), this translates into timescales of  $10^3$ – $10^4$  years. The accumulation of meteoric  $^{10}\text{Be}$  integrates over similar depths and timescales. Soils are generally no thicker than a meter or two in many landscapes. Hence, the depths and timescales of  $^{10}\text{Be}$  accumulation are consistent with the depths and timescales of pedogenesis. This makes  $^{10}\text{Be}$  a powerful tool for studying soil production, erosion, and weathering in landscapes.

Studies of in situ-produced  $^{10}\text{Be}$  have thus far been limited to sites where quartz is present, which excludes some settings, such as mafic and ultramafic landscapes. However, quartz is fairly common at Earth's surface, in part because it is highly resistant to weathering. This makes measurements possible in many landscapes. Somewhat paradoxically, quartz's resistance to weathering introduces complications in cosmogenic nuclide analyses. The ideal tracer of soil erosion is a mineral that is eroded from soil at the same rate as the soil as a whole. Because quartz is relatively insoluble, it can become enriched during chemical erosion, giving it a longer residence time than other minerals in regolith (Small et al. 1999). This leads to an enrichment of  $^{10}\text{Be}$  in quartz that can be accounted for using measurements of soil density, soil thickness, and concentrations of quartz or an insoluble proxy such as zirconium (Riebe and Granger 2013). Thus, cosmogenic nuclides in quartz collected from any depth shed light on rates of erosion and soil transformation in landscapes (Fig. 1). For example, a sample collected from beneath soil reveals the downward-propagation rate of the soil-saprolite or soil-rock interface, which is equivalent to the soil production rate (e.g. Heimsath et al. 2012).



**FIGURE 1** Soil is the mobile layer that sits atop saprolite, the physically intact product of chemical weathering of fresh bedrock at depth; together, they make up "regolith." In steady state, production of regolith from both bedrock and atmospheric dust replaces regolith lost due to chemical and physical erosion of soil and saprolite. Chemical erosion of relatively soluble elements in the soil leads to the enrichment of immobile elements such as Zr and stable minerals such as quartz.  $^{10}\text{Be}$  accumulates in regolith in two ways: in situ production in quartz (in atoms  $\text{g}^{-1} \text{y}^{-1}$ ), which declines exponentially with increasing mass of overburden, and delivery to the surface as meteoric fallout. Concentrations of  $^{10}\text{Be}$  reflect the balance between soil production, physical erosion, and chemical erosion. In well-mixed soils, in situ-produced  $^{10}\text{Be}$  (in atoms  $\text{g}^{-1}$ ) is uniform with depth down to the top of saprolite and then decreases exponentially in the deeper subsurface (solid lines). The case of erosion for an unmixed soil is also shown (dotted lines). The enrichment of quartz in saprolite and soil due to chemical erosion of more weatherable minerals increases its residence time relative to profiles with erosion that is strictly physical. Thus the nuclide concentration profile will vary based on the amount of chemical erosion ( $W$ ) and quartz enrichment (blue versus red lines; see text).

The applications of cosmogenic nuclides mentioned above require the assumptions of steady erosion and steady soil thickness. This limits them to upland settings where deposition is minimal and where erosion has been uniform over the timescales of nuclide buildup. The application of cosmogenic nuclides to lowland depositional settings is an area of active research that lies outside the scope of this article. In the sections that follow, we explore how cosmogenic nuclide techniques have shed new light on the formation, maintenance, and erosion of the upland soils that make up much of our habitable world (Fig. 2).

