Supplementary methods section for **"High natural erosion rates are the backdrop for enhanced anthropogenic soil erosion in the Middle Hills of Nepal"**; by A. Joshua West, The ASTER Team, Mike Bickle, and Tank Ojha

Evaluating long-term denudation rates inferred from $^{10}Be_{qtz}$ subject to agricultural reworking of a landscape with mass wasting

S1. Conceptual framework: Basics of ^{10}Be during active erosion

The general equation for the accumulation of ^{10}Be as a function of time t with depth z below the Earth's surface (where the surface is defined as depth z=0) follows (Dunai, 2010; Granger and Riebe, 2007; Lal, 1991; see main text for definition of variables):

$$C(z,t) = \sum_i \frac{P_i(0)}{\lambda+\rho\varepsilon/\Lambda_i} e^{-z\rho/\Lambda_i}\left(1-e^{-t(\lambda+\rho\varepsilon/\Lambda_i)}\right) \quad \text{(S1)}$$

Over a sufficiently long period of time, the profile will reach a steady state between production of ^{10}Be and loss by erosion and decay, leading to a concentration-depth profile characterized by:

$$C(z)_{steadystate} = \sum_i \frac{P_i(0)}{\lambda+\rho\varepsilon/\Lambda_i} e^{-z\rho/\Lambda_i} \quad \text{(S2)}$$

which reduces to the expression for steady state composition of C_{sed} (Eq. 1 of the main text) when taking z=0, i.e. assuming sediment is derived entirely by erosion from the surface. In this supplement we consider the implications for the inferred denudation rates in the Likhu of (i) disturbing the steady state profiles over the long-term by repeated mass wasting, and (ii) mobilizing sediment from below a steady-state surface, as may happen during agricultural reworking. We do this by modeling perturbations to the theoretical depth profiles described by Eqs. S1 and S2.

Actual depth-profiles on soil-mantled slopes typically depart from Eq. S2 because of mixing within the mobile soil, for example due to bioturbation and downslope transport (e.g. Heimsath et al., 1997; Lal and Chen, 2005, 2006). Mixing does not affect the calculation of unperturbed steady state denudation rate in Eq. 1 of the main text (see Granger and Riebe, 2007 for more on this problem), but mixing does affect the calculation of C(z) for a given profile. It is possible to account for the effect of mixing by calculating the concentration C_{mix} within a mixed layer as (following Brown et al., 1995; Lal and Chen, 2005, 2006; Schaller et al., 2009):

$$C_{mix} = \sum_i \frac{\Lambda_i \exp\left(-\rho z_{mix}/\Lambda_i\right)}{\Lambda_i - \rho z_{mix}} \frac{P_i(0)}{\lambda + \rho\varepsilon/\Lambda_i}\left(1 - \mathrm{e}^{\left(-t(\lambda+\rho\varepsilon/\Lambda_i)\right)}\right) + \left(1 - \frac{\Lambda_i \exp\left(-\rho z_{mix}/\Lambda_i\right)}{\Lambda_i - \rho z_{mix}}\right) \frac{P_i(0)}{\lambda\rho z_{mix}/\Lambda_i + \rho\varepsilon/\Lambda_i}\left(1 - \mathrm{e}^{\left(-t(\lambda+\rho\varepsilon/\rho z_{mix})\right)}\right) \tag{S3}$$

where z_{mix} is the depth of the mixed layer of mobile soil and the other variables are as in Eqs. 1 and S1. For steady state profiles, the exponential terms with time t are assumed to reduce to zero, so:

$$C_{mix} = \sum_i \frac{\Lambda_i \exp\left(-\rho z_{mix}/\Lambda_i\right)}{\Lambda_i - \rho z_{mix}} \frac{P_i(0)}{\lambda + \rho\varepsilon/\Lambda_i} + \left(1 - \frac{\Lambda_i \exp\left(-\rho z_{mix}/\Lambda_i\right)}{\Lambda_i - \rho z_{mix}}\right) \frac{P_i(0)}{\lambda\rho z_{mix}/\Lambda_i + \rho\varepsilon/\Lambda_i} \tag{S4}$$

In order to consider the effect of mixing, we assign concentration C_{mix} to the mixed material, i.e. to all material above z_{mix}, and a depth-dependent concentration (following Eq. S2) to material below depth z_{mix}.

