GEOCHEMISTRY

Limits of Soil Production?

Steep mountain regions can weather faster and produce soil more quickly than previously thought.

Arjun M. Heimsath

Rocky mountain ranges may appear static but are constantly in motion. Tectonic forces push the mountains up, while physical and chemical processes break rocks down to sediment that is transported to river plains and ultimately to the sea. This cycle is thought to regulate global climate over million-year time scales (*1*) while also responding to climate forcing itself (*2*). It remains unclear whether mountain uplift drives climate change, or whether climatic cooling drives uplift by causing faster erosion (*3*). On page 637 of this issue, Larsen *et al*. (*4*) provide data that help to quantify these controls on mountain building, reporting faster sediment production rates and higher chemical weathering rates than previously measured. Their results also provide key insights into soil sustainability over shorter time scales (*5*).

Mountain building can only drive global climate trajectories if weathering of silicate rocks removes enough CO_2 from the atmosphere over geologic time scales to lower atmospheric concentrations of this critical greenhouse gas. Proponents for mountain controls on climate point to extensive bedrock exposure, ready for weathering, in young mountain ranges and to the temporal correlation between periods of active mountain building and global cooling. However, it remains unclear whether mountainous regions are big enough and weather fast enough to account for the CO_2 drawdown needed to change climate (*6*) and whether the few measured weathering rates can be extrapolated across mountain ranges. It is also unknown whether there are limits to the rate of soil production, which helps to govern the presence of soil.

Soil can only persist at a given location if erosion is not removing it faster than it is being produced. On steep slopes there are typically extensive areas of bare rock, as well as areas where soil cover allows forests, tundra, and other forms of life to exist (see the figure). These steep slopes are thought, therefore, to exist at the threshold of soil production and provide the opportunity to examine the complex response of a hillslope to a wide range of erosion rates (*7*). If there is an upper limit to soil production rates (*8*), it is unclear how soil cover can be present in regions thought to be eroding well beyond the purported upper soil production limit.

Competing processes. The steep slopes of Mount Lukens rise abruptly from the suburban sprawl of Los Angeles, California. Landslides and debris flows remove sediment produced from the weathered rock, while active tectonic forces push the mountains higher. The extent of rock outcrop is shown in red on the overlain shaded relief map (*12*). Larsen *et al*. report that soil-mantled landscapes in much wetter New Zealand can persist in rapidly uplifting mountain ranges because of high rates of soil production and chemical weathering.

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Many challenges remain before these debates can be fully resolved. First and foremost, rates of soil production, erosion, and chemical weathering must be quantified across different landscapes. Larsen *et al*. now report exactly these data from the western Southern Alps of New Zealand. They also document pervasive soil and vegetation cover on slopes that erode faster than 1 mm per year. Their findings are based on concentrations of rare isotopes (^{10}Be) produced in the very grains of silicate minerals that react with CO_2 during chemical weathering. This isotope is produced by cosmic-ray bombardment of Earth's surface and is widely used to determine average erosion rates and point-specific soil production rates. Larsen *et al*. also measure concentrations of a nonreactive element (Zr) in the same samples to quantify the degree of chemical depletion in the weathered rocks producing the sediments. They use these depletion fractions in concert with the erosion and soil production rates to infer chemical weathering rates.

These data are not easy to come by. Larsen and colleagues traversed some of Earth's most rugged topography to collect their samples. The data reveal an exponential decline of soil production with increasing soil thickness, defining a higher soil production function, at higher erosion rates, than previously predicted. The data thus support the view that feedback between erosion and soil production enables rapidly eroding landscapes to retain a cloak of soil (*7*). Larsen *et al*. also show that chemical weathering rates are higher than a previously suggested kinetically controlled limit (*9*), providing key evidence for the important role that mountains play in controlling climate.

Resolving the couplings between silicate weathering and global climate requires similar data from both mountains and lowlands. Sample collection is the first challenge. The logistics are demanding even in locations not ravaged by war or severely affected by human development. Extracting and measuring ^{10}Be concentrations is expensive, involves specialized laboratoriess, and is time-consuming. ^{10}Be concentrations yield rates averaged over hundreds to hundreds of thousands of years, making it difficult to use the method to quantify rates that change over time. Calculated chemical weathering rates depend on the assumption that Zr concentrations are homogenous in unweathered rock and that

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the Zr is immobile in solution. Given these challenges, field-based data such as those reported by Larsen *et al*. are indispensable and provide crucial tests for models (*10*).

