Wherever a loose bed of sand is subject to sufficiently strong winds, aeolian dunes form at predictable wavelengths and growth rates. As dunes mature and coarsen, however, their growth trajectories become more idiosyncratic; nonlinear effects, sediment supply, wind variability and geologic constraints become increasingly relevant, resulting in complex and history-dependent dune amalgamations. Here we examine a fundamental question: do aeolian dunes stop growing and, if so, what determines their ultimate size? Earth’s major sand seas are populated by giant sand dunes, evolved over tens of thousands of years. We perform a global analysis of the topography of these giant dunes, and their associated atmospheric forcings and geologic constraints, and we perform numerical experiments to gain insight on temporal evolution of dune growth. We find no evidence of a previously proposed limit to dune size by atmospheric boundary layer height. Rather, our findings indicate that dunes may grow indefinitely in principle; but growth depends on morphology, slows with increasing size, and may ultimately be limited by sand supply.
Earth’s major sand seas are often populated with giant dunes, up to hundreds of meters in height and kilometers in wavelength. These massive sediment piles, visible from space on our planet and across the Solar System, indicate that conditions for sand transport have persisted for millennia. Unraveling how giant dunes form therefore has implications for understanding atmospheric flows and climatic stability. The initial wavelength and growth rate of aeolian dunes from a flat sand bed are well understood; aerodynamic theory developed for idealized conditions has recently been extended and successfully applied to predict dune formation in nature1–3. Once dunes grow large enough to perturb the flow nonlinearly, however, size regulation becomes more complicated. Dunes calve and merge through collisions and wake interactions4,5; but the net effect is pattern coarsening through time6–9. Is there any limit to the size that aeolian dunes can grow, besides time? One elegant hypothesis is that the size of giant dunes is limited by the averaged mixed layer height (MLH), where a stable resonance condition is found between topographic and capping-layer waves7. This prediction is appealing because it suggests a general and physical (rather than site specific and geological) control by atmospheric forcing, and that the scale of giant dunes can be used to infer the MLH on other planets10. An alternative hypothesis, however, is that dune growth just slows logarithmically with time, as dunes grow larger and their migration rates diminish9. As real dune fields evolve over century and longer timescales, additional site-specific boundary conditions have been suggested to exert a control on dune size11,12: sediment supply, geologic constraints, wind variability, and climatic stability. Neither the MLH control, or the logarithmic slowing hypothesis, have been directly tested in nature.

Results

Observations. Global LANDSAT imagery was used to manually identify and delineate the boundaries of 38 dune fields (Methods). We utilized ERA5 reanalysis data to determine 10-m hourly wind velocity for the 2008–2017 decade on a nominally 32-km horizontal grid13. Potential sand flux (\( \sum \mathbf{q} \)) was estimated from these data with a linear excess stress model that explicitly incorporates an entrainment threshold14,15 (Methods); it is important to note that this corresponds to the saturated sand flux, and true flux could be less if supply is limited. We utilized SRTM ASTER GDEM V3 topography to determine the average dune geometry—wavelength, \( \lambda \), height, \( h \), and width, \( w \)—within each 322-km² tile16 (Figs. 1 and S1; Methods); topographic resolution prohibits detection of dunes with \( \lambda < 100 \) m. Corresponding dune morphology was manually categorized into the canonical types; barchanoid, transverse, linear, and star15,17,18. Taken together, our analysis produces estimates of modern sand flux, and dune geometry and morphology, for 2,093 322-km² tiles on Earth. Where possible, we used published data to estimate dune-field age (Methods). Mixed layer height was determined using all available daytime CALIPSO satellite measurements collected from 2006 to 2019 over each dune field (Methods). These are always collected in the early afternoon, where the boundary layer is convective and most likely to promote sand transport19, but there is still a clearly identifiable delineation between the aerosol-laden mixed layer at the free-atmosphere above20.

We first examine patterns in dune geometry for the global dataset. Although previous studies have documented self-similar scaling of barchan dune geometry21, those observations did not include other dune geometries or giant dunes. Our compiled data show that dune geometry is not self similar for the largest wavelengths, where very high aspect-ratio dunes are observed (Fig. 2a). Plotting width against wavelength produces distinct clouds of data that correspond to dune morphology; barchanoid and star dunes follow a 1:1 line, while linear dunes are the widest and transverse dunes show intermediate behavior (Fig. 2d). Another distinction is that the highest dunes in the dataset (\( \lambda > 100 \) m) are disproportionately represented by star dunes, which also appear to form at large wavelengths22,23 (generally > 1 km) (Fig. 2a). In contrast, aspect-ratio scaling for barchanoid and transverse dunes generally follows observed patterns for subaqueous dunes24,25.