S2. Effect of mass wasting on calculated denudation rates

S2.1 Model setup

As noted in the main text, erosion in mountain environments takes place both through downslope transport of soils produced on hillslopes (described in previous work as 'bedrock weathering' or 'soil production', the latter term being used here) and through mass wasting events, such as landslides, slumps and debris flows. Unlike erosion via soil production, mass wasting can remove material below the well-mixed soil zone and disturb the steady state ^{10}Be concentration-depth profiles. Such disturbance can affect the interpretation of denudation rate from $^{10}Be_{qtz}$ in a given sediment sample (Brown et al., 1995; Niemi et al., 2005; Yanites et al., 2009).

We assess the potential bias from mass wasting on our estimates of long-term denudation rates for the Likhu by calculating the combinations of soil production rate (ε_{soil}) and mass wasting denudation rate (ε_{ls}) that can explain the observed $^{10}Be_{qtz}$ data at each site. To do this, we model mass wasting based on repeated landslides of a characteristic size. In this case, for a given ε_{ls} and a characteristic depth of landslide (z_{ls}), the time interval between landslides is $\tau_{ls} = z_{ls}/\varepsilon_{ls}$. Following a landslide event, the surface is reset to the $^{10}Be_{qtz}$ concentration at depth z_{ls}, and then $^{10}Be_{qtz}$ accumulates as a function of time t, following Eq. S1, until time τ_{ls}, when a landslide re-occurs. We calculate a ^{10}Be concentration depth profile C'(z) for $t=\tau_{ls}$ from Eq. S1 and truncate this profile at $z=z_{ls}$ to calculate the ^{10}Be inherited (C_{inh}) immediately following a landslide event, i.e. the starting point for development of a new depth profile is defined by $C_{inh}(0)=C'(z_{ls})$. For a given combination of ε_{ls} and z_{ls}, the depth profile $C(z)^*$ expected immediately prior to landslide removal is then:

$$C(z)^* = C_{inh}(z) + \sum_i \frac{P_i(0)}{\lambda+\rho\varepsilon/\Lambda_i} e^{-z\rho/\Lambda_i}\left(1 - e^{-\tau(\lambda+\rho\varepsilon/\Lambda_i)}\right) \tag{S5}$$

The ^{10}Be concentration of the mass wasting flux, C_{ls}, is calculated by numerically integrating $C(z)^*$ above depth z_{ls} and determining the weighted average value. C_{sed} is the weighted average of C_{ls} plus the contribution from soil production:

$$C_{sed} = (\varepsilon_{ls}C_{ls} + \varepsilon_{soil}C_{soil}) \,/\, (\varepsilon_{ls} + \varepsilon_{soil}) \tag{S6}$$

where C_{soil} is the composition of material eroded from the surface. For the purposes of this modeling exercise, we assume that landslides of the same size occur periodically across the landscape to maintain spatially uniform rates of lowering over long time scales, so for any given point on the landscape there is a uniform chance of having an effective age varying between t=0 and $t=\tau_{ls}$. We determine C(z=0,t) from Eq. S5 for one-year intervals, integrate the resulting distribution numerically between t=0 and τ_{ls}, and assign C_{soil} as the weighted average concentration.

In addition to considering profiles defined by Eq. S5 alone, we also explore the additional case where the surface layer that forms following each landslide event is continuously mixed to a depth of z_{mix}. We choose z_{mix}=1m as broadly representative of soil depth in the Nepal Middle Hills, in order to illustrate the effect of mixing. In this case, the depth profile prior to landslide occurrence is defined by Eq. S3 for z<1m (with the addition of a term for inherited ^{10}Be) and by Eq. S5 for z>1m. C_{ls} is calculated from the integration of the profile to depth z_{ls}, as in the case without mixing. Similarly, C_{soil} is calculated as in the case above without mixing, by instead determining the weighted average concentration for the surface of all profiles with effective age between t=0 and $t=\tau_{ls}$. C_{ls} and C_{soil} are then used in Eq. 6, as above.

It is important to emphasize that this model is not intended to provide a complete simulation of landslide occurrence but is used to explore the potential scale of bias in inferred denudation rates that may be expected as a result of mass wasting processes.