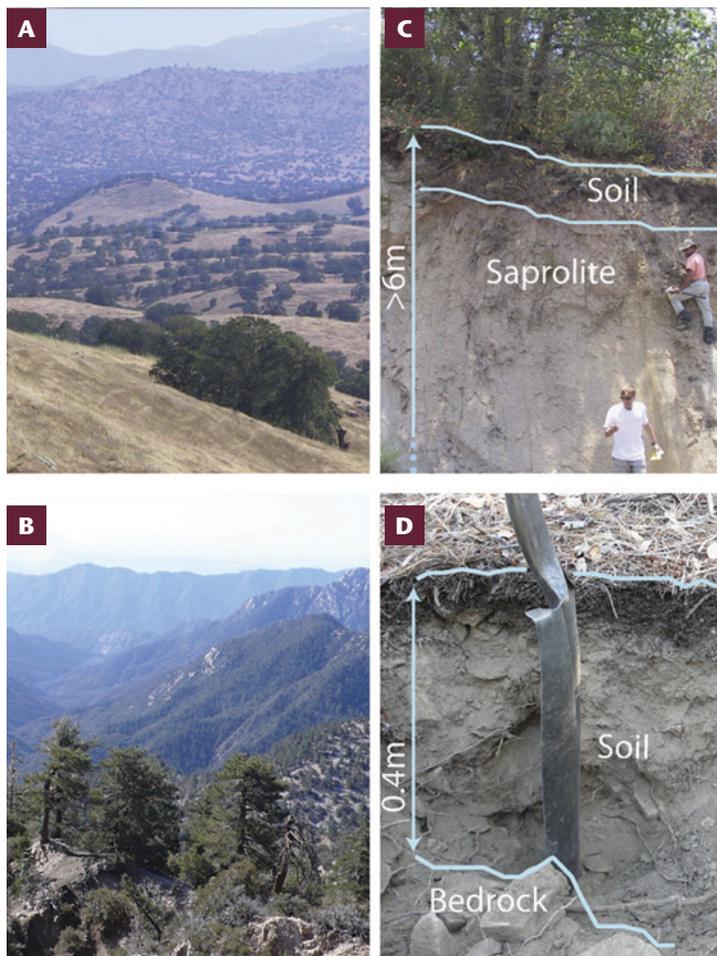
## TURNED FROM STONE TO SOIL

One of the great long-standing mysteries surrounding soils is their widespread presence in hills and mountains around the world (Fig. 2). Landscape-scale erosion rates, which can be measured from cosmogenic nuclides in stream sediment (Granger and Schaller 2014 this issue), have been shown to span roughly four orders of magnitude. Yet soils cover much of Earth's surface, including some of the most rapidly eroding mountain ranges. Moreover, the range in soil thickness is remarkably narrow, typically <2 m in hilly and mountainous terrain. The pervasiveness and consistent thickness of soils implies that there must often

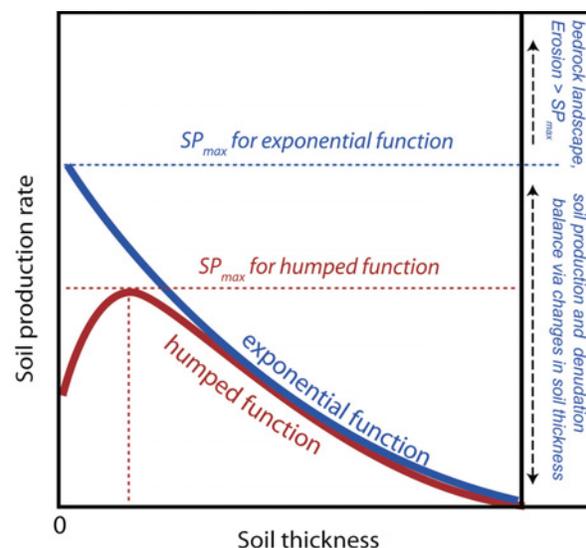
be a natural balance between rates of soil production and erosion. Otherwise, bare bedrock and very thick soils would be far more common than observed in upland landscapes.

What mechanisms keep soil production and erosion in balance? One possibility is a negative feedback between the production rate and thickness of soils. Such a feedback can arise if soil production rate is inversely related to soil thickness (Fig. 3). In that case, any increases in thickness would tend to decrease the production rate at the base of soil. This would allow erosion of the landscape surface to briefly outpace the soil production rate, resulting in removal of the excess soil (Carson and Kirkby 1972). G. K. Gilbert (1877) was perhaps the first to suggest that such an inverse relationship might be present in landscapes due to decreased dissolution and frost action with depth. In addition, he proposed that soil production would be slowest in the thinnest soils due to their low water-holding capacity. Thus Gilbert described what would later be known as the "humped" soil production function (Fig. 3), wherein soil production rates attain a maximum at an intermediate soil thickness. Today, it is widely thought that other processes, such as root wedging and animal burrowing, could contribute to humped soil production functions in landscapes. Other functional relationships, including exponentials (Fig. 3), hyperbolas, and even hinged curves, have nevertheless been proposed as alternatives to the hump over the years (Cox 1980). However, before the advent of cosmogenic nuclide techniques, geomorphologists and soil scientists lacked a widely applicable tool for quantifying how soil production rates vary with soil thickness in landscapes (Humphreys and Wilkinson 2007). Hence, they couldn't easily tell which, if any, of the proposed relationships were realistic.