It is well established that dune morphology is a consequence of variability in wind direction: predominantly unidirectional sand flux results in barchanoid and transverse dunes under conditions of relatively low and high sand supply, respectively; oblique and bi-directional sand flux creates linear dunes; and highly variable sand flux directionality gives rise to star dunes15,17,18,26,27. How this variability influences dune geometry and ultimate size, however, has not been fully examined. We compute a flux directionality measure as the ratio of the magnitude of the resultant potential sand flux vector (\( \sum |q| \)) over the absolute potential sand flux (\( \sum q \)) that varies from 0 associated with net-zero flux, to 1 corresponding to unidirectional flux (Fig. 1f). This is similar to the ratio of resultant to absolute so-called ‘drift’ potential18,28 (i.e., RDP/DP). Perhaps unexpectedly, ostensibly unidirectional barchanoid and transverse dunes exhibit a wide

Fig. 1 Extraction of dune geometry and sand flux. a LANDSAT imagery of part of the Namib Sand Sea, one dune field in the dataset. b Hillshade SRTM topography from an example 322-km² tile. c The high-pass autocorrelation of the topography in b overlaid by the extracted characteristic planform dune geometry in black (zoomed inset in yellow defines wavelength \( \lambda \) in magenta and width \( w \) in blue). d Grid of prospective tiles intersecting the dune field (yellow); tiles included in the dataset (where dune geometry can be measured) are colored by mean sand flux \( |q| \) inferred from ERAS 10-m winds. e Probability distribution of local relief \( \delta H \) found by convolution of SRTM topography with a min-max box of width \( x \); the peak marks the characteristic dune height \( \delta H \). f Time-means of the resultant sand flux vector (magenta) and cumulative sand flux vectors (blue) for b; terms denote their lengths, and arrows their directions. g The probability distribution of sand flux directions for b. Black lines denote scale in a, f & g. N is the number of hourly measurements over the decade of ERA5 reanalysis, north is up in a-d, f & g, and magenta boxes in b-d outline the common tile.
dune size; in fact, dune wavelength exceeds MLH for most dune data do not support the proposed control of MLH on limiting between MLH and dune wavelength (Fig. 3b). In other words, among dune height, and its potential control on the size of giant dunes.

These observations suggest that highly variable winds act to “pile up” sand, while more unidirectional winds create lower dunes. We now turn our attention to the dune-field mixed layer height, and its potential control on the size of giant dunes. Although there are seasonal fluctuations in MLH, and variations among dune fields (Fig. 3), the averaged midday MLH H varies little (1 < H < 2 km). Most importantly, we find no correlation between MLH and dune wavelength (Fig. 3b). In other words, data do not support the proposed control of MLH on limiting dune size; in fact, dune wavelength exceeds MLH for most dune fields. To understand why, we must consider the proposed mechanism in light of the atmospheric conditions that give rise to sand transport. The MLH hypothesis assumed that the mixed layer is neutrally stable such that the interface between it and the free-atmosphere at H is a capping interface; in this scenario, large dunes that perturb the flow can excite waves at the interface, which then limit dune wavelength through a resonance condition. While stability conditions that permit this behavior may sometimes occur, our analysis suggests that these conditions are not associated with sand transport. Rather, winds exceeding threshold are typically associated with strong instability; the convection-enhanced mixing that enhances surface wind strength also destroys wave propagation, inhibiting resonance when sand transport occurs (see Text S1 for details).

While our observations are the most comprehensive to date, they still represent only a snapshot in time of the dune coarsening process. Factors important for the evolution of large dunes over millenia, such as sand supply and past variations in wind climate, are completely unconstrained. Further, the central question of what sets aeolian dune height remains unanswered. To access the trajectory of dune growth through time, and isolate and control boundary conditions that influence dune dynamics, we turn to numerical experiments.

Numerical experiments. We perform a suite of numerical experiments using ReSCAL, a model that couples cellular automaton rules for sediment transport with a lattice gas method for turbulent wind. ReSCAL has been shown to produce many salient aspects of aeolian dune dynamics and morphology, and can be quantitatively scaled to nature. Given that the history and boundary conditions of dune fields examined here are not known, however, we do not attempt a quantitative comparison of model runs with field data. Instead, we perform six numerical experiments that essentially bracket the range of Earth’s aeolian landscapes. Model runs conserve sand in a domain that is horizontally periodic. Domain height is set to be sufficiently large that it does not influence dune growth, informed by the lack of MLH control shown previously (Methods).