S2.2 Applying the mass wasting model to the Likhu case

To apply our simple landslide recurrence model to the Likhu data, we fix the total mass wasting denudation rate (ε_{ls}) for a given site to match the measured mass wasting flux in each catchment, equivalent to 0.325 mm/yr denudation for the Likhu and 0.05 mm/yr for the Bore and Chinnya (Table 3). We consider a range of values for z_{ls} and ε and determine the misfit between C_{sed} (from Eq. S6) and C_{meas}, the measured $^{10}Be_{qtz}$ concentration from each catchment, as $\chi^2 = (C_{sed} - C_{meas})^2$. Model results are shown in Figure S1. A subset of the sampled parameter space are statistically consistent with the measured $^{10}Be_{qtz}$, specifically those combinations of z_{ls} and ε that yield $\chi < \sigma_C$, where σ_C is the uncertainty on the concentration measurements,. The erosion rates associated with these misfits define a valley that illustrates how possible solutions for long-term erosion rate depend on the nature of mass wasting – and specifically on the depth of repeated failures. In the real world, landslides are not all of the same size, as assumed in our model, but instead generally follow an inverse gamma distribution (e.g. Malamud et al., 2004). Considering the full size distribution requires a more complete stochastic model (cf. Niemi et al., 2005; Yanites et al., 2009), but Figure S1 offers a first-order view of the degree to which mass wasting may affect calculated rates and provides a framework for assessing bias in our inferred denudation rates in the Likhu basin.

S2.3 Mass wasting model results and implications for inferred rates

It can readily be seen from Figure S1 that the long-term total denudation rate inferred for a given $^{10}Be_{qtz}$ concentration in the Likhu catchments would depend on the depth and associated return time of landslides. If mass wasting consists only of small, frequent failures, then the actual long-term denudation rate would be lower than implied by the steady state calculation. If mass wasting consists of rare large failures, actual long-term denudation rate would be slightly higher.

The associated bias is small for the Bore and the Chinnya, and is within the uncertainty in the inferred steady state denudation rate, unless landslides are all very small (i.e. in the case that all landslides were <~50cm depth). The flux from such extremely shallow landslide probably does not dominate the erosional budget (e.g., Gerrard and Gardner, 2002), so the effect of these landslides is not likely to have an important effect on our estimates of denudation rate. We thus view the steady state long-term denudation rates (reported in Table 2) as reasonable estimates for the Bore and the Chinnya.

For the Likhu mainstem, the potential bias could be more significant, since there is a range of total erosion rates that can describe the data for plausible landslide depths (e.g. 0.5-10m depths; Gerrard and Gardner, 2002). The catchment area of the Likhu Khola is large enough (>100 km^2) that stochastic landslide processes, i.e. the occurrence of a range of different-sized landslides across the catchment area at any given time, may be expected to average across the catchment area, yielding an integrated $^{10}Be_{qtz}$-derived denudation rate that approximates the steady state value (cf. results from stochastic models from Niemi et al., 2005; Yanites et al., 2009). As a result, the inferred steady state denudation rate from the Likhu mainstem may be representative of the long-term rate, although we emphasize caution in the interpretation of this value. In any case, we do not use the rates from the Likhu mainstem in our comparison to short-term erosion rates, and we provide the result from this site primarily for reference.

Event-triggered landslide pulses can mean that measured $^{10}Be_{qtz}$ may not accurately reflect long-term concentrations; samples collected soon after a large-magnitude, low-frequency event may overestimate rates while those collected long after such an event may underestimate actual rates (e.g. Ouimet, 2009; West et al., 2014). Since there were no known large-magnitude events within several decades (at least 10-20 years) of when our samples were collected, we anticipate that our observed concentrations represent an upper limit of long-term $^{10}Be_{qtz}$, and thus provide a lower limit on estimated denudation rate. This suggests that any bias from the time of sampling would not change our overall conclusions (e.g. in Figure 2 of the main text), i.e. that short-term, anthropogenically perturbed rates do not appear to be significantly higher than long-term denudation rates in the Likhu Khola.

S3. Anthropogenic perturbation of $^{10}Be_{qtz}$ in eroding sediment?