Today, several hundred soil production rates have been measured across the world using cosmogenic nuclides (Fig. 4A). It has taken more than a century, but it is finally possible to test Gilbert's (1877) ideas about soil production with observations from the field. In many cases, the



**FIGURE 2** Cosmogenic nuclide methods are shedding light on the processes that shape soils in eroding, upland landscapes, including rolling hills and mountain slopes such as these from central and southern California (A, B). Regolith (including soil and saprolite) character, regolith thickness, and extent of cover differ with climatic and tectonic forcing (C, D). But the pervasiveness of soils across diverse eroding landscapes suggests a ubiquitous balance between the processes that produce and remove soils.



**FIGURE 3** Soil-production functions describe the relationship between soil production rate and soil thickness. "Humped" functions predict a maximum soil production rate ( $SP_{max}$ ) beneath a soil with intermediate thickness (red dashed lines), while exponential functions predict that the rate is greatest where soil thickness is zero (blue dashed line). If the soil erosion rate exceeds the maximum soil production rate, the soil will be stripped to bedrock and the erosion will ultimately be limited by the maximum soil production rate or by another process such as landsliding (noted in the right panel; after Dixon and von Blanckenburg 2012).

soil production function is captured in an exponential decline in soil production rates with increasing thickness (e.g. Heimsath et al. 2012). Together these data provide support for Gilbert's hypothesis that mobile soil thickness might be steady over time due to a self-arresting feedback between soil production rate and thickness. However, not all landscapes show a clear or universal relationship between soil production and thickness (FIG. 4A, B). Instead, the maximum soil production rate (explained in FIGURE 3) seems to keep pace with erosion rate across a wide range of settings, including some very rapidly eroding sites (Heimsath et al. 2012). The mechanisms behind the connection remain an area of active research that may one day help solve the longstanding mystery of widespread soil and its consistent thickness across diverse landscapes.

