



Testing for steady-state soils in eroding landscapes

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Abstract. Quantifying soil production rates is central to understanding landscape evolution, critical-zone development, and
carbon cycling, but commonly relies on cosmogenic nuclide methods conditioned on the steady-state status of soil thickness.
Here we introduce a two-sample test for steady-state that uses the ratio of ¹⁰Be-inferred erosion rates from soil and saprolite.
Across ridgetops spanning a wide range of erosion rates, land uses, and soil thicknesses, the test reveals both steady- and non-
20 steady-state soils, sometimes on adjacent ridges. We numerically modelled soil disturbances to explore the implications of
non-steady-state soils for ¹⁰Be concentrations, erosion-rate estimates, and inferred soil production functions under a range of
disturbance scenarios. The models show that non-steady soils can create apparent variability in soil production functions. Our
two-sample test enables widespread verification of steady state assumptions, strengthening ¹⁰Be-based interpretations of
erosion, weathering, and soil development in upland landscapes.

25 1 Introduction

The balance between soil production and erosion determines whether soil thickness increases, decreases, or remains steady,
with implications for landscape evolution, critical-zone development, and soil carbon storage (Reed et al., 2023; Riebe et al.,
2017; Doetterl et al., 2016). Cosmogenic nuclide studies have been used at hundreds of upland locations to estimate soil
production rates using ¹⁰Be in saprolite or soil (Humphreys & Wilkinson, 2007; Richter et al., 2020), typically from just one
30 sample. But this approach requires steady-state soil thickness over the timescale of nuclide accumulation. This assumption
may be invalid in landscapes affected by landsliding, land use, climate variability, or episodic tectonic forcing (Marshall et al.,



2015; Mudd et al., 2017). Since many soil-mantled landscapes are affected by potentially destabilizing factors, non-steady state soils may be the norm rather than the exception (Phillips, 2010).

35 This possibility has been supported in several previous studies of cosmogenic nuclides in soil and saprolite. For example, climate change and episodic channel incision have been invoked to explain departures from steady state in ^{10}Be depth profiles in the Yanshan Mountains, China (Yang et al., 2022) and the Colorado Front Range (Foster et al., 2015). Similarly, the differential decay of ^{10}Be , ^{26}Al , and ^{14}C in quartz has been exploited at sites in South America to detect non-steady soils that have been attributed to changes in climate and land use (Hippe et al., 2021; Godard et al., 2024). This demonstrates that a
 40 soil's history can be decoded using one cosmogenic nuclide from multiple depths or multiple nuclides from a single sample. However, depth profiles require many analyses, and measurements of ^{14}C , unlike ^{10}Be , have not yet been widely applied due to difficulties in sample processing (Lifton et al., 2023). This limits the number of locations where steady state has been assessed. As a result, the assumption has not been widely validated in studies of soil production and erosion.

45 Here we introduce a test involving just two ^{10}Be measurements, one from soil and one from saprolite, thus enabling widespread testing of the steady-state assumption. We applied the test across sites in South Carolina and New Zealand that span three orders of magnitude in erosion rates. Our ^{10}Be measurements reveal the coexistence of steady- and non-steady-state soils both within and among the sites. This demonstrates the need to understand how non-steady conditions might be expressed in the soil production function—i.e., the relationship between soil thickness and soil production—which has been central to studies
 50 of landscape evolution for decades (Heimsath et al., 1997; Larsen et al., 2023). We evaluate the sensitivity of the relationship using a numerical model of cosmogenic nuclides and soil thickness after disturbances of various types and scales. Our results show that the departures from steady state observed at our sites can amplify, suppress, or even distort the relationship between soil thickness and production rate. Hence, our findings underscore the importance of understanding the sensitivity of soils to disturbance in cosmogenic nuclide studies of geomorphic processes.

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2 Theoretical Framework

On ridgetops with no influx of material from upslope, ^{10}Be accumulation in quartz creates a characteristic, poly-exponential profile through soil and saprolite when the rates of erosion and soil production are equal and steady over sufficient time. If the ^{10}Be concentrations at multiple depths in soil and saprolite match the characteristic profile (Fig. 1), it indicates the soil is in
 60 steady state (e.g., Yang et al., 2022). However, if the soil is well mixed by chemical, biological, and physical processes (Gabet et al., 2003), just two ^{10}Be samples are needed: one from the soil to calculate the erosion rate of the soil (E_s); and the other from saprolite to calculate the apparent soil production rate from saprolite (E_R). Each sample can be taken from any depth so long as the saprolite sampling depth and the density of overburden are measured and used in the soil-production rate estimate. The depth of the sampled soil is not needed since the concentration is uniform with depth in well-mixed soils (Fig. 1b).

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Together, E_S and E_R reveal the steady-state status of the soil when expressed as a ratio, E_S/E_R . This ratio will differ from unity and indicate that the soil is not in steady state when the thickness or density of soil has recently changed. This is because the soil mass (density times thickness) required to estimate the attenuation of ^{10}Be -producing cosmic radiation will be incorrect in the calculation of E_R . Hence E_R will differ from the true long-term rate. For example, when the soil has recently thinned, the denominator, E_R , will be erroneously high and E_S/E_R will be less than unity, because the apparent attenuation will be erroneously low. Note that, counterintuitively, E_S will be insensitive to changes in soil thickness because the remaining soil will retain the average ^{10}Be concentration of pre-disturbed mixed layer (Fig. 1b) and thus reliably reflect the long-term average erosion rate. Since the erosion rate equals the soil production rate in steady state, the ratio E_S/E_R provides a two-sample test for the status of soils: in steady state, $E_S/E_R = 1$; in thinned soils, $E_S/E_R < 1$, because E_R is erroneously high; and in thickened soils, $E_S/E_R > 1$, because E_R is erroneously low.