S3.1 Agricultural reworking of simple steady state profile

The supply of cosmogenically shielded rock to stream sediment as a result of agricultural or other land use activity can, like mass wasting, disturb the sourcing of sediment from depth z=0 and so can potentially bias calculation of long-term denudation rates. If land use activities generate river sediment that is characterized by lower $^{10}Be_{qtz}$ than background denudation, then the estimated denudation rates may be higher than the actual long-term background rate. For example, Brown et al. (1998) observed ~2x higher cosmogenically-derived rates in an agriculturally disturbed catchment in Puerto Rico when compared to an undisturbed catchment, and von Blanckenburg et al. (2004) suggested that the dissection of rills in agricultural areas could explain the discrepancy between inferred denudation rates in large river basins versus small headwater catchments in the Sri Lanka highlands. We have assessed the effect of anthropogenic perturbation on estimates of $^{10}Be_{qtz}$-derived denudation rates in the Likhu Khola by considering theoretical $^{10}Be_{qtz}$ vs. depth curves (from Eq. S2) and determining an integrated average ^{10}Be concentration, $\hat{C}$, for material that is eroding from each depth profile. We find $\hat{C}$ by numerically integrating the profile over depth z_e, the depth of erosion. For unperturbed steady state denudation, the depth of eroding material is zero, because erosion occurs from the top of the profile (cf. Granger and Riebe, 2007). Land use perturbation may contribute material from greater depth, for example through tilling and/or enhanced soil erosion. We calculate integrated $\hat{C}_{pred}$ for a given depth z_e of anthropogenic erosion and find the steady-state depth profile from Eq. S2 that minimizes the chi-square misfit statistic $\chi^2 = (\hat{C}_{pred} - C_{meas})^2$, where C_{meas} is the measured concentration in each sediment sample. The denudation rate ε associated with the best-fit profile represents the inferred "real background" (i.e. unperturbed) steady-state rate. Since the depth of anthropogenic erosion is not precisely known, we plot variability in ε as a function of z_e (Figure S2). For z_e=0, the resulting value for ε matches the rate calculated directly from solving Eq. 1 (main text), as expected. For z_e>0, the resulting value of ε is typically somewhat lower than the steady-state value.

S3.2 Agricultural reworking of profile with mixed soil layer

Mixing will affect the calculation of $\hat{C}$ for a given perturbed erosion depth. We consider a range of possible mixing depths z_{mix}, and in each case assign concentration C_{mix} to the mixed material (Eq. S4) and a depth-dependent concentration (following Eq. S2) to material below depth z_{mix}. We then repeat the χ^2 inversion for the range of depths of anthropogenic perturbation (Figure S2).

S3.3 Agricultural reworking of profile characterized by mass wasting

The effect of agricultural reworking of the surface may differ if the depth profile of $^{10}Be_{qtz}$ is defined by repeated mass wasting, rather than by steady state erosion (as assumed in the calculations above). Many different pre-perturbation depth profiles are theoretically plausible and consistent with the measured $^{10}Be_{qtz}$, depending on the combinations of landslide depth, return time, and soil production (cf. Figure S1). This complicates quantifying the effect of agricultural reworking; accurately predicting the effect of agricultural disturbance would require knowing the distribution of landslide depths and ages across the landscape, and the spatial relation of landslides to the extent of agricultural reworking.

However, we can still explore the effect of agricultural reworking of a mass-wasting dominated landscape on calculated denudation rates, by making some simplifying assumptions. We consider a few example cases based on the mass-wasting model presented in Section S2. We modify Eq. S6 to account for anthropogenic disturbance by assuming that agriculture removes the layer of each profile down to depth z_e, and we calculate C_{soil} to include the additional input. We then recalculate the best-fit total erosion rate for a given landslide depth and recurrence time. As in the case above for steady state erosion, we repeat the exercise for a range of depths of anthropogenic perturbation, to yield a plot of ε vs. z_e for a given depth of characteristic landslides (Figure S2c). We consider a range of landslide depths and associated recurrence timescales. This is a simplified framework for illustrating the effects of mass wasting; actual landslide failures are expected to span a range of depths, but the simple model allows us to test how much bias may be introduced under some plausible scenarios.

S3.4 Results of model of anthropogenic perturbation of ^{10}Be

As expected, when the depth of perturbation is lower than the depth of natural mixing ($z_e<z_{mix}$), steady-state denudation rates (from Eq. 1) yield representative long-term rates (cf. Granger and Riebe, 2007). If land-use perturbation exceeds the depth of natural mixing ($z_e>z_{mix}$), then rates calculated from Eq. 1 can overestimate actual rates in the Likhu Khola by as much as a factor of ~2. In the case of the Likhu, soil depths are on the order of 100-200cm, and the steep slopes mean that downslope transport is expected to mix soils (cf. Heimsath et al., 1997), so any bias in long-term rates from anthropogenic perturbation is likely to be small. Moreover, the sites we use to establish reference long-term rates (the 1st-order Bore and Chinnya catchments) have minimal agricultural influence. This latter observation gives us increased confidence in making the key comparisons in the main text, where we focus our analysis on the magnitude of land use effects on erosion rates in the Middle Hills.

