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Landform evolution modelling using transitional soil moisture content-modifying factors for erodibility

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Abstract

In this study, the long-term stability of a closure landform was evaluated in a landform evolution model (LEM) that permits soil erodibility parameters to change with soil moisture. Recent advances in soil mechanics indicate soil erodibility is a function of soil moisture and may increase by up to a thousandfold as soils dry. Therefore, including soil moisture erodibility feedback in LEMs is especially important for evaluating long-term closure stability under climate change, as warming climates are expected to result in a long-term decrease in soil moisture. For the analysis, mean annual erosion rates from a 30 m-tall by 500 m-square plateau with 1V:3H side slopes were computed from a LEM using meteorological data from Central Queensland, Australia, and published soil erodibility measurements. Including soil moisture-erodibility feedback increased mean annual erosion rates by more than tenfold as compared to the LEM run assuming constant soil erodibility.

Additional soil erosion measurements from closure structures at various soil moisture conditions are needed as the soil erodibility data utilised results from laboratory-compacted soils. That said, an increase in erosion rates following drying of soils is consistent with many field-based studies of erodibility. Accounting for the soil moisture erodibility feedback in LEM predictions is important because LEMs are especially sensitive to soil erodibility-related parameters (i.e. soil detachment rate and critical shear stress). Furthermore, the dependency of erodibility on soil moisture is important to note in subtropical climates where significant wetting and drying of mechanically placed soils can result in the degradation of soil structure and increases in soil erodibility with time.

Results of this work indicate that wetting and drying of closure landform soils may reduce the long-term stability of closure landforms, especially for climates expected to warm into the coming decades. Establishing vegetation cover is expected to stabilise mechanically placed soils from degradation caused by wetting and drying cycles. Furthermore, since soil erodibility is strongly affected by soil moisture and changes in vegetation cover, accounting for these changes in LEMs may be needed to assess the long-term stability of closure landforms more accurately under climate change.

Keywords: *landform, landform evolution model, soil moisture, soil erosion*

1 Introduction

Landform evolution models (LEM) are increasingly utilised to assess the long-term stability of post-mining closure landforms under future climate scenarios (e.g. Khalifa et al. 2023). When using numerical models that integrate over time, such as LEMs, removing numerical bias is critical for accurate long-term predictions because model bias compounds with time (Livsey et al. 2020; Chen et al. 2025). Model bias in numerical methods may arise for numerous reasons but will especially arise if numerical results are especially sensitive to nonstationary parameters that are presumed constant.

Relevant to LEMs, the sensitivity of model results to erodibility parameters has long been recognised (Davy & Lague 2009); however, soil erodibility is generally held constant during model simulation (Shmilovitz et al.

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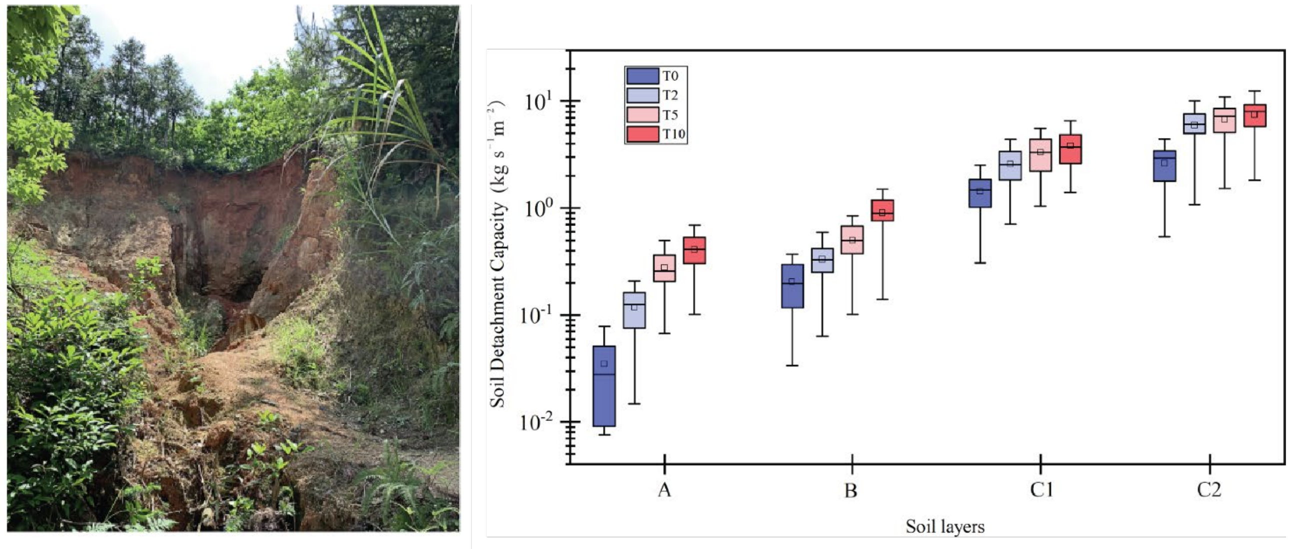
2025). To the authors' knowledge, no LEM has been implemented wherein changes in soil erodibility with soil moisture has been considered. This omission is critical to note since numerous field and laboratory studies indicate that soil erodibility is strongly impacted by wetting and drying cycles (Zhou et al. 2021; Tohm 2025) and soil moisture (Livsey et al. 2025 and references therein). Wetting and drying cycles may impact erodibility through changes in soil structure (Figure 1; Zhou et al. 2021) and especially affects mechanically placed soils (Tohm 2025), such as those found in closure landforms.