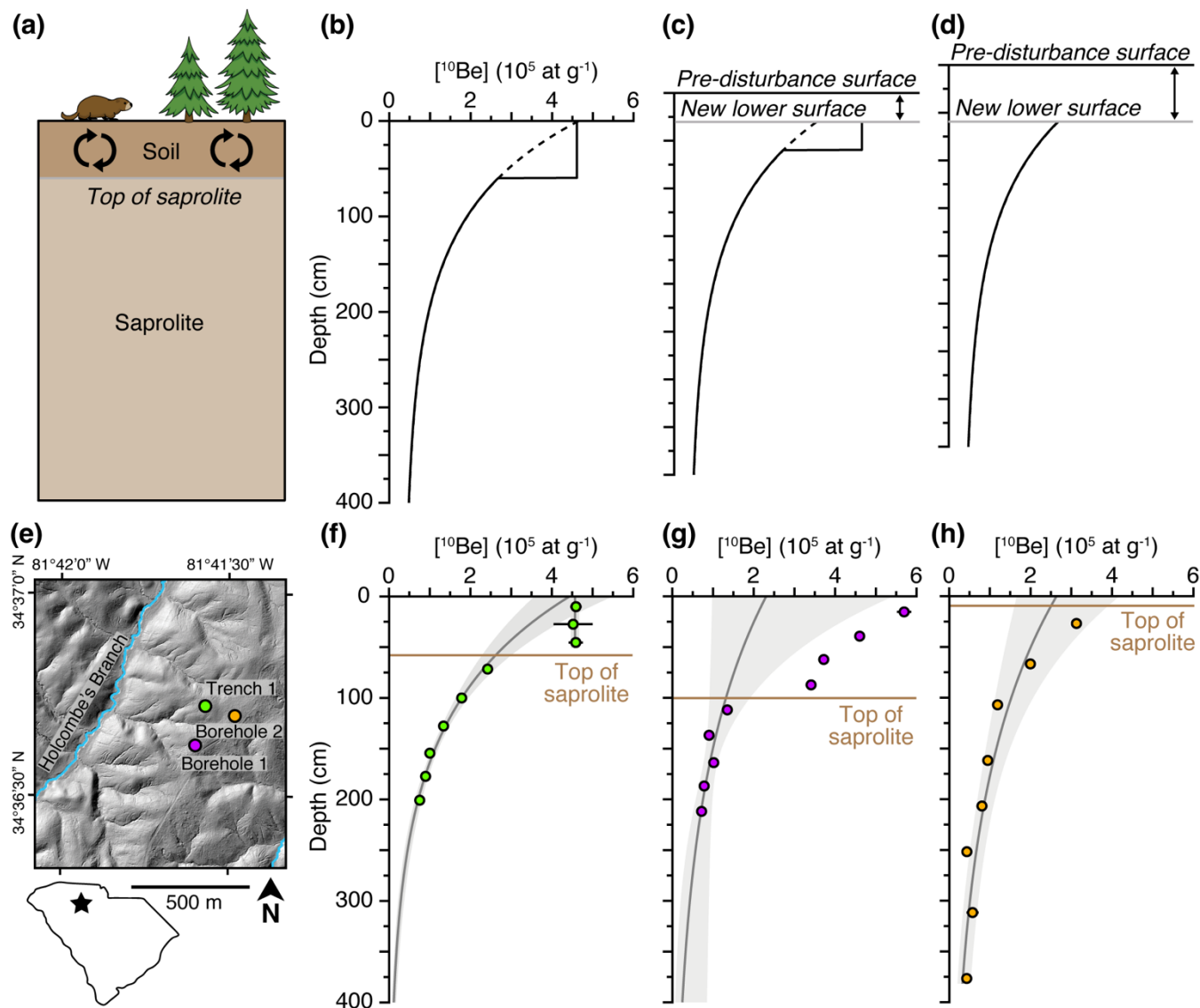


Figure 1. Modelled (a-d) and measured (e-h) ^{10}Be profiles from South Carolina field site. Subsurface schematic (a) and modelled profiles of ^{10}Be in quartz at ridgetop location for steady-state (b) and non-steady-state soils (c-d). Solid lines show numerical solutions for 10 m Myr^{-1} erosion rate at South Carolina site (34.6°N). Dashed lines show projected values through soil from profile in saprolite. Vertical lines show values in mixed layer at steady state. In a 60-cm mixed, steady-state soil (b), the projected value at surface should equal the mixed layer ^{10}Be concentration (Granger & Riebe, 2007), which can be used to calculate the long-term average erosion rate (see Eq. S1). If the soil has recently thinned, ^{10}Be in the mixed soil will be higher than the projected value by an amount that reveals the depth of truncation (spanned by arrows in c and d) relative to the predisturbance surface. If the mixed soil has been entirely removed, ^{10}Be will decline exponentially with depth (d). Measured ^{10}Be depth profiles (f-h) from South Carolina site (e) show both steady- and non-steady-state soils at three ridgetop profiles.



(f) Trench 1 matches modelled steady-state profile in Fig. 1a. Boreholes 1 and 2 (g, h) are consistent with soil thinning models in c and d, respectively. Error bars show 95% CI on ^{10}Be concentrations (though many are smaller than symbol size). Gray bands show 95% CI on best-fit exponential regressions to ^{10}Be in saprolite.

90 3 Field Methods

We collected soil and saprolite samples from soil pits, trenches, and drill cores on ridgetops at three sites: one in the South Carolina Piedmont and two in mountain landscapes of New Zealand (Fig. 2; Supplementary Data S1). Regional erosion rates vary from $\sim 10^0$ m Myr $^{-1}$ in South Carolina to $\sim 10^3$ m Myr $^{-1}$ in the New Zealand Southern Alps (Reusser et al., 2015; Larsen et al., 2014). Locally, land-use history also differs markedly, from sharecropping and more recent plantation logging in South Carolina (Coughlan et al., 2017), to undisturbed native bush in New Zealand. Hence, these sites are suitable for exploring how erosion and land use influence the steady-state status of soils.

At the South Carolina site, we quantified ^{10}Be profiles using samples from eight or nine depths through soil and saprolite at each of three adjacent ridgetops (Fig. 1e-h). These high-resolution depth profiles permit us to evaluate the reliability of the two-sample test by providing both a check on whether ^{10}Be is well mixed in the soil and a direct comparison with the characteristic steady-state ^{10}Be profile. To further evaluate the two-sample test, we also applied it at an upland plot in a remnant hardwood stand considered an undisturbed control site in previous studies (Fig. S1; Bacon et al., 2012; Holbrook et al., 2019; Richter et al., 2014). To also consider locations with more rapid background erosion rates, we sampled three ridgetops in the Tararua Range, on New Zealand's North Island (Fig. S2), and two ridgetops in the eastern Southern Alps, on the South Island (Fig. S3).

To obtain ^{10}Be concentrations in quartz from our samples, we used standard techniques for purifying (Kohl & Nishiizumi, 1992) and dissolving quartz and extracting Be via ion exchange chromatography (Corbett et al., 2016). $^{10}\text{Be}/^9\text{Be}$ ratios were measured by accelerator mass spectrometry at Purdue University and Lawrence Livermore National Lab. We converted the ratios to ^{10}Be concentrations using masses of quartz and ^9Be added to each sample (Supplementary Data S1) and calculated erosion rates and soil production rates using Eq. (S1).

4 Results

At South Carolina, the profile at Trench 1 closely matches the characteristic profile for steady state in a mixed soil over saprolite (cf. Figs. 1b and 1f), despite the long (10^2 year) history of intensive land use and the long (10^5 year) timescale of nuclide accumulation associated with the slow erosion rate. The steady-state status of the soil is also confirmed by the two-sample test: E_S/E_R is indistinguishable from unity at 1.02 ± 0.16 ($\pm 95\%$ CI). Long-term stability at Trench 1 is also supported by the persistence of a ~ 20 -30 cm thick A-E horizon (Fig. S4). The two-sample test likewise yields an E_S/E_R ratio equal to

unity (0.90 ± 0.17 ; $\pm 95\%$ CI) at the remnant hardwood control plot, consistent with its previous interpretation as representing undisturbed conditions (Fig. 2; Richter et al., 2014).