Fig. 2 Trends in Earth’s aeolian dunes. a Characteristic dune wavelength x and height z for 2,093 322-km tiles. Points and kernel density estimates for each axis colored by type (barchanoid, cyan; transverse, magenta; linear, yellow; star, black), power-laws bounding the distribution given in gray, and a schematic defining x, y and z for an example star dune in upper left. b Flux directionality (i.e., the resultant sand flux magnitude over the sand flux magnitude sum, or purple over blue in Fig. 1f) against dune height z. Points and kernel density estimate colors defined in a. c Dune wavelength x against aspect z/x, points colored by flux directionality using the colorbar above. d Wavelength x against width y colored as in a. The dashed black line marks y = x, by definition points lie above this line. e Dune-field age T against area A for 29 dune fields with a powerlaw $A = c_{\text{mp}} T$ (dot-dashed gray line), where $c_{\text{mp}} = 0.48$ (m/yr) is a representative dune migration rate. Blue points (n = 11) are included in the geometric analysis, red are not. Using the blue points and sharing the age-axis, dune-type ages (mean ± standard deviation) are given above the parametric plot. Red lines in (a, c, d) mark measurement limits.
The initial conditions are flat sand beds of two thicknesses, \( \eta(t = 0) = 3.5 \) m and \( \eta(t = 0) = 35 \) m, to simulate sediment-starved and sediment-saturated systems, respectively. Three forcing regimes are chosen to mimic winds that produce unidirectional (barchanoid and transverse), linear, and star dune forcing regimes are chosen to mimic winds that produce unidirectional (barchanoid and transverse), linear, and star dune

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Discussion

The distilled interpretation of our findings is this: Earth’s giant dunes are growing ever-slower with size, and are not limited in size by MLH generically. This calls into question planetary studies that use the capping layer hypothesis to estimate MLH from observed dune wavelength. Nevertheless, the presence of dune fields still places a strong constraint on atmospheric dynamics: near-surface winds must regularly exceed the entrainment threshold, but not by much, in order to maintain saltation that grows dunes.

With rudimentary knowledge of the composition...
of the atmosphere and the sand grains, the dune-forming wind conditions on other planets may be determined with reasonable confidence37.

Returning to our findings, snapshots of mature dunes in the numerical experiments (taken at $T \geq 500$ yrs) are similar in geometry and morphology to the large dunes populating Earth's sur-
face today. Estimating dune age using available measurements (Methods), we see the four morphologies of dunes have similar mean ages; if anything, star dunes are slightly younger than other large dunes (Table S1, Fig 2e). We conclude that Earth's star and linear dunes, with low flux directionality, are taller because they grow faster; reversing winds act to pile up sand. The numerical experiments also explain other details in the observed data: dune aspect is more sensitive to sediment supply in low flux directionality systems (Figs. 4a and 2c), and ever-slowing coarsening produces the negative skew of dune size probability distributions (Fig. 4a).

But these conclusions leave us with a conundrum: why are there no dunes for $x \geq 2$ km, if they always grow? Coarsening rates for such large dunes are exceedingly slow. Over the millennia required to evolve dunes of this size, we hypothesize that climatic and geologic constraints become limiting. First of all, climate must remain sufficiently arid and windy for dunes to remain unvegetated and active; this becomes increasingly unlikely for timescales longer than the Holocene, i.e., $10^4$ yr38,39. Second of all, sand supply becomes increasingly likely to limit dune growth, as dunes pile sand higher and scour deeper into the substrate; many of the world's giant dunes show signs of sand limitation such as bare non-erodible interdune surfaces.26,34. While perhaps neither satisfying nor surprising,41,11,12,40 our findings suggest that both the size and morphology of Earth's largest dunes are the integrated product of the unique geology and climatic history of each dune field. Nevertheless, universal trends in aeolian dune geometry, and the new relations observed between geometry and morphology, may be used to understand where observed dunes sit in their respective growth trajectories alongside other metrics such as defect density.41.