In this study, the long-term stability of a closure landform was evaluated in LandLab, an open-source LEM (Shobe et al. 2017), that permits soil erodibility parameters to change with soil moisture. The soil moisture-erodibility feedback was considered because soil moisture is declining over much of the globe and is expected to decline into the coming decades, with declines enhanced by warming and drying climates (Liu et al 2025). Furthermore, recent advances in soil mechanics indicate soil erodibility is a function of soil moisture and may increase by up to a thousandfold as soils dry, even with no change in soil density or porosity (Livsey et al. 2025).



(a) (b)

Figure 1 (a) Gully erosion; (b) Gully enhanced by wetting and drying of soils and an increase in soil erodibility (Modified from Zhou et al. 2023)

2 Methods

For the analysis, mean annual erosion rates from a 30 m-tall by 500 m-square plateau with 1V:3H side slopes were computed from LandLab, an open-source LEM (Shobe et al. 2017), using meteorological data from Central Queensland, Australia, and published soil erodibility measurements. Grid cell size was set to 10 m × 10 m. The slope on the top of the idealised landform was set to 1V:100H. The geometry of the closure landform is idealised only but is typical of the authors' experience.

The landform evolution model of Shobe et al (2017) was utilised assuming no threshold stream power for soil detachment and no bedrock in the closure landform. Applying these assumptions to the LEM of Shobe et al (2017) yields:

$$\frac{\delta\eta}{\delta t} = \frac{\delta H}{\delta t} = \frac{D_s - E_s}{1 - \phi} \tag{1}$$

$$E_s = K_s q^m S^n \tag{2}$$

$$D_s = c_s \omega_s \tag{3}$$

where:

η = landform elevation (m)

t = time(s)

H = soil thickness (m)

D_s = the deposition rate of suspended sediment (m/s)

c_s = a dimensionless suspended sediment concentration computed from volumetric sediment flux divided by volumetric water flux (-)

ω_s = effective settling velocity of suspended sediment (m/s)

E_s = the erosion rate of suspended sediment (m/s)

ϕ = the porosity of the bed sediment (-)

K_s = the sediment erodibility parameter (units vary, herein 1/m)

q = unit charge (m^2/s)

S = channel-bed slope

m and n = scaling exponents.

For this study, nominal values of m and n were utilised (1 and 0.5, respectively) – see Davy & Lague (2009) and references therein – yielding units of 1/m for the sediment erodibility parameter (K_s).

The LandLab sediment transport component of Shobe et al (2017) was utilised because the open-source code could be readily changed to account for spatiotemporal changes in the sediment erodibility parameter (K_s). Equations 1 to 3 are consistent with the SIBERIA LEM; however, SIBERIA does not directly account for deposition by computing suspended sediment concentration (c_s) or setting suspended sediment settling velocity (ω_s; Hancock et al. 2017). Rather, the SIBERIA LEM accounts for deposition by computing gradients in sediment flux across the model domain. Herein we assume all suspended sediment is comprised of clay and silt, and utilise a nominal value of 0.33 mm/s for suspended sediment settling velocity (ω_s) per Lamb et al (2020).