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In contrast to the stability at Trench 1 and the reference site, the soil at Boreholes 1 and 2 appear to be out of steady state. For example, the projected ^{10}Be at the surface in Borehole 1 is lower than the average in the soil (Fig. 1g), and $E_S/E_R = 0.50 \pm 0.09$ ($\pm 95\%$ CI). Both of these findings are consistent with recent thinning (Fig. 1c). In addition, high-resolution core images show just ~ 10 cm of organic and gray-brown soil on top of a clay rich layer (Fig. S5), indicating that the layer of mixing is thin. A shallow depth of mixing is also supported by the decrease in ^{10}Be in the top four samples (Fig. 1g). However, the offset in ^{10}Be between the top four and bottom five profile samples suggests a complicated history of mixing. One way for such a profile to develop is through an initial period of steady state followed by a soil thinning event and cessation of mixing. Thinning would explain the higher-than-projected surface concentrations in the top four samples (Fig. 1c), and the cessation of mixing in the top 100 cm would explain the decrease in ^{10}Be in the top four samples. Non-steady conditions are also evident at Borehole 2: ^{10}Be decreases exponentially with depth across the full range of samples (Fig. 1h), and the gray-brown surface horizons are absent (Fig. S5), consistent with complete stripping of the mixed layer (Fig. 1d), possibly associated with clear cutting of the surrounding loblolly pine plantation in the late 1990s (Fig. S6).

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Given that Trench 1 and Boreholes 1 and 2 are spaced <200 m apart, their locations should have similar erosion rates averaged over the 10^5 -year timescale of ^{10}Be accumulation in the profiles. However, the apparent erosion rates of the locations are 6 m Myr^{-1} , 13 m Myr^{-1} , and 11 m Myr^{-1} , respectively, based on the ^{10}Be projected to the surface from the underlying saprolite. We interpret the result from Trench 1 to be correct because $E_S/E_R = 1$, the ^{10}Be profile closely matches the predicted steady-state profile for an erosion rate of 6 m Myr^{-1} , and E_S matches the 6 m Myr^{-1} long-term average erosion rates measured in the adjacent Wateree and Saluda river catchments (Reusser et al., 2015). The high erosion rates implied by the borehole profiles are consistent with the removal of ~ 70 cm of soil by recent disturbances at both locations, leading to erroneously low shielding adjustments to the ^{10}Be production rate (Eq. S1).

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We also found a mix of steady and non-steady conditions at the two sites in New Zealand, where the dominant drivers of non-steady conditions are geomorphic rather than anthropogenic. In the Tararua Range, where erosion rates are $\sim 10\times$ faster than South Carolina, soil pits at sites that differ by ~ 1 km in elevation each have E_S/E_R ratios that are consistent with steady state (Fig. 2), despite marked differences in vegetation, local slope, and soil thickness. In contrast, in the central Southern Alps, where erosion rates are an order of magnitude faster still, E_S/E_R ratios from two soil pits on a narrow ridge show that both locations are out of steady state. One ratio indicates recent thinning ($E_S/E_R = 0.32 \pm 0.04$; $\pm 95\%$ CI); the other, recent thickening ($E_S/E_R = 1.42 \pm 0.11$; $\pm 95\%$ CI). (Fig. 2). The thinning could reflect soil loss due to shallow landsliding, which is evident in the landscape (Figs. S3 and S7). However, the thickening signal is enigmatic because ridges typically shed sediment rather than accumulate it. To elevate E_S/E_R on a ridge, the soil production rate would need to increase without a concurrent

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increase in surface erosion rate. One possible mechanism is that climate-driven treeline migration could have extended the elevational range of woody vegetation, potentially increasing soil production and allowing the soil to thicken, consistent with nearby paleoecological evidence of upslope forest migration (McGlone & Basher, 2012).

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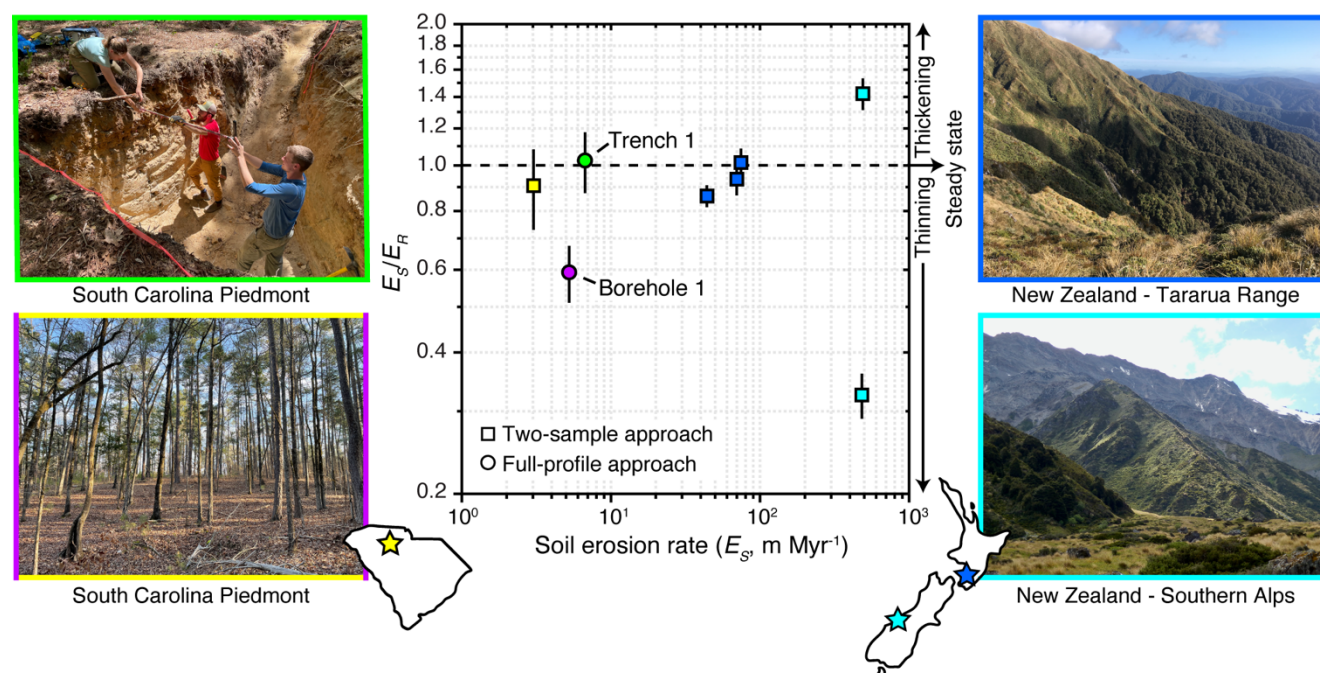


Figure 2. The ratio E_s/E_r indicates departures from steady state. $E_s/E_r > 1$ implies soil thickening, and $E_s/E_r < 1$ implies soil thinning. Error bars show 95% confidence intervals. Sites in South Carolina are either close to steady state or thinned. Circles represent profiles; squares represent two-sample tests. Borehole 2 not shown because E_s/E_r cannot be calculated due to absence of soil (see Fig. 1h). Adjacent locations in the Tararua Range of New Zealand are in or close to steady state, whereas locations along a ridge in the Southern Alps are out of steady in both directions, indicating both thickening and thinning.