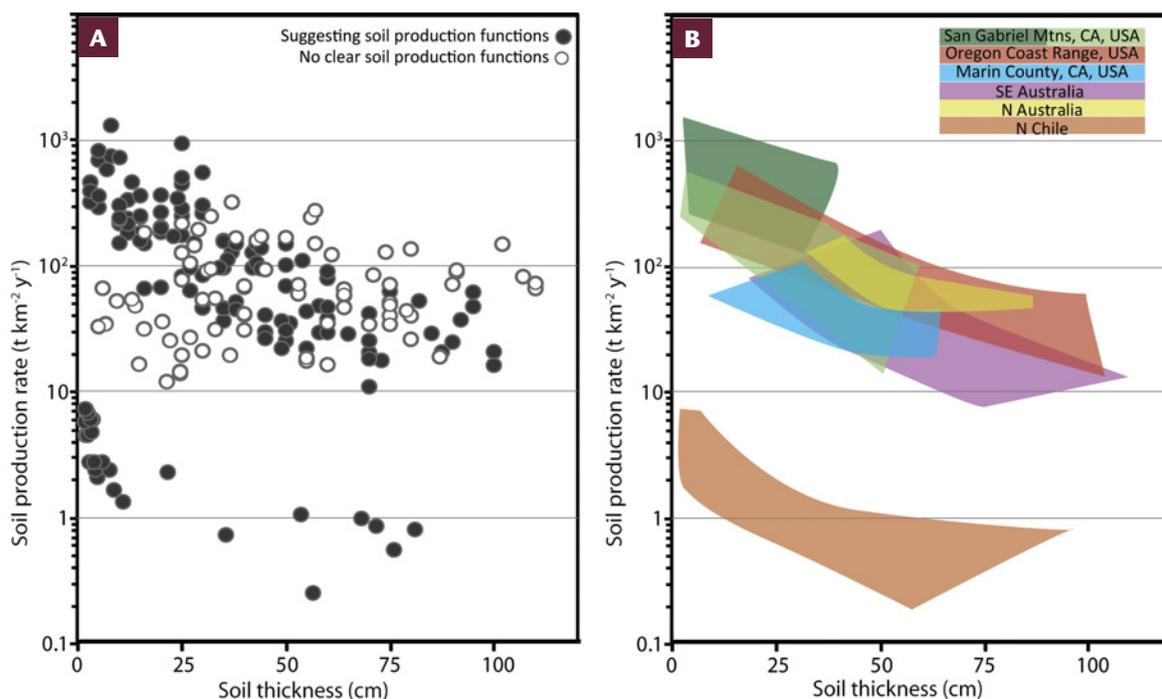
## DISSOLVED AND ENRICHED

The production of soil is just one step in a mineral's journey through the zone where air, water, rock, and life meet. Other transformations are equally vital to the fluxes and biogeochemical cycling of elements at Earth's surface. Hence, it would be useful if cosmogenic nuclide measurements of erosion rates could be teased apart into their chemical and physical components. Geochemical mass-balance techniques provide a framework for doing so.

More than a century ago, it was recognized that the enrichment of relatively insoluble elements and minerals in soils could be used to quantify the mass loss of other, more soluble elements during weathering (Merrill 1897). Crude initial estimates using Al and Fe (Merrill 1897) were followed by more accurate estimates based on chemically inert elements, such as Zr and Ti (Marshall and Haseman 1942). The enrichment of an inert element from parent bedrock to soil can be expressed as the fractional mass of the parent rock that was lost due to chemical erosion of other, less-inert elements. Stallard (1985) was the first to

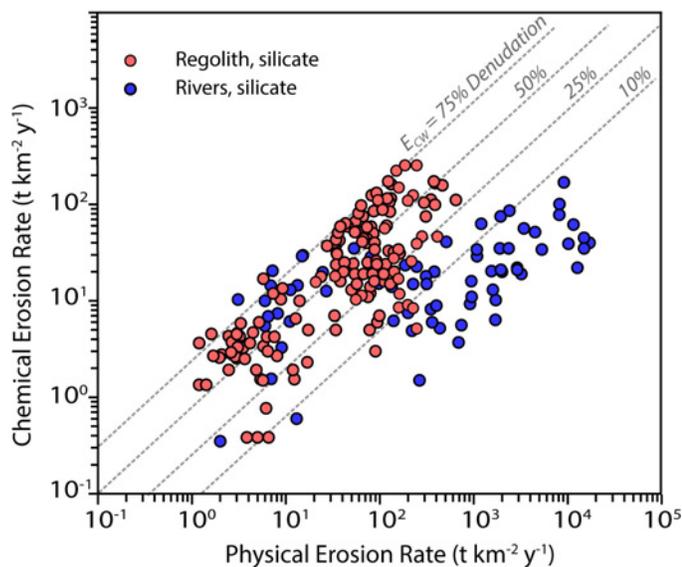
formally express the mass balance in terms of chemical enrichments for an eroding soil column. In theory, this was an important advance, because much of Earth's surface is eroding at a nontrivial pace. In practice, however, the formulation could not be applied in the field because there was no way to measure physical erosion rates—at least not until a few years later, after the advent of cosmogenic nuclide techniques.

Now, with the help of cosmogenic nuclides, the geochemical mass-balance approach can be used to measure chemical erosion rates in landscapes undergoing active physical erosion (White et al. 1998). In the first widespread application of the approach, the rate of chemical erosion was shown to be tightly coupled with the overall rate of erosion and thus presumably to the supply of minerals from the conversion of rock to soil (Riebe et al. 2001). Strong connections between chemical erosion and the supply of fresh, weatherable minerals to regolith have since been confirmed in numerous studies (FIG. 5). Eventually, enough global data were gathered for broad comparisons with independent (noncosmogenic) estimates of chemical and physical erosion from solute and sediment loads in rivers (FIG. 5). These data have revealed large differences that are not easy to explain. At high physical erosion rates ( $>100 \text{ t km}^{-2} \text{ y}^{-1}$ ), cosmogenic-based rates of chemical erosion exceed rates of solute export in rivers. The disparity might reflect differences in the timescales integrated by cosmogenic nuclides (millennial) and river loads (daily to decadal). It could instead reflect a sampling bias due to more intense weathering of upland soils relative to the average landscape surface (Dixon and von Blanckenburg 2012); river loads average across all surfaces in a catchment, whereas measurements of regolith geochemistry only integrate over sampling areas where regolith is present. More work is needed to explain these discrepancies.