Discharge was computed using the flow router algorithm of Holmgren (1994) with discharge driven by stochastic rainfall time series generated from CoSMoS-2s, an R package from Papalexiou (2022). CoSMoS-2s provides fitting methods and stochastic time series generation to provide synthetic rainfall time series that reproduce rainfall properties and wet/dry periods characteristic of observed data. Fifty years of hourly rainfall data from (Hersbach et al. 2023) for an undisclosed project site in Central Queensland was fit using CoSMoS-2s and used to generate 100 years of synthetic hourly rainfall data for model simulations. Rainfall was distributed uniformly across the model domain.

For all model runs, a 12-hr timestep was utilised with hourly rainfall data aggregated over the 12-hr timestep. Individual storms were defined by periods when no rainfall occurred within a 6-hour time frame. Changes in soil moisture were computed using the single moisture layer model of Laio et al (2001), where surface soil moisture is computed as a function of initial soil moisture, rainfall amount, storm duration, inter-storm duration (time between storms) and potential evapotranspiration (PET). A reference PET rate of 8 mm/day was assumed; a rate characteristic of annual rates in Central Queensland (Bureau of Meteorology 2026).

Sediment erodibility (K_s) was computed as a function of soil moisture (θ_v) using erosion test data from Livsey et al (2025) and assuming an active layer (δ_a) depth for the single moisture layer model. Below the active layer, soil moisture is assumed to be near saturation and K_s is not changed; while above the active layer depth, changes in wetting and drying cycles affect soil structure (Tohm 2025). Per Australian Standard (AS) 2870, changes in soil moisture that impact soil matric suction may extend to 3 m in dry temperate regions of Australia. For all model scenarios a constant nominal value of 1.5 m was used for the active layer depth (δ_a); a value expected to be conservative for impacts of changes in soil moisture on soil erodibility, given the expected variability in suction change from AS 2870 and published works cited in Tohm (2025).

Livsey et al (2025) provide laboratory measurements of changes in cohesive soil sediment erodibility as function of soil moisture for 2 cohesive soils (a lean clay and a fat clay). Livsey et al. (2025) utilised the so-called excess shear stress equation for erosion rate:

$$E_s = k_d(\tau_b - \tau_c)^{\alpha} \tag{4}$$

where:

k_d = a detachment coefficient (m^3/(N-s))

τ_b = boundary shear stress (Pa)

τ_c = critical shear stress (Pa)

α = an empirical exponent [assumed one in Livsey et al (2025)].

$K_s \propto k_d$ and under simplifying assumptions (α = 1, m = 1, n = 0.5 and $\tau_b \gg \tau_c$), K_s is equivalent to k_d [Davy & Lague (2009)]; therefore, instead of implementing Equation 4 in the LEM, a reference soil erodibility, denoted by K_{so}, was computed by tuning a 3-year model run to provide a reference annual erosion rate of 12.5 t/ha/year – a target erosion rate commonly utilised in Australia closure projects (Khalifa et al. 2023). For tuning K_{so}, all other model parameters were held constant and the parameter was manually adjusted to achieve an annual erosion rate of 12.5 t/ha/year. K_{so} represents the erodibility of soil as measured in laboratory or field erosion tests where the soil has yet to undergo wetting and drying cycles (e.g. an erodibility coefficient computed from test data on as-compacted soils at or above optimum moisture content).

For model runs that permit soil erodibility to vary as a function of soil moisture, $K_s(\theta_v)$ was computed using:

$$K_s(S) = K_{so}\frac{k_d(S)}{k_d(S_{max})} \tag{5}$$

where:

S = the degree of saturation (i.e. $S = \frac{\theta_v}{\phi}$).

K_{so} is the tuned K_s that provides the reference annual erosion rate of 12.5 metric tonnes per hectare per year (i.e. 3.3e–5/m) for a 3-year model run. $\frac{k_d(S)}{k_d(S_{max})}$ is taken from the lean clay data of Livsey et al (2025) with the ratio of k_d at degree of saturation (S) relative to the k_d at the maximum degree of saturation tested (S = 0.98). $\frac{k_d(S)}{k_d(S_{max})}$ from laboratory testing was utilised to model $K_s(\theta_v)$ due to a lack of field-test data; that said, Equation 5 is expected to be a reasonable first-order approximation as $K_s \propto k_d$. Threshold shear stress was not considered as a simplifying assumption, but this term could be included in future work as critical shear stress decreased with decreasing soil moisture (Livsey et al. 2025).