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5 Implications of Non-Steady Soils

Our field observations show that non-steady soils can occur in both slowly and quickly eroding landscapes and can even coexist with steady soils on adjacent slopes. This suggests that non-steady soils may be widespread and can manifest non-uniformly across landscapes. These findings also raise a broader question of how transient changes in soil thickness affect interpretations of cosmogenic nuclide measurements and the geomorphic process laws derived from them.

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One process law that may be sensitive to non-steady soil thicknesses is the soil production function—the exponential decline in soil production with increasing soil thickness caused by the decreasing effectiveness of production mechanisms with depth (Gilbert, 1877). In theory, the best-fit slope and intercept of the exponential relationship should vary from landscape to

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landscape depending on factors such as climate, lithology, and biotic activity (Heimsath et al., 2012; Larsen et al., 2023). However, the slope and intercept parameters can be biased by erroneously fast or slow apparent soil production rates in non-steady soils such as those found in South Carolina and New Zealand.

175 To evaluate the potential for bias we developed a numerical model that simulates how changes in soil thickness affect apparent erosion and soil production rates. We applied the model to plausible disturbance scenarios, including soil thinning, thickening, and spatially heterogeneous changes in soil thickness (Fig. 3). The pre-disturbance baseline in each scenario is a hillslope where factors that control soil production (climate, lithology, and biotic activity) are uniform and soil thickness and production are in steady state. The soil production rate (E_R) is calculated using soil thickness (h)

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$$E_R = ae^{bh} \quad (1)$$

with previously published values of slope (b , cm^{-1}) and intercept (a , m Myr^{-1}). For each soil production rate, we obtain the steady-state ^{10}Be concentration profile for a well-mixed soil over saprolite (Eq. S2; e.g., Fig. 1b) before applying the disturbance. After applying each disturbance scenario, we fit an exponential function to the modelled apparent soil production rates (Eq. S3) to obtain the soil production function that would be observed if samples were collected from the top of saprolite
 185 immediately after the disturbance.

In one disturbance scenario, each thickness is decreased by a constant percentage, causing apparent soil production to be higher because the shielding correction is reduced. Each point moves up and left on the plot. For $E_R = 80e^{-0.06h}$, a soil with 80 cm thickness that thins by 50% would have pre- and post-disturbance soil production rates of 0.66 and 1.27 m Myr^{-1} , respectively
 190 (Fig. 3a), with $E_S/E_R = 0.52$. Thinner soils shift less because they thin less in absolute terms, making the apparent soil production function rotate clockwise—steepening—with increasing thinning percentage (Fig. 3a). Lower thinning percentages lead to smaller increases in slope (Fig. 3a), which also occur when the slope of the pre-disturbance soil production function is lower (Figs. 3b-c).

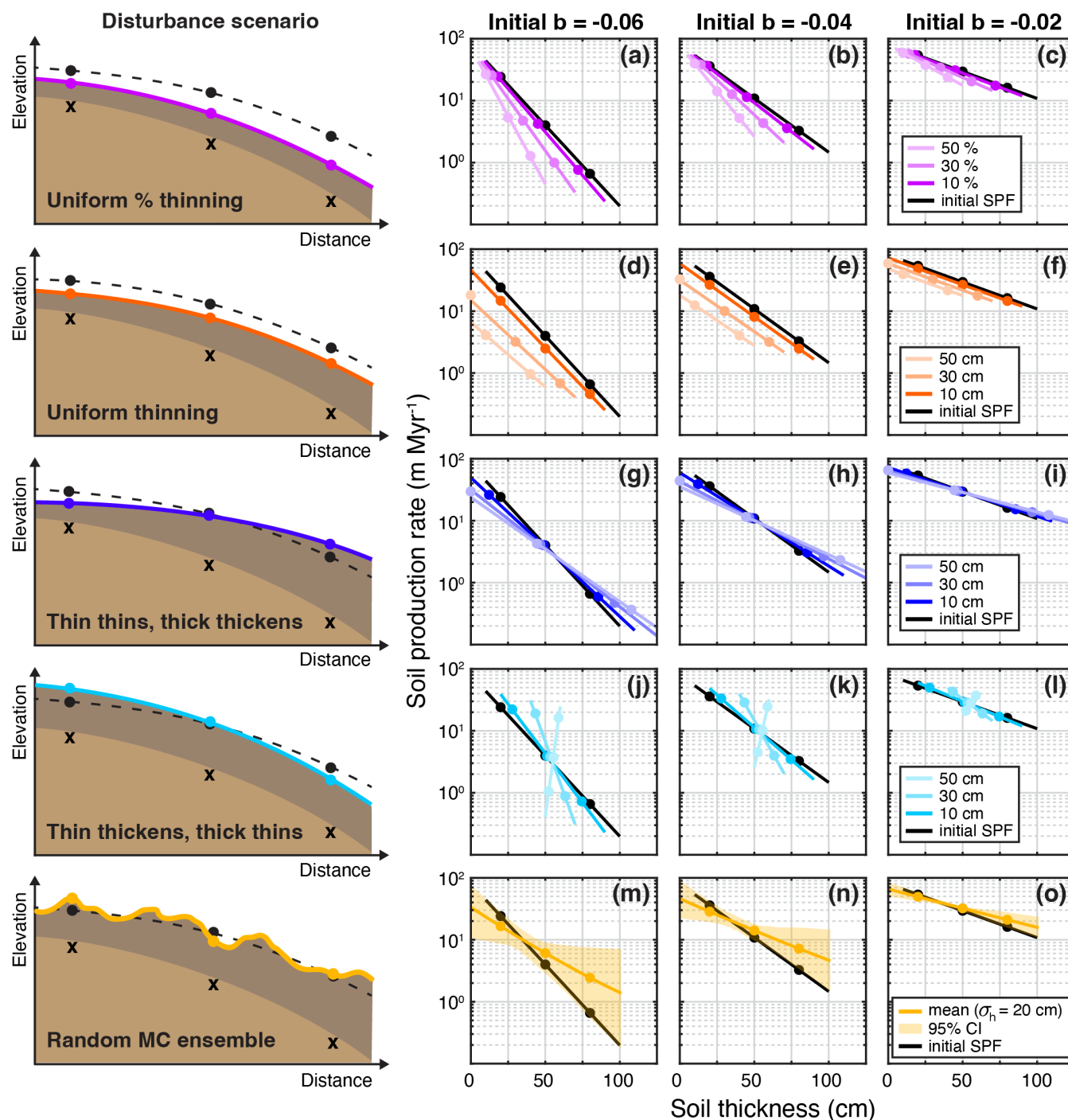


Figure 3. Effects of soil disturbance type and magnitude on apparent soil production rates. Left panels illustrate idealized disturbance scenarios applied to initially steady-state hillslope (dashed lines). Schematics show thin soils near ridge and thick soils near hillslope base; however, our analysis considers each point in isolation without regard to relative hillslope position



or soil transport. X's indicate cosmogenic nuclide sampling locations. Plots show apparent soil production rate versus soil thickness for three initial slopes ($b = -0.06, -0.04$, and -0.02 cm^{-1}). Black lines indicate initial pre-disturbance soil production function (SPF); colored lines show apparent soil production function for different disturbance magnitudes. Shaded envelopes denote 95% CI for Monte Carlo ensemble of random disturbances with Gaussian $\mu = 0$; $\sigma_h = 20 \text{ cm}$; 100,000 runs.