Our results also contribute to understanding the size of aeolian dune fields themselves.42. Although scattered, we observe a positive trend in dune-field age (T) against area (A) (Fig. 2e), which could imply that dune-field expansion is driven by dune migration19,28. To test this idea, we utilize a representative upper bound on dune migration speeds from the numerical experiments: $c_{epp}$, the mean celery after $t = 500$ yr for all six experiments (Fig. 4d). A first-order advective growth scaling can be anticipated, $\sqrt{A} = c_{epp}T$. The data follow the scaling, which indicates that at least some component of dune-field boundary expansion may be driven by dune migration itself. On the other hand, most dune fields lie above the scaling line, indicating they are larger than implied from expansion by dune migration alone; if true, this would suggest that dune-field size is set by properties of the sand supply11. It seems likely that flux directionality plays some role; in strongly unidirectional cases like White Sands, boundary expansion is clearly related to dune migration33,43 but for stationary fields of star dunes like the southeast Grand Erg Oriental23, sand supply must be the dominant factor.

These findings serve as a springboard for investigating how, and how fast, dunes respond to transient forcing. In particular, how will aeolian landscapes adjust to changing climate, and how does their maturity and history influence this change? We see two features of our data that suggest that dunes can be sluggish relative to changing winds. First is the observation of superimposed dunes, with morphologies that are distinct from the larger dunes they rode on22. This implies that changing wind may not reorient the entire dune, but rather initiate the formation of new (and much smaller) dunes that slowly cannibalize the underlying larger dune as they grow — as observed for fluvial dunes in response to rapid changes in flow44,45. Second is the unexpectedly large variance in flux directionality for ostensibly unidirectional dunes (Fig. 2a), which indicates that many large dunes may have been sculpted by wind conditions that are different from those of the last decade. A rate-and-state framework where dune form, rather than scale, is the measure of landscape adjustment may be useful for understanding dune-field evolution and anticipating dune responses to climate change46.

Methods

Dune-field ages & areas. Dune-field age estimates are found from a literature review38,46 and summarized in Table S2. These data are a subset of the INQUA Dune Atlas. Methods of estimation are from geochemical and optical dating techniques of the sediments beneath dune fields, aeolian accumulation rates and deposit thicknesses, and aerial imagery. Uncertainty in each age is subject to a variety of inconsistent processes and is reported differently across the data aggregation. Dune-field areas are found simply by tracing the dune-field extent in Google Earth using LANDSAT imagery, also provided in Table S2.

Sand flux from ERAS reanalysis. A time-series of 87,672 hourly 10-m winds $U_{10}$ (ensuring from 2008 to 2017 inclusive are transformed into approximate sand flux $\dot{\mathbf{q}} = \mu \chi_{\text{lr}} \sqrt{\dot{\mathbf{q}}}$ (where $\mu$ is a standard and climate-dependent approach using threshold friction velocity. Friction velocity, $u_*$, is calculated as $u_* = \sqrt{\frac{\dot{\mathbf{q}}}{\rho_{\text{air}}}}, \text{log} 10(\dot{\mathbf{q}})$, where $\epsilon$ is 0.41 is von Karman's constant and $z_0 = 10^{-2}$ m is the roughness length at the scale of sand transport43. Next a threshold friction velocity is defined as $u_{\text{crit}} = \sqrt{\dot{\mathbf{q}}}/\rho_{\text{air}}/10$, where $\rho_{\text{air}} = 9.81 \text{ m s}^{-1}$ is gravity acceleration, $d_{30}$ is grain diameter, $\dot{\mathbf{q}} = 2650 \text{ kg m}^{-3}$ sand density and $\rho_{\text{air}} = 1.225 \text{ kg m}^{-3}$ is fluid (air) density, giving $u_{\text{crit}} = 0.252 \text{ m s}^{-1}$ as a representative value45. Finally sand flux magnitude is defined as $\dot{\mathbf{q}}^2 = \frac{1}{2} \log 10(\dot{\mathbf{q}}) \frac{d_{30}}{\rho_{\text{air}}} \sqrt{\dot{\mathbf{q}}(\dot{\mathbf{q}}^2 - \dot{\mathbf{q}}^2)}$ for $u_* > u_{\text{crit}}$, and $\dot{\mathbf{q}}^2 = (\text{NaN}0)$ otherwise44. In lieu of grain-size data for all locations, we chose constants for this calculation that are representative for Earth and not specific to any particular dune field.