Obtaining similar data for agricultural soils presents challenges not faced by studies such as that of Larsen *et al*., yet this is where the greatest societal concerns lie (*11*). As food demand increases, so too will the need to conserve Earth's soil resources. The extent of soil conservation measures will depend on which side of the soil production–erosion balance agricultural soils fall.

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ATMOSPHERE

Next Season's Hurricanes

Seasonal predictions of hurricane activity remain challenging, especially at a regional scale.

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Tropical cyclones (TCs) are a hazard to life and property (*1*, *2*), as was tragically apparent following Super Typhoon Haiyan's landfall in the Philippines in 2013 and Hurricane/extratropical system Sandy's landfall in the New York tri-state area in 2012. Yet TCs also provide vital water, sometimes relieving drought (*3*). Predictions of the path and intensity of individual TCs are usually sufficiently good several days in advance that action can be taken. In contrast, predictions of seasonal TC activity months in advance must still be made more regionally relevant to produce information that can be acted on, for example, to improve storm preparedness.

Seasonal TC predictions focus on the probability of a range of outcomes integrated over broad regions, rather than the individual storms and narrower geographic foci used in 3- to 5-day weather forecasts. Whereas weather-scale TC predictions may lead to targeted actions such as evacuations, seasonal predictions are currently used to develop and price instruments to distribute risk (such as insurance). Improved skill and regional specificity of seasonal TC prediction could be useful to water resource, emergency, and energy management efforts. Furthermore, a better ability to forecast seasonal hurricanes can help build a more robust understanding of the ways in which climate controls hurricane activity, perhaps leading to increased confidence in multidecadal hurricane projections.

Challenges in
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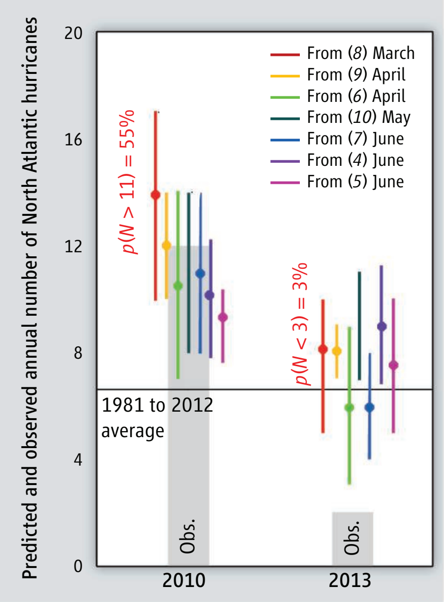
Basin-Wide Success

In recent years, several approaches have been developed to predict seasonal TC activity averaged over an entire basin, such as the North Atlantic or Northwest Pacific, several months before the season in question. These approaches include statistical (*4*) and dynamical general circulation models (*5*–*7*), as well as hybrid statistical-dynamical methods (*8*–*10*). They are used in operational seasonal TC outlooks made by meteorological agencies. Evaluated over multiple years and decades, these predictions are skillful at predicting the year-to-year changes in the total number of hurricanes, when compared to forecasts based on knowing only the long-term average or activity over the years preceding a season. The predictive skill of basin-wide activity can be seen in individual years. For example, for months prior to the 2010 season, Atlantic hurricane frequency was consistently predicted to be large (see the first figure), and 2010 was indeed the second most active hurricane season since 1970.

Learning from Failure

Even though predictions are skillful in predicting year-to-year changes in TC activity over many years, they are not perfect. A glaring example is the recent 2013 Atlantic hurricane season (see the first figure), for which nature failed to follow the almost unanimous prediction that the North Atlantic should have a normal to slightly enhanced number of hurricanes (~6 to 9). Instead, it was one of the most anemic hurricane seasons ever recorded.

A season like 2013 is humbling. Yet only by understanding and learning from past failed predictions will the prediction community be able to successfully move forward. In disentangling the causes of the low hurricane activity of 2013, we must ask ourselves whether our prediction systems neglected something foreseeable, and then account for this in future predictions. But



Seasonal North Atlantic hurricane prediction. The very active 2010 season was successfully predicted by a range of methodologies (*4*–*10*), but these prediction systems generally failed for the very inactive 2013 season. Central estimates are circles; vertical bars show ranges [70% range for (*8*, *10*); ±1σ for (*4*–*7*, *9*)]. The legend gives the month when each prediction was issued. For (*8*), the predicted exceedance probabilities for the observed hurricane counts are given to the left of the vertical bar. For data, see supplementary materials.

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