We use the same baseline conditions in four additional disturbance scenarios: spatially uniform thinning (Fig 3d-f); increases in soil thickness variability, where thin soils thin and thick soils thicken (Fig. 3g-i); decreases in soil thickness variability, where thin soils thicken and thick soils thin (Fig. 3j-l); and a Monte-Carlo ensemble of random thinning and thickening (Fig. 3m-o). The results show that disturbance type affects both the slope and intercept, with the magnitude depending on the slope of the soil production function before the disturbance (Fig. 3). To compare scenarios, we isolate the moderate disturbance magnitude of Figure 3 and plot the change in slope (Fig. 4a) and the absolute value of the intercept (Fig. 4b) of the apparent soil production function for each scenario across the range of soil production function slopes reported in previous work (Fig. 4c).

Together, the scenarios point to three findings. First, while disturbances can drive substantial changes in ^{10}Be -derived soil production rates, the stronger effect on the apparent soil production function comes from the change in soil thickness (Fig. 3). Second, even a moderate soil disturbance can bias the slope and intercept of the soil production function (Fig. 4a,b), emphasizing the need to account for disturbances when interpreting ^{10}Be -derived soil production functions. Finally, the directions of the changes in intercept and slope are consistent with the relationship between slope and intercept from the global database (Fig. 4c), suggesting that the trend may be partly due to non-steady conditions.

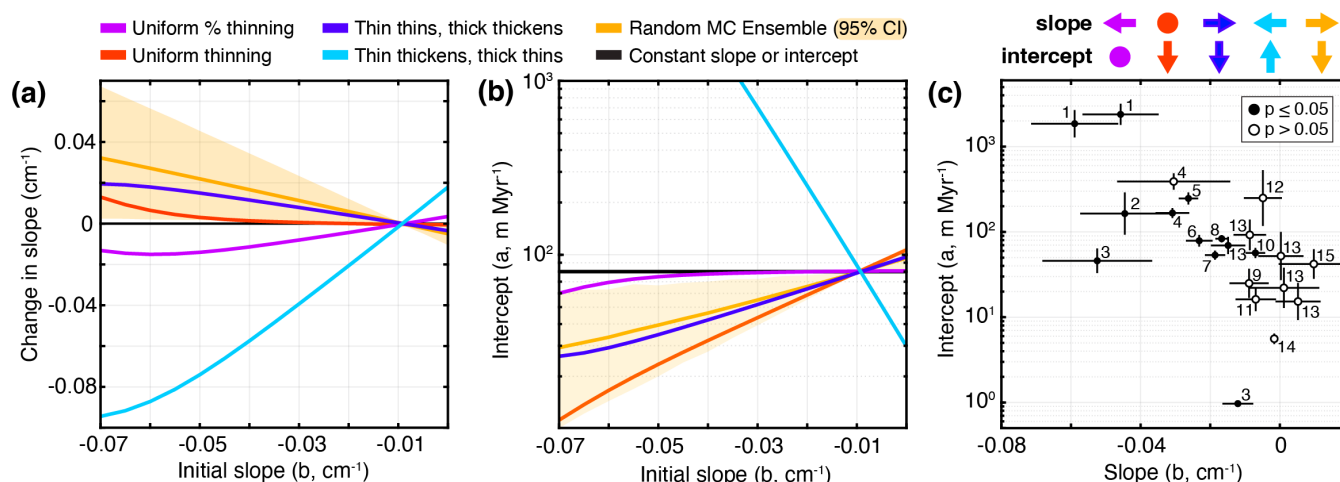


Figure 4. Model results illustrating how different disturbance scenarios modify soil production function slope (a) and intercept (b) for intermediate magnitudes of Fig. 3. (c) Field-determined slopes and intercepts of soil production functions for significant



and non-significant exponential relationships with 1 s.e.m. error bars. Colored arrows (and circles) above (c) show directions of shifts (or lack thereof) in intercept and slope due to modelled disturbances, showing trend in observed soil production function parameters may be influenced by undetected non-steady conditions. Labels in 4c: ¹Larsen et al. (2014), ²Heimsath et al. (2001a), ³Owen et al. (2010), ⁴Heimsath et al. (2012), ⁵Heimsath et al. (2001b), ⁶Heimsath et al. (1997), ⁷Heimsath et al. (2000), ⁸Heimsath et al. (2005), ⁹Riggins et al. (2011), ¹⁰Byun et al. (2015), ¹¹Wilkinson et al. (2005), ¹²Harrison et al. (2021), ¹³Dixon et al. (2009), ¹⁴Heimsath et al. (2019), ¹⁵Ferrier et al. (2012).

6 Discussion and Conclusion

We show that steady- and non-steady-state soils coexist across short spatial scales and across geomorphic settings, suggesting that departures from steady state may be both common and spatially heterogeneous in soil-mantled landscapes. Moreover, the finding of steady and non-steady soils on neighbouring ridgetops with similar lithology, climate, and long-term erosion histories indicates that local disturbance history may be as important as regional factors in whether steady-state assumptions are valid. Consequently, steady state cannot be assumed and should instead be verified at sampling locations.

Just two samples, one in saprolite and one in soil, are sufficient to quantify the long-term erosion rate and test for steady state provided that the soil is mixed over the timescale of ¹⁰Be accumulation. The two-sample test can also reveal departures from steady state in soils that are not completely mixed (Fig. 1g), although the magnitude of the departure, expressed as the deviation of E_s/E_r from unity, will be uncertain. The degree of mixing (i.e., pedoturbation) has been assessed using additional ¹⁰Be measurements from the soil (Small et al., 1999), depth profiles of optically stimulated luminescence measurements (Gray et al., 2019), soil spectroscopy (Sweeney et al., 2012), or theoretical considerations based on the site-specific processes of soil production and transport (van der Meij et al., 2025; Furbish et al., 2018). Our results also show how limited resources can be optimized by combining the two-sample test with more costly ¹⁰Be depth profiles through soil and saprolite to document the spatial distribution of steady and non-steady soils while providing localized assessments of soil mixing and disturbance history.