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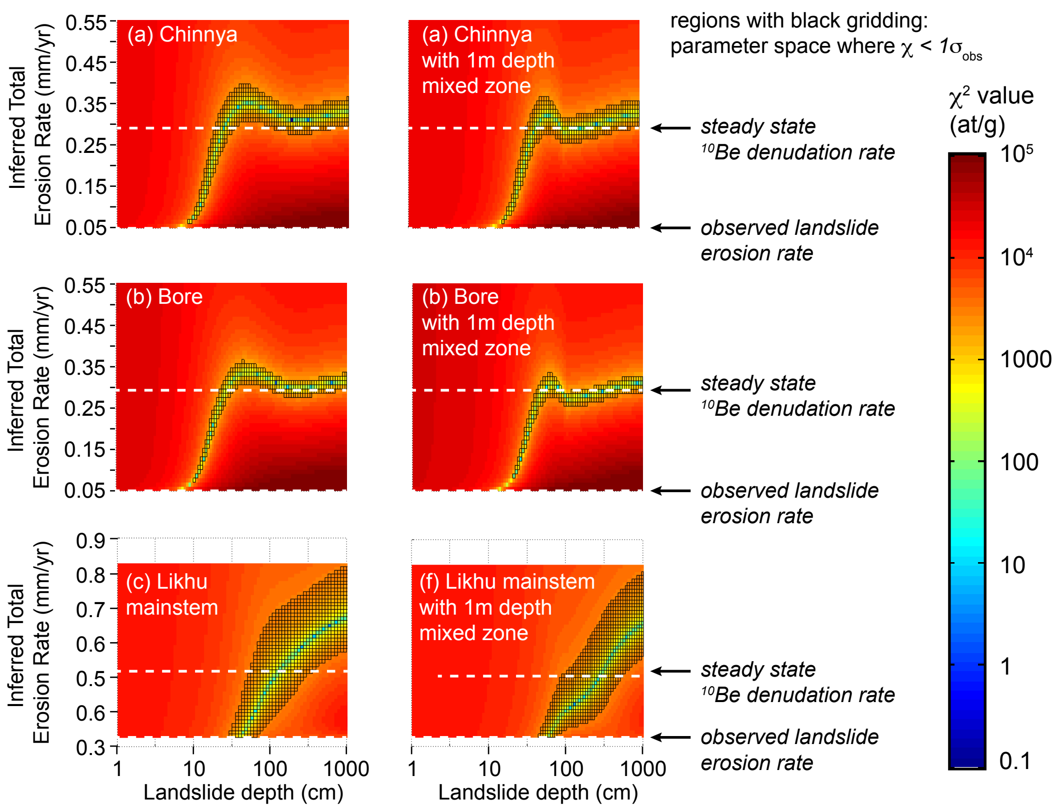
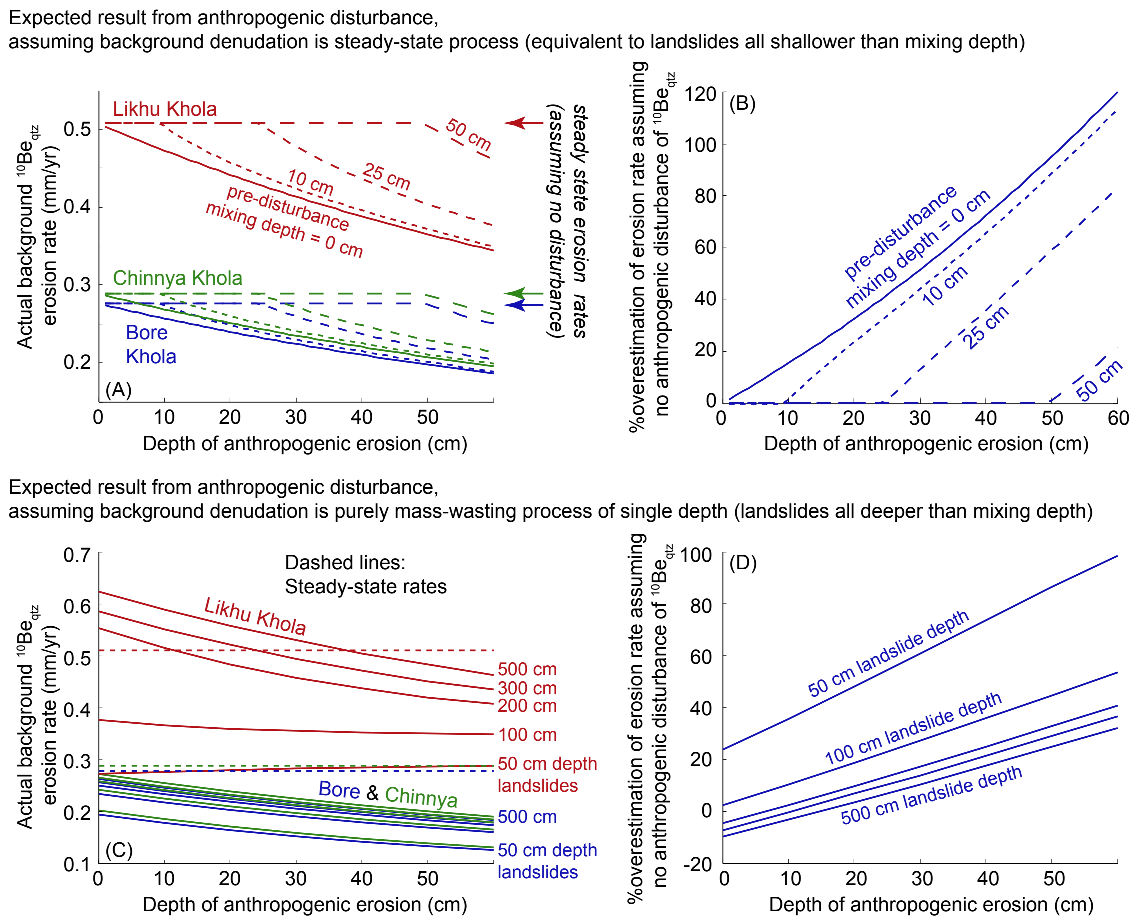