Dune geometry extraction. Planform dune geometry is found through the following algorithm designed to automate the extraction of the characteristic dune geometry of each dune field. In this algorithm, the tile is set by the gridding of the wind data such that each character-
istic dune geometry found has corresponding saturated ERA5-derived sand flux data calculated at the tile center. The tiles analyzed are those that have a majority of their area shared with a dune-field area (Methods) and meet the following criteria: they do not contain ocean or non-dune relief, and are not exclusively uninformed sand sheets. These constraints leave us with 2093 tiles to extract dune geometry from. Below we first explain the algorithm precisely, then explain how it maps onto a physical definition of dune dimensions.

First, an auto-correlation $R_y$ of a $32^2 \times 23$ km$^2$ tile of ASTER topography $h(x,y)$ (where $x$ is longitude and $y$ is latitude) is created using FFT (blue-red shaded fields in Supplementary Fig. S1b,m). The two largest modes are omitted so that any broad, non-dune slopes in the topography do not impact dune-pattern identification; and the square tile is masked by a circle so that dune width is not biased by orientation. We take specific level-sets $\partial \Omega = \{R_y = \text{max}(R_y) \text{ or } \text{max}(R_y) - \text{min}(R_y) \}$. We take the only, or two largest $R_y$ that bound the origin as shapes which represent the planform dune geometry (green-yellow lines in Supplementary Fig. S1b,m). Taking $\partial \Omega$ is a poor level-set since patterns are complex and include dislocations (upper example in Supplementary Fig. S1g). Instead, we identify the appropriate level-sets by finding one or two local maxima in a plot of a against $x = \text{Area}(\partial \Omega)/(\text{Area}(\partial \Omega))$, the ratio of level-set area $\text{Area}(\partial \Omega) = \text{Area}(\partial \Omega)/\text{Area}(\partial \Omega)$ over its convex hull area $\text{Area}(\partial \Omega) = \text{Area}(\partial \Omega)$ (black lines in Supplementary Fig. S1h,p). We take the only, or two largest $\lambda_{\text{max}}$, maxima, excluding trivial maxima where $\text{Area}(\partial \Omega) > 1 - \text{Area}(\partial \Omega)$ or $\text{Area}(\partial \Omega) = \text{Area}(\partial \Omega)$, as the planform shape of dunes in the tile (cyan points in Supplementary Fig. S1p). This is unless there is no local maxima because $\chi_{\text{lr}}$ decays monotonically, in which case we found $\chi_{\text{lr}} = 1.1$ as the representative level-set (cyan point in Supplementary Fig. S1b). Over all this method is robust and general for all tiles and allows extraction of the sole dune type, or both dune types if one is superimposed on the other, in the tile. The level-set is then converted from longitude-
latitude coordinates to local meters and finally dune wavelength $\lambda_{\text{max}}$ and width $\delta$ are defined as its short- and long-axes, respectively.

Dune height is then extracted afterward by first convolving a min-max box of width $\lambda_{\text{max}}$ (in lon-lat) across $h(x,y)$, which gives a map $\chi_{\text{lr}}(x,y)$ where each point has the value of the local range in $h$ within $\lambda_{\text{max}}/2$ or $\lambda_{\text{max}}$ (Supplementary Fig. S1b,8). The peak of a histogram of this elevation range map is defined as the characteristic dune height $\lambda_{\text{max}}$ (cyan in Supplementary Fig. S1a,c).
using image] with a linear scaling such that \( \Delta x_{\text{max}} = y_{\text{max}} - 1.51 \) and \( y_{\text{max}} = 0.85 \). This method is outlined graphically for two illustrative examples in Supplementary Fig. S1 and processed geometry data are available in the Source Data file.

This process is specifically aimed at identifying the dimensions of the constituent and representative dune—or small-scale dune and large-scale dune superposition—for each tile. Planoform dune dimensions of 'wavelength' and 'width' are named as such to follow standard nomenclature; but strictly these are just the short- and long-axis dimensions of the extracted characteristic platoform dune shape, respectively. The short-axis dimension 'wavelength' has been defined as the past as the distance between crests or troughs, or the shortest distance across the erodible surface where the non-erodible inter-dune surface is exposed\(^{19,20}\). Here we are using a self-consistent measure which represents the short-axis of the dune itself, i.e., the shortest distance across and isolated dune (schematic of Fig. 1a), most similar to the latter previous definitions but it does not depend on a recognizable inter-dune and can also be defined for superimposed dunes. True wavelength extraction using the auto-correlation would find the distance from the origin to the nearest high maxima (as has been done before for dunes\(^{21}\)), however this does not allow identification of superimposed structures or the width of dunes. The representative height of a dune is found by looking at the most common range in topographic height found when looking within an area spanned by the planform wavelength of the dune.