Numerical modelling demonstrates that departures from steady state can bias both the slope and intercept of inferred soil production functions. Biases span a range large enough to complicate interpretation of published soil production functions (Fig. 4c). For gently sloping production functions, disturbance-induced changes are comparable to analytical uncertainty, whereas for steeper production functions some disturbance scenarios produce deviations that span nearly the full range of reported slopes. Hence, variability in soil production functions may partly reflect differing transient histories rather than differences in lithology, climate, and erosion rate (Norton et al., 2014; Pelletier et al., 2017; Geyman et al., 2025).

Together, the field observations and numerical modelling suggest that both the magnitude and timescale of disturbance influence the scale of the departure from steady state. Small deviations from unity, such as those observed in the Tararua Range (Fig.2), may record subtle or slowly progressing adjustments following modest disturbances, such as gradual climatic change



255 (e.g., Marshall et al., 2015). Larger departures, such as those observed in the Southern Alps and Borehole 1 at South Carolina
 (Fig. 2), are consistent with larger or more abrupt disturbances, such as the landsliding shown in Fig. S3. Conversely, similar
 apparent departures from steady state can be produced from disturbances over different timescales—such as instantaneous
 landsliding, decades to centuries of land-use change, or long-term climatic adjustment—if they are shorter in duration than the
 103–105-year timescales of ^{10}Be recovery in soil and saprolite (Reed et al., 2023; Godard et al., 2025).

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More work is needed to understand the influence of recovery after disturbance on soil production functions. However, it stands
 to reason that some of the observed variability in slopes and intercepts of published soil production functions may arise from
 disturbance history rather than from fundamental differences in soil-production processes. Measuring cosmogenic nuclides in
 two samples rather than one can help distinguish between competing explanations and strengthen interpretations of erosion,
 265 weathering, and landscape evolution.

Code and data availability

The data supporting this study, including measured cosmogenic nuclide concentrations, site characteristics, and calculated soil
 erosion and production rates, are provided in the supplementary dataset (Excel file). These data will be archived in Zenodo
 prior to final acceptance (insert DOI here). The MATLAB scripts used to model ^{10}Be depth profiles and soil production
 270 function disturbances are publicly available through GitHub (<https://github.com/nlweinheimer/TestingForSteadyStateSoils>).
 The version used in this study will be archived in Zenodo as version 1.0.0 prior to final acceptance (insert DOI here). The lidar
 data used to produce the study figures are available from OpenTopography as the Calhoun Critical Zone Observatory 2014
 Leaf On Survey (<https://doi.org/10.5069/G9125QK4>).

Supplement link

275 The supplement is available online.

Author contributions

N.W., C.L., C.R., L.S., and R.C. conceptualized the study and developed the methodology. N.W. and C.R. developed the
 software and performed the formal analysis. N.W., C.L., C.R., and L.S. validated the results. N.W., C.L., C.R., L.S., RC, DR,
 and K.N. conducted the investigation. N.W., C.L., C.R., D.R., and K.N. provided resources, and N.W., C.L., C.R., R.C., D.R.,
 280 and K.N. curated the data. N.W., C.R., and L.S. prepared the visualizations. N.W., C.R., and R.C. supervised the research, and
 C.R. administered the project. N.W., C.L., C.R., L.S., S.M., W.S.H., and K.N. acquired funding. N.W., C.L., C.R., and L.S.



prepared the original manuscript draft. N.W., C.L., C.R., L.S., R.C., S.M., D.R., and W.S.H. reviewed and edited the manuscript.

Competing interests

285 The authors declare there are no conflicts of interest for this manuscript.

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References

- 305 Bacon, A. R., Richter, D. D., Bierman, P. R., and Rood, D. H.: Coupling meteoric ^{10}Be with pedogenic losses of ^9Be to improve soil residence time estimates on an ancient North American interfluvium, *Geology*, 40, 847–850, <https://doi.org/10.1130/G33449.1>, 2012.
- Byun, J., Heimsath, A. M., Seong, Y. B., and Lee, S. Y.: Erosion of a high-altitude, low-relief area on the Korean Peninsula: implications for its development processes and evolution, *Earth Surf. Proc. Land.*, 40, 1730–1745, <https://doi.org/10.1002/esp.3749>, 2015.
- 310 Corbett, L. B., Bierman, P. R., and Rood, D. H.: An approach for optimizing in situ cosmogenic ^{10}Be sample preparation, *Quat. Geochronol.*, 33, 24–34, <https://doi.org/10.1016/j.quageo.2016.02.001>, 2016.
- Coughlan, M. R., Nelson, D. R., Lonneman, M., and Block, A. E.: Historical Land Use Dynamics in the Highly Degraded Landscape of the Calhoun Critical Zone Observatory, *Land*, 6, 32, <https://doi.org/10.3390/land6020032>, 2017.
- 315 Dietrich, W., Bellugi, D., Sklar, L. S., Stock, J., Heimsath, A., and Roering, J.: Geomorphic transport laws for predicting landscape form and dynamics, in: *Prediction in Geomorphology*, edited by: Wilcock, P. R. and Iverson, R. M., 103–132, <https://doi.org/10.1029/135GM09>, 2003.
- Dixon, J. L., Heimsath, A. M., and Amundson, R.: The critical role of climate and saprolite weathering in landscape evolution, *Earth Surf. Proc. Land.*, 34, 1507–1521, <https://doi.org/10.1002/esp.1836>, 2009.
- 320 Doetterl, S., Berhe, A. A., Nadeu, E., Wang, Z., Sommer, M., and Fiener, P.: Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes, *Earth-Sci. Rev.*, 154, 102–122, <https://doi.org/10.1016/j.earscirev.2015.12.005>, 2016.
- Ferrier, K. L., Kirchner, J. W., and Finkel, R. C.: Weak influences of climate and mineral supply rates on chemical erosion rates: Measurements along two altitudinal transects in the Idaho Batholith, *J. Geophys. Res.-Earth*, 117, <https://doi.org/10.1029/2011JF002231>, 2012.
- 325 Foster, M. A., Anderson, R. S., Wyshnytzky, C. E., Ouimet, W. B., and Dethier, D. P.: Hillslope lowering rates and mobile-regolith residence times from in situ and meteoric ^{10}Be analysis, Boulder Creek Critical Zone Observatory, Colorado, *Geol. Soc. Am. Bull.*, 127, 862–878, <https://doi.org/10.1130/B31115.1>, 2015.
- Furbish, D. J., Schumier, R., and Keen-Zebert, A.: The rarefied (non-continuum) conditions of tracer particle transport in soils, with implications for assessing the intensity and depth dependence of mixing from geochronology, *Earth Surf. Dynam.*, 6, 1169–1202, <https://doi.org/10.5194/esurf-6-1169-2018>, 2018.
- 330 Gabet, E. J., Reichman, O. J., and Seabloom, E. W.: The Effects of Bioturbation on Soil Processes and Sediment Transport, *Annu. Rev. Earth Planet. Sci.*, 31, 249–273, <https://doi.org/10.1146/annurev.earth.31.100901.141314>, 2003.
- Geyman, E. C., Paige, D. A., and Lamb, M. P.: The contribution of rock strength to soil production, *Nature*, 647, 921–927, <https://doi.org/10.1038/s41586-025-09751-z>, 2025.
- 335