Supplementary Figure S1 for “High natural erosion rates are the backdrop for enhanced anthropogenic soil erosion in the Middle Hills of Nepal”, by A. Joshua West, The ASTER Team, Mike Bickle, Tank Ohja

Figure S1. Results of model testing sensitivity of denudation rates estimates to mass wasting. Results from model calculating $^{10}Be_{qtz}$ produced in sediment from repeated landslides of a characteristic depth, z_{ls}, where the return time is fixed so that the total landslide flux adds up to the observed mass wasting flux in each catchment. Color shading shows the χ^2 value describing the misfit between modeled $^{10}Be_{qtz}$ concentration and the observed sediment $^{10}Be_{qtz}$ concentration. Gridded regions define parameter space where the misfit (χ) is less than analytical uncertainty, reflecting combinations of z_{ls} and denudation rate ε that fit the data. The values of ε that fit the data depend on the depth of landslides; the lowest value for ε is set by the imposed landslide erosion rate. Actual landslides are not uniform in size but are sampled from a distribution, and the small landslides (<50 cm) probably do not dominate the erosional budget.



Supplementary Figure S2 for "High natural erosion rates are the backdrop for enhanced anthropogenic soil erosion in the Middle Hills of Nepal", by A. Joshua West, The ASTER Team, Mike Bickle, Tank Ohja

Figure S2. Results of model testing sensitivity of denudation rates estimates to agricultural reworking. Effect of anthropogenic disturbance on long-term erosion rates inferred from $^{10}Be_{qtz}$, associated with increased erosion removing soil from below the surface. (A) and (B) show the case for steady state denudation prior to disturbance; (C) and (D) for mass wasting denudation. In (A) and (B), the effect of disturbance depends on the depth of the mixed layer relative to the depth of agricultural reworking. In (C) and (D), mixing is not considered explicitly, for simplicity. Note that the implied erosion rate at z_e = 0 in (C) and (D) differs from the steady state erosion rate, because of the influence of mass wasting depth and recurrence interval on inferred rates (cf. Fig S1).