**FIGURE 4** For nearly two decades, soil production rates have been measured across a suite of global settings. (A) Soil production rates are often observed to decrease with soil thickness (black circles). However, in some landscapes, there is little to no relationship (open circles). (B) Colored swaths highlight ranges of data from landscapes that exhibit correlations between

soil production rate and soil thickness (corresponding to black circles in A). Rates of mass loss (as represented by  $\text{t km}^{-2} \text{ y}^{-1}$  units) can be converted to rates of landscape lowering (e.g.  $\text{mm/ky}$ ) if the sample density is known (typically  $1.6\text{--}2.6 \text{ g cm}^{-3}$ ). The original data sources are cited in the compilation by Dixon and von Blanckenburg (2012).



**FIGURE 5** Variations in physical and chemical erosion rates across diverse landscapes. Regolith-based data reflect a combination of immobile-element enrichment data and cosmogenic  $^{10}\text{Be}$  concentrations. River-based data are a global compilation of sediment and dissolved loads. These data are corrected for atmospheric and carbonate contributions such that chemical fluxes reflect silicate weathering only. The grey dotted lines correspond to weathering intensity ( $E_{cw}$ ), calculated as the percentage of total erosion accomplished via chemical processes. A difference is evident between regolith-based and river-based data in rapidly eroding landscapes, where soil cover is not always continuous (after Dixon and von Blanckenburg 2012).

The explicit inclusion of physical erosion in studies of immobile-element enrichment was an important advance, improving the basis for understanding of chemical erosion in both nonglaciated and glaciated landscapes (e.g. Dixon and von Blanckenburg 2012; Schaller et al. 2009). Yet the mass balance was still incomplete. Atmospheric inputs were missing, despite their long-recognized importance in modulating the geochemistry of soils (Derry and Chadwick 2007). Minerals from dust deposition can enrich soils in both immobile and soluble elements and also make a significant contribution to soil mass. To account for this effect, an expanded mass-balance formulation was needed; two, not one, immobile elements must be measured in the soil, underlying rock, and incoming dust (Ferrier et al. 2011). The approach distinguishes the relative contributions of bedrock and dust to soils if their geochemistry is sufficiently distinct. Thus, the magnitude of dust contributions to soils can now be quantified. In the first application of the approach, in the Idaho Batholith, dust was found to contribute up to 13% of soil production (Ferrier et al. 2011). Accounting for this input can result in significantly improved measurements of physical and chemical erosion rates.

### STIRRED AND TRANSPORTED

Thus far, we have shown that cosmogenic nuclides can yield a 2-D view of the conveyor that channels Earth materials through weathering profiles and across landscape surfaces. Yet, as soils and solutes journey downslope, they may follow more complex pathways. The legacy of production, mixing, and downslope transport is encoded in the geochemistry and cosmogenic nuclide concentrations of the soil. If this legacy could be decoded, it would shed light on physical and chemical processes at work along slopes. The outlook is promising for interpreting the complexities of downslope soil and solute transport using cosmogenic nuclides and geochemical mass balance. For example,

$^{10}\text{Be}$ - and  $^{26}\text{Al}$ -derived soil production rates can be used in concert with numerical simulations and luminescence dating to calculate rates of downslope transport and to explore the creep-like way that soil particles move down slopes (Heimsath et al. 2002); this yields a snapshot of the complex pathways that individual grains follow in the subsurface. A similarly detailed view can be obtained using a combination of  $^{10}\text{Be}$ -based soil production rates, geochemical mass balance, and inverse methods to interpret downslope complexities in chemical erosion (Yoo et al. 2007). In addition, the measurement of cosmogenic nuclides in individual grains is showing promise as a tool for tracing the paths of soil and sediment down slopes (Codilean et al. 2010).