- Gilbert, G. K.: Geology of the Henry Mountains, Government Printing Office, Washington, D.C., <https://doi.org/10.3133/70038096>, 1877.
- Godard, V., Siame, L. L., Salgado, A. A. R., and ASTER Team: Erosional Response to Pleistocene Climate Changes in the Brazilian Highlands, *J. Geophys. Res.-Earth*, 129, e2024JF007671, <https://doi.org/10.1029/2024JF007671>, 2024.
- 340 Godard, V., Mudd, S. M., and Attal, M.: Constraining the global variations in denudation rates associated with the last post-glacial transition, *Earth Surf. Proc. Land.*, 50, e70181, <https://doi.org/10.1002/esp.70181>, 2025.
- Granger, D. E. and Riebe, C. S.: Cosmogenic Nuclides in Weathering and Erosion, in: *Treatise on Geochemistry*, vol. 5, Elsevier, 1–43, <https://doi.org/10.1016/B978-008043751-4/00238-8>, 2007.
- Gray, H. J., Jain, M., Sawakuchi, A. O., Mahan, S. A., and Tucker, G. E.: Luminescence as a Sediment Tracer and Provenance
 345 Tool, *Rev. Geophys.*, 57, 987–1017, <https://doi.org/10.1029/2019RG000646>, 2019.
- Harrison, E. J., Willenbring, J., and Brocard, G.: Global rates of soil production independent of soil depth, *EarthArXiv* [preprint], <https://doi.org/10.31223/X5B30J>, 2021.
- Heimsath, A. M., Dietrich, W. E., Nishiizumi, K., and Finkel, R. C.: The soil production function and landscape equilibrium, *Nature*, 388, 358–361, <https://doi.org/10.1038/41056>, 1997.
- 350 Heimsath, A. M., Chappell, J., Dietrich, W. E., Nishiizumi, K., and Finkel, R. C.: Soil production on a retreating escarpment in southeastern Australia, *Geology*, 28, 787–790, [https://doi.org/10.1130/0091-7613\(2000\)28%3C787:SPOARE%3E2.0.CO;2](https://doi.org/10.1130/0091-7613(2000)28%3C787:SPOARE%3E2.0.CO;2), 2000.
- Heimsath, A. M., Chappell, J., Dietrich, W. E., Nishiizumi, K., and Finkel, R. C.: Late Quaternary erosion in southeastern Australia: a field example using cosmogenic nuclides, *Quat. Int.*, 83–85, 169–185, [https://doi.org/10.1016/S1040-6182\(01\)00038-6](https://doi.org/10.1016/S1040-6182(01)00038-6), 2001a.
- 355 Heimsath, A. M., Dietrich, W. E., Nishiizumi, K., and Finkel, R. C.: Stochastic processes of soil production and transport: erosion rates, topographic variation and cosmogenic nuclides in the Oregon Coast Range, *Earth Surf. Proc. Land.*, 26, 531–552, <https://doi.org/10.1002/esp.209>, 2001b.
- Heimsath, A. M., Furbish, D. J., and Dietrich, W. E.: The illusion of diffusion: Field evidence for depth-dependent sediment
 360 transport, *Geology*, 33, 949–952, <https://doi.org/10.1130/G21868.1>, 2005.
- Heimsath, A. M., DiBiase, R. A., and Whipple, K. X.: Soil production limits and the transition to bedrock-dominated landscapes, *Nat. Geosci.*, 5, 210–214, <https://doi.org/10.1038/ngeo1380>, 2012.
- Heimsath, A. M., Chadwick, O. A., Roering, J. J., and Levick, S. R.: Quantifying erosional equilibrium across a slowly eroding, soil mantled landscape, *Earth Surf. Proc. Land.*, 45, 499–510, <https://doi.org/10.1002/esp.4725>, 2020.
- 365 Hippe, K., Jansen, J. D., Skov, D. S., Lupker, M., Ivy-Ochs, S., Kober, F., Zellinger, G., Capriles, J. M., Christl, M., Maden, C., Vockenhuber, C., and Egholm, D. L.: Cosmogenic in situ ^{14}C - ^{10}Be reveals abrupt Late Holocene soil loss in the Andean Altiplano, *Nat. Commun.*, 12, 2546, <https://doi.org/10.1038/s41467-021-22825-6>, 2021.



- Holbrook, W. S., Marcon, V., Bacon, A. R., Brantley, S. L., Carr, B. J., Flinchum, B. A., Richter, D. D., and Riebe, C. S.: Links between physical and chemical weathering inferred from a 65-m-deep borehole through Earth's critical zone, *Sci. Rep.*, 9, 4495, <https://doi.org/10.1038/s41598-019-40819-9>, 2019.
- Humphreys, G. S. and Wilkinson, M. T.: The soil production function: A brief history and its rediscovery, *Geoderma*, 139, 73–78, <https://doi.org/10.1016/j.geoderma.2007.01.004>, 2007.
- Knudsen, M. F., Egholm, D. L., and Jansen, J. D.: Time-integrating cosmogenic nuclide inventories under the influence of variable erosion, exposure, and sediment mixing, *Quat. Geochronol.*, 51, 110–119, <https://doi.org/10.1016/j.quageo.2019.02.005>, 2019.
- Kohl, C. P. and Nishiizumi, K.: Chemical isolation of quartz for measurement of in situ-produced cosmogenic nuclides, *Geochim. Cosmochim. Acta*, 56, 3583–3587, [https://doi.org/10.1016/0016-7037\(92\)90401-4](https://doi.org/10.1016/0016-7037(92)90401-4), 1992.
- Larsen, I. J., Almond, P. C., Eger, A., Stone, J. O., Montgomery, D. R., and Malcolm, B.: Rapid Soil Production and Weathering in the Southern Alps, New Zealand, *Science*, 343, 637–640, <https://doi.org/10.1126/science.1244908>, 2014.
- Larsen, I. J., Eger, A., Almond, P. C., Thaler, E. A., Rhodes, J. M., and Prasicek, G.: The influence of erosion and vegetation on soil production and chemical weathering rates in the Southern Alps, New Zealand, *Earth Planet. Sc. Lett.*, 608, 118036, <https://doi.org/10.1016/j.epsl.2023.118036>, 2023.
- Lifton, N., Wilson, J., and Koester, A.: Technical note: Studying lithium metaborate fluxes and extraction protocols with a new, fully automated in situ cosmogenic ^{14}C processing system at PRIME Lab, *Geochronology*, 5, 361–375, <https://doi.org/10.5194/gchron-5-361-2023>, 2023.
- Marshall, J. A., Roering, J. J., Bartlein, P. J., Gavin, D. G., Granger, D. E., Rempel, A. W., Praskievicz, S. J., and Hales, T. C.: Frost for the trees: Did climate increase erosion in unglaciated landscapes during the late Pleistocene?, *Sci. Adv.*, 1, e1500715, <https://doi.org/10.1126/sciadv.1500715>, 2015.
- Marshall, J. A., Roering, J. J., Gavin, D. G., and Granger, D. E.: Late Quaternary climatic controls on erosion rates and geomorphic processes in western Oregon, USA, *Geol. Soc. Am. Bull.*, 129, 715–731, <https://doi.org/10.1130/B31509.1>, 2017.
- McGlone, M. S. and Basher, L.: Holocene vegetation change at treeline, Cropp Valley, Southern Alps, New Zealand, in: *Peopled landscapes: Archaeological and biogeographic approaches to landscapes*, edited by: Haberle, S. G. and David, B., ANU E Press, 343–358, <https://doi.org/10.22459/TA34.01.2012.16>, 2012.
- Mudd, S. M.: Detection of transience in eroding landscapes, *Earth Surf. Proc. Land.*, 42, 24–41, <https://doi.org/10.1002/esp.3923>, 2017.
- Norton, K. P., Molnar, P., and Schlunegger, F.: The role of climate-driven chemical weathering on soil production, *Geomorphology*, 204, 510–517, <https://doi.org/10.1016/j.geomorph.2013.08.030>, 2014.
- Owen, J. J., Amundson, R., Dietrich, W. E., Nishiizumi, K., Sutter, B., and Chong, G.: The sensitivity of hillslope bedrock erosion to precipitation, *Earth Surf. Proc. Land.*, 36, 117–135, <https://doi.org/10.1002/esp.2083>, 2011.
- Pelletier, J. D.: Quantifying the controls on potential soil production rates: a case study of the San Gabriel Mountains, California, *Earth Surf. Dynam.*, 5, 479–492, <https://doi.org/10.5194/esurf-5-479-2017>, 2017.