2.1 Model runs

To evaluate the sensitivity of the LEM to soil erosion feedback, 100-year model simulation runs were conducted for the following cases: case A (LEM with no soil erosion feedback), case B (LEM with soil erosion feedback) and case C (LEM with soil erosion feedback and climate change) (Table 1). To simulate the impact of climate change on soil moisture and soil erodibility, a 10% linear increase in PET was assumed for case C. To assess the sensitivity of model runs to δ_a, δ_a was held constant for 100-year simulations but varied between 0.01 and 4 m for separate model runs for case D. All model runs used the same rainfall time series.

Table 1 Model scenarios and key assumptions

Scenario label	Scenario name	Sediment erodibility ($K_s{}^1$) (1/m) used in Equation (Eq) 2	Active layer depth (δ_a) (m)	Potential evapotranspiration (PET) (mm/year)
Case A	LEM with no soil erosion feedback	K_{so}	Not applicable	Not applicable
Case B	LEM with soil erosion feedback	$K_s(S)$ (Eq 5)	1.5	Constant
Case C	LEM with soil erosion feedback and climate change	$K_s(S)$ (Eq 5)	1.5	Linear increase with time
Case D	LEM with soil erosion feedback but varied δ_a	$K_s(S)$ (Eq 5)	0.01–4	Constant

3 Results

Model run time for case A was 4.3 seconds/year; while model run time for cases B, C and D was near 8 seconds/year for all cases. Including a soil moisture feedback (cases B and C) increases mean annual erosion rates by roughly fiftyfold (Table 2; Figures 2 and 3). Including a 10% increase in PET did not significantly affect LEM results, with no difference between cases B and C erodibility at 3-significant digits (Table 2). Lastly, for case D, varying δ_a between 0.01 and 4 m indicates a power function between mean annual erosion rate of between 22.1 and 1,670 t/ha/year (Figure 2). Including a soil erosion feedback resulted in significantly different landforms at the end of model runs (Figure 3), with no perceptible difference between model runs in cases B and C (Figure 4).

Table 2 Mean annual erosion rates for landform evolution model (LEM) scenarios, with all rates computed on 100-year model simulations

Scenario label	Scenario name	Mean annual erosion rate (t/ha/year)
Case A	LEM with no soil erosion feedback	15.5
Case B	LEM with soil erosion feedback	813
Case C	LEM with soil erosion feedback and climate change	813
Case D	LEM with soil erosion feedback but varied δ_a	22.1–1,670