### LABELLED BY THE RAIN

Up to here, we have focused on applications of in situ-produced  $^{10}\text{Be}$  in quartz. Meteoric  $^{10}\text{Be}$  can also be used to gauge soil residence times and track soil and sediment movement across landscapes. Rather than building up within mineral grains, this so-called “garden variety” of  $^{10}\text{Be}$  binds strongly onto mineral surfaces after being scavenged from the atmosphere and delivered to Earth’s surface by precipitation. Meteoric  $^{10}\text{Be}$  emerged as a prospective tool to quantify soil production and erosion in the early 1980s (Pavich et al. 1984; Monaghan et al. 1992), a decade before in situ-produced  $^{10}\text{Be}$ . Yet, as in situ-produced  $^{10}\text{Be}$  was growing in popularity, meteoric  $^{10}\text{Be}$  was falling out of favor due to large uncertainties in both its fallout rate from the atmosphere and its behavior in soil. These limitations made it less robust in quantitative studies of geomorphic problems. Some of the uncertainties have been resolved, and the method is now experiencing a resurgence in popularity (Willenbring and von Blanckenburg 2010). Recent studies have adapted the traditional approach (following Pavich et al. 1984 and Monaghan et al. 1992), which quantifies physical erosion and tracks sediment across slopes using  $^{10}\text{Be}$  inventories in soils (e.g. West et al. 2013). In a new development, von Blanckenburg et al. (2012) showed that rates of physical and chemical erosion can be quantified from meteoric  $^{10}\text{Be}$  and its stable counterpart  $^9\text{Be}$ , which is released from minerals during weathering.

The use of meteoric  $^{10}\text{Be}$  in the study of soils is a promising research frontier, but hillslope-scale studies have remained rare due to a number of obstacles. For example, the temporal and spatial controls on  $^{10}\text{Be}$  delivery from the atmosphere remain controversial, despite recent comprehensive studies of existing data sets (Willenbring and von Blanckenburg 2010; Graly et al. 2011). Moreover, the complex geochemical behavior of Be in soils still poses challenges to interpreting meteoric  $^{10}\text{Be}$  concentrations in landscapes; Be may be leached more readily than previously thought (e.g. Bacon et al. 2012) and may have complex pathways of redistribution due to mixing of soil and the production and movement of secondary clays and oxides. Resolving uncertainties in meteoric  $^{10}\text{Be}$  deposition from the atmosphere and its behavior in soils is an area of much-needed research.

### CONCLUSIONS

Cosmogenic nuclide measurements have revolutionized our understanding of how soils are made, altered, and removed from landscapes over the millennial timescales of pedogenesis. Just three decades ago, the factors that regulate erosion and soil production were the subjects of thoughtful conjecture but little hard evidence. Today, a globe-spanning data set shows that soil production rates often decrease with soil thickness, much as G. K. Gilbert proposed more

than 130 years ago. This advance is remarkable given that there was no widely applicable way to measure long-term rates of soil production and erosion until the 1980s. Now, researchers measure them almost routinely and often partition them into their chemical and physical components using mass-balance principles introduced by G. P. Merrill at the turn of the twentieth century.

Each of the cosmogenic nuclide techniques discussed here integrates over the  $10^3$ – $10^4$  year timescales required to erode the top few meters in landscapes. Thus they are relatively insensitive to the effects of recent disturbance, making them nearly ideal for exploring the fundamental controls on soil formation and weathering. The long-term perspective of cosmogenic nuclides also makes them relevant to land-use managers, providing a baseline for evaluating the resilience of soils under scenarios of climate change and land-use intensification.

Over the past thirty years, geomorphologists, geochemists, and soil scientists have been measuring cosmogenic nuclides in soils from around the world. The results are helping to quantify how soils and landscapes evolve over

time. This in turn is fueling new questions, which are being explored with increasingly sophisticated process-based models. Future advances in cosmogenic nuclide methods will likely include improved use of meteoric  $^{10}\text{Be}$  and studies of multiple nuclides that quantify complex pathways and timescales of soil weathering. Geomorphologists have only just begun to scratch the surface of what can be learned from cosmogenic nuclides in soil. New data and methodological improvements will continue to define and refine our understanding of climatic, geologic, and biotic controls on the rates and pathways of soil evolution.

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