- Phillips, J. D.: The convenient fiction of steady-state soil thickness, *Geoderma*, 156, 389–398, <https://doi.org/10.1016/j.geoderma.2010.03.008>, 2010.
- Reed, M. M., Ferrier, K. L., and Perron, J. T.: Modeling Cosmogenic Nuclides in Transiently Evolving Topography and
 405 Chemically Weathering Soils, *J. Geophys. Res.-Earth*, 128, e2023JF007201, <https://doi.org/10.1029/2023JF007201>, 2023.
- Reusser, L., Bierman, P., and Rood, D.: Quantifying human impacts on rates of erosion and sediment transport at a landscape scale, *Geology*, 43, 171–174, <https://doi.org/10.1130/G36272.1>, 2015.
- Richter, D.: Lidar survey of the Calhoun Critical Zone Observatory, SC 2014, National Center for Airborne Laser Mapping (NCALM), OpenTopography [data set], <https://doi.org/10.5069/G9125QK4> (last access: 25 May 2023), 2014.
- 410 Richter, D. D., Bacon, A. R., Billings, S. A., Binkley, D., Buford, M., Callahan, M. A., Curry, A. E., Fimmen, R. L., Grandy, A. S., Heine, P. R., Hofmockel, M., Jackson, J. A., LeMaster, E., Li, J., Markewitz, D., Mobley, M. L., Morrison, M. W., Strickland, M. S., Waldrop, T., and Wells, C. G.: Evolution of Soil, Ecosystem, and Critical Zone Research at the USDA FS Calhoun Experimental Forest, in: *USDA Forest Service Experimental Forests and Ranges: Research for the Long Term*, edited by: Hayes, D. C., Stout, S. L., Crawford, R. H., and Hoover, A. P., Springer, New York, NY, 405–433,
 415 https://doi.org/10.1007/978-1-4614-1818-4_18, 2014.
- Richter, D. D., Eppes, M.-C., Austin, J. C., Bacon, A. R., Billings, S. A., Brecheisen, Z., Ferguson, T. A., Markewitz, D., Pachon, J., Schroeder, P. A., and Wade, A. M.: Soil production and the soil geomorphology legacy of Grove Karl Gilbert, *Soil Sci. Soc. Am. J.*, 84, 1–20, <https://doi.org/10.1002/saj2.20030>, 2020.
- Riebe, C. S., Hahm, W. J., and Brantley, S. L.: Controls on deep critical zone architecture: a historical review and four testable
 420 hypotheses, *Earth Surf. Proc. Land.*, 42, 128–156, <https://doi.org/10.1002/esp.4052>, 2017.
- Riggins, S. G., Anderson, R. S., Anderson, S. P., and Tye, A. M.: Solving a conundrum of a steady-state hilltop with variable soil depths and production rates, Bodmin Moor, UK, *Geomorphology*, 128, 73–84, <https://doi.org/10.1016/j.geomorph.2010.12.023>, 2011.
- Roering, J. J., Marshall, J., Booth, A. M., Mort, M., and Jin, Q.: Evidence for biotic controls on topography and soil production,
 425 *Earth Planet. Sc. Lett.*, 298, 183–190, <https://doi.org/10.1016/j.epsl.2010.07.040>, 2010.
- Small, E. E., Anderson, R. S., and Hancock, G. S.: Estimates of the rate of regolith production using ^{10}Be and ^{26}Al from an alpine hillslope, *Geomorphology*, 27, 131–150, [https://doi.org/10.1016/S0169-555X\(98\)00094-4](https://doi.org/10.1016/S0169-555X(98)00094-4), 1999.
- Sweeney, K. E., Roering, J. J., Almond, P., and Reckling, T.: How steady are steady-state landscapes? Using visible–near-infrared soil spectroscopy to quantify erosional variability, *Geology*, 40, 807–810, <https://doi.org/10.1130/G33167.1>, 2012.
- 430 van der Meij, W. M., Riedesel, S., and Reimann, T.: Mixed Signals: interpreting mixing patterns of different soil bioturbation processes through luminescence and numerical modelling, *SOIL*, 11, 51–66, <https://doi.org/10.5194/soil-11-51-2025>, 2025.
- Wilkinson, M. T., Chappell, J., Humphreys, G. S., Fifield, K., Smith, B., and Hesse, P.: Soil production in heath and forest, Blue Mountains, Australia: influence of lithology and palaeoclimate, *Earth Surf. Proc. Land.*, 30, 923–934, <https://doi.org/10.1002/esp.1254>, 2005.



- 435 Yang, Y., Cui, L., Xu, S., Cao, Z., Zhang, S., and Liu, C.: Deciphering non-steady landscape evolution by in-situ cosmogenic nuclide depth profile, *Sci. China Earth Sci.*, 65, 490–502, <https://doi.org/10.1007/s11430-021-9856-x>, 2022.