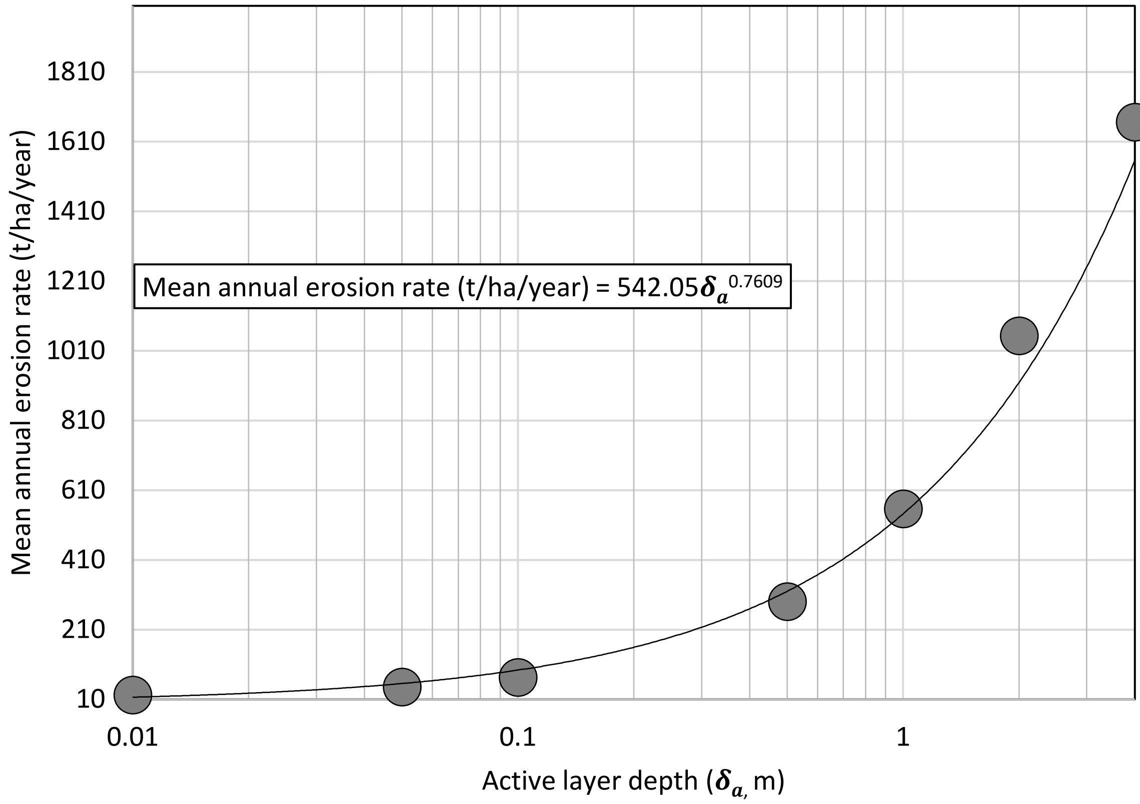


Figure 2 Mean annual erosion rate as a function of active layer depth specified

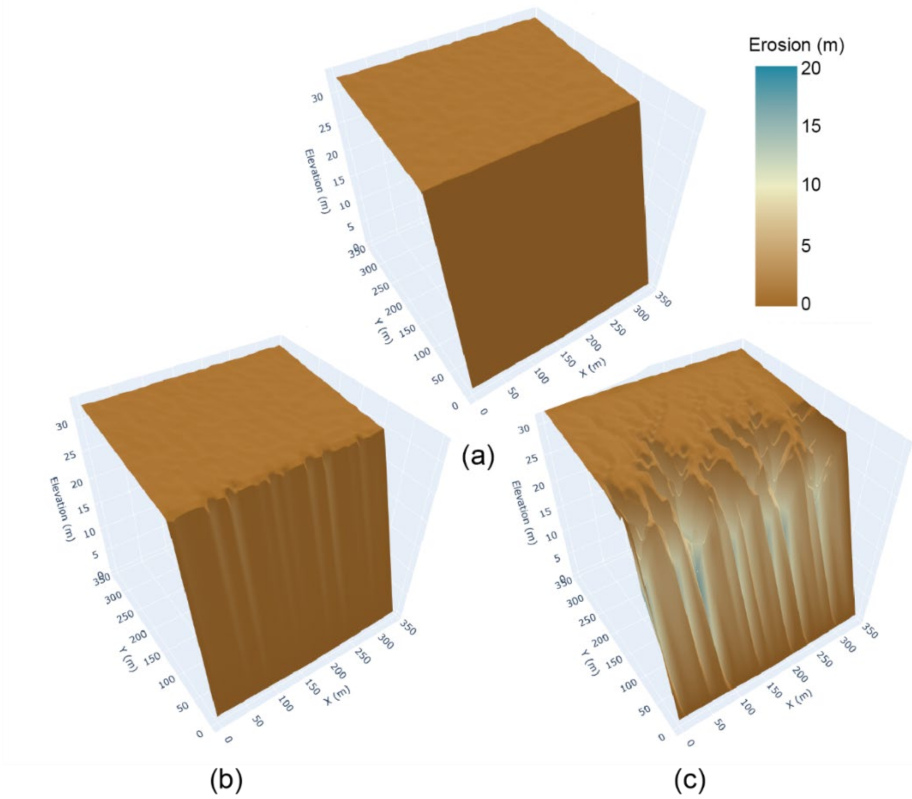


Figure 3 (a) Original closure landform surface used in landscape evolution model (LEM); (b) Post-100-year LEM simulation with no soil erosion feedback (Case A); (c) Post-100-year LEM simulation with soil erosion feedback (Case B). X and Y indicate LEM domain coordinates.