**Mixed layer height measurements.** MLH values are found from the CALIOP version V4-20 Level 2 aerosol layer product\(^{20}\). We identify the MLH as the lowest mixing height (MLH) as the lowest 34 dune duration to ensure no aliasing or spurious stationarity.

- **Data availability**
  - The dune geometry and specific CALIOP MLH height data generated in this study are provided in the Source Data file. The SRMT ASTER GDEM V3\(^{18}\) and CALIPSO\(^{30}\) data used in this study are available in the NASA Earthdata database https://earthdata.nasa.gov/. The ERA5 reanalysis\(^{13}\) data used in this study are available in the NASA Earthdata database https://earthdata.nasa.gov/.

- **Numerical setup & analysis.** ReSCAL\(^{30,74}\), an open-source parallelizable code, is used to simulate dune growth. Details on the cellular automation (CA) and lattice gas rules are published elsewhere extensively, notably by Netz et al.\(^{30}\). Relative occurrence of CA transition rules that develop topography through fluid transport and avalanches are set by rate & threshold stress r constants. We use the following values and note dune morphology and dynamics are generally insensitive to changes in these parameters\(^74\): \( l_0 = \lambda (\frac{\tau_{\text{init}}}{\lambda}) \). The incipient dune wavelength has been shown in the field\(^{22}\) to obey \( \lambda = 2\mu L_{\text{sat}} A(1 - (u_{\text{ws}}/C_0)^2)/\mu \), where \( L_{\text{sat}} = 2.2\mu \rho_0 g \). Hydrodynamic constants are \( A = 3.6 \) & \( B = 1.9 \), friction angle is \( \mu = \tan(34\degree) \), for the ERA5 measurements we find the global mean of the critical to mean above-threshold friction velocity as \( u_{\text{ws}}/C_0 = 0.89 \), and representative values of grain diameter d = 300 \( \mu \) m, \( 2650 \) kg/m\(^3\) and \( \rho_0 = 1.225 \) kg/m\(^3\) are taken. This leaves us with a reasonable incipient dune wavelength of \( \lambda_0 = 34.7 \) m\(^2\)/yr. In ReSCAL we measure the dispersion relation \( s_0 = k_0 \) for wavelengths \( k = 2\pi/n \) and find \( \kappa = \kappa_{\text{c}} + \kappa_{\text{e}} \) as the most unstable mode and \( \lambda = 2\pi/n \). This is done by blowing wind over sand strips of small-amplitude perturbations of wavelengths \( \kappa \) and watching the decay or amplification of topography like \( s_0 \) to \( \kappa_{\text{c}} \). We find \( \kappa_{\text{c}} = 49.9 \), giving \( \lambda_0 = 0.698 \) m. See Supplementary Fig. S4a & c for the dispersion relationship and the experiment to measure it.

To find \( \kappa_{\text{c}} \) we must match sand flux magnitudes in the real-world \( Q_r \) (m\(^2\)/yr) and ReSCAL \( Q_r/l_0^2 \). In the real-world we simply find the mean \( Q_r = \frac{\lambda_0}{\kappa_{\text{c}}} = 12.78 \) m\(^2\)/yr from the ERA5 measurements (Methods). In the simulations \( Q_s \) is defined which can be found using \( Q_s = \frac{\lambda_s}{\kappa_{\text{e}}} \), where \( \lambda_s = 200\tau_{\text{init}}, \quad \kappa_{\text{e}} = 10^{-2} \). Then the timestep can be calculated as \( \tau_t = \frac{l_0^2(Q_s/l_0^2)/Q_r}{\kappa_{\text{e}}} \) (yr) using the \( l_0 \) calculated previously. To find \( l_0 \), we measure sand flux downwind of a non-erodible to erodible bed transition with \( \tau_t = 0.05 \) and all other parameters as in the numerical experiments\(^{90}\). The flux increases from the transition and saturates like \( \lambda_0/\kappa_{\text{c}} = 0.5 \), making \( \kappa_{\text{c}} = 14.2 \) h. See Supplementary Fig. S4b & d for the \( Q_s/\kappa_{\text{c}} \) calculation and the experiment to measure it.

- **Code availability**
  - This code reproduction can be found at https://doi.org/10.5281/zenodo.5718792.

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The authors declare no competing interests.

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