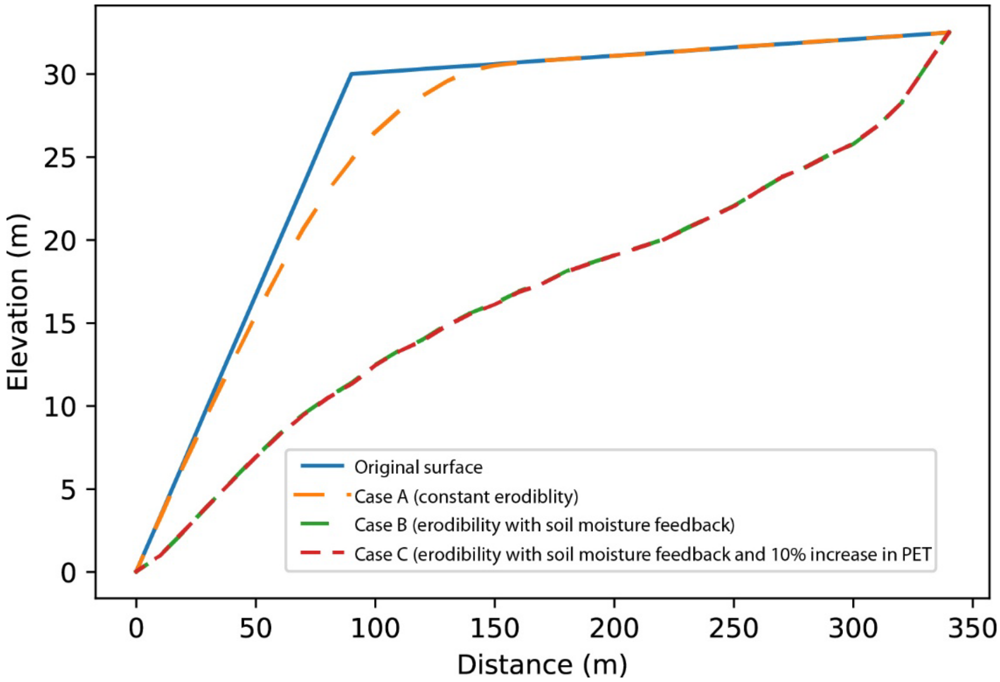


Figure 4 Closure landform profiles following 100 years of model simulation for cases A, B and C. Profiles shown are the minimum elevation across all grid cells on the X-axis

4 Discussion

Including a soil moisture erosion feedback in LEMs is considered reasonable given: (1) the sensitivity of model results to soil moisture and active layer depth (Table 2; Figures 3 and 4), (2) field observations of wetting and drying impacts on mechanically placed soils (Tohm 2025), and (3) advances in soil mechanics that link soil moisture and soil erodibility (Livsey et al. 2025). The difference between cases A and B is consistent with field observations where erosion in the field following site material placement is much higher than expected (Tohm 2025). This difference is expected to be driven by processes in the active layer wherein wet and dry cycles affect soil structure and soil moisture, especially for mechanically placed soils.

Future modelling work will aim to couple a multilayer soil moisture model for the simulation of changes in soil erodibility with depth and incorporate seasonal variability in PET. Numerical modelling with a LEM coupled to a multilayered soil moisture model may affect how mean annual erosion rate increases with active layer depth and also affect model sensitivity to an increase in PET.

Lack of model sensitivity to an increase in PET was not expected but may differ for other scenarios and/or other soils as the second term in Equation 5 (i.e. $\frac{k_d(S)}{k_d(S_{max})}$) depends on numerous soil mechanical properties (Livsey et al. 2025). Additional sensitivity analysis across various grid cell sizes, temporal resolution and parameter ranges is needed (e.g. Coulthard & Skinner 2016; Skinner et al. 2018; Skinner & Coulthard 2022). Furthermore, no vegetation cover was assumed in the LEM; considering changes in vegetation cover and vegetation-soil moisture feedback could affect model results.

6 Conclusion

Results of this work indicate that considering the wetting-drying cycles in erosion and landform evolution models (LEMs) may be needed, especially for climates expected to warm into the coming decades and in landforms where soils have been mechanically placed. Modelling the dependency of erodibility on soil moisture is important to note for landforms built of mechanically placed soils because wetting and drying can result in degradation of soil structure and increases in soil erodibility with time. Although naturally structured soils are not expected to exhibit the same increase in soil erodibility as with decreasing soil moisture as mechanically placed soils; field-based measurements cited herein indicate an increase in soil erodibility with wetting and drying cycles. If soil erodibility is strongly affected by soil moisture and/or changes in vegetation cover, accounting for these changes in LEMs may be needed to assess the long-term stability of closure landforms more accurately under climate change.

Establishment of vegetation cover is expected to reduce the degradation of mechanically placed soils with wetting and drying. The substantial increase in predicted erosion rates with drying soil is consistent with laboratory and field-based measurements; however, incorporating vegetation is expected to reduce the sensitivity of soil erodibility to changes in soil moisture. Due to a lack of field-based measurements, the effect of including vegetation on model results was not evaluated. Additional laboratory and, especially, field-based soil erosion measurements for various soil moisture conditions, vegetation cover amounts and vegetation cover types are needed as the soil erodibility data from Livsey et al. (2025) utilised results from laboratory-compacted soils with no roots.

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