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High natural erosion rates are the backdrop for enhanced anthropogenic soil erosion in the Middle Hills of Nepal

A. J. West[1], M. Arnold[2,*], G. Aumaître[2,*], D. L. Bourlès[2,*], K. Keddadouche[2,*], M. Bickle[3], and T. Ojha[4]

[1]Department of Earth Sciences, University of Southern California,
Los Angeles, CA 90089, USA
[2]Aix-Marseille Université CNRS-IRD-Collège de France, UM 34 CEREGE, Technopôle de l'Environnement Arbois-Méditerranée, BP80, 13545 Aix-en-Provence, France
[3]Department of Earth Sciences, University of Cambridge, Cambridge, CB2 3EQ, UK
[4]Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA
[*]The ASTER Team

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Correspondence to: A. J. West (joshwest@usc.edu)

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Abstract

Although agriculturally accelerated soil erosion is implicated in the unsustainable environmental degradation of mountain environments, such as in the Himalaya, the effects of land use can be difficult to quantify in many mountain settings because of the high and variable natural background rates of erosion. In this study, we present new long-term denudation rates, derived from cosmogenic ^{10}Be analysis of quartz in river sediment from the Likhu Khola, a small agricultural river basin in the Middle Hills of central Nepal. Calculated long-term denudation rates, which reflect background natural erosion processes over 1000+ years prior to agricultural intensification, are similar to present-day sediment yields and to soil loss rates from terraces that are well-maintained. Similarity in short- and long-term catchment-wide erosion rates for the Likhu is consistent with data from elsewhere in the Nepal Middle Hills, but contrasts with the very large increases in short-term erosion rates seen in agricultural catchments in other steep mountain settings. Our results suggest that the large sediment fluxes exported from the Likhu and other Middle Hills rivers in the Himalaya are derived in large part from natural processes, rather than from soil erosion as a result of agricultural activity. Because of the high natural background rates, simple comparison of short- and long-term rates may not reveal unsustainable soil degradation, particularly if much of the catchment-scale erosion flux derives from mass wasting. Correcting for the mass wasting contribution in the Likhu implies minimum catchment-averaged soil production rates of ~ 0.25–$0.35\,\mathrm{mm\,yr^{-1}}$. The deficit between these production rates and soil losses suggests that terraced agriculture in the Likhu may not be associated with a large systematic soil deficit, at least when terraces are well maintained, but that poorly managed terraces, forest and scrubland may lead to rapid depletion of soil resources.

1 Introduction

The loss of soil by erosion can present an environmental challenge with potentially grave social and economic consequences, including decreased agricultural productivity (Pimentel et al., 1995; Montgomery, 2007), damage to hydropower infrastructure and reduction of reservoir lifespans (e.g., Harden, 1993), and increased flooding hazards (e.g., Costa, 1975). In steep mountain environments, deforestation and agricultural intensification have been linked to increased soil loss (Eckholm, 1975; Hewawasam et al., 2003; Rapp, 1975; Swanson and Dyrness, 1975) and associated "environmental degradation" (Ives and Messerli, 1989). Unsustainable soil loss potentially puts at risk rural mountain communities that rely on the economy of local agriculture and that are highly susceptible to sediment-related hazards in downstream environments (Brown, 1981). Restoration of dense vegetation has been shown to remediate erosional losses (Vanacker et al., 2007), but population pressure and intense competition for land use means that permanent re-vegetation is not always possible or sustainable for rural communities. Techniques such as terracing and low-till agriculture can mitigate erosional losses (Chow et al., 1999; van Dijk and Bruijnzeel, 2003; Gardner and Gerrard, 2003; Inbar and Llerena, 2000; Montgomery, 2007; Morgan, 2005), but significant questions remain about the extent to which specific agricultural practices prevent or exacerbate erosion. Answering these questions is critical to optimizing the strategy for preventing unsustainable soil loss in mountain regions.

One major challenge is that robust data on how erosion rates change under mountain agriculture remain limited. In particular, it is often difficult to define baseline "natural" rates of erosion for comparison to the present-day rates that are influenced by agricultural land uses. The simple observation of rapid erosion from hillslopes and high sediment fluxes in rivers does not distinguish agricultural effects, because background rates of landscape denudation are high in mountain environments. Plot studies are frequently used to compare soil loss under different land uses (e.g., Boix-Fayos et al., 2006; Hudson, 1993; Morgan, 2005; Mutchler et al., 1970). Plots provide valuable information but face methodological challenges (e.g., Boardman, 2006) and are inherently small in scale and site-specific. Other studies have compared catchments with different land use make-up, but natural spatial heterogeneity can make it difficult to find appropriate catchments that effectively isolate variables such as agriculture (e.g., Heimsath, 1993).

An alternative approach is to compare erosion rates before and after the onset of intensive agricultural activity. Sediment yield data are rarely available prior to agricultural land use, but the concentration of ^{10}Be, a cosmogenic nuclide, in quartz separated from river sands (hereafter "$^{10}\mathrm{Be}_{\mathrm{qtz}}$") can be used to infer long-term denudation rates, typically integrated over ~ 1000+ year timescales (von Blanckenburg, 2006; Brown et al., 1995; Granger et al., 1996). Catchment-scale effects of land use may be identifiable by comparing the $^{10}\mathrm{Be}_{\mathrm{qtz}}$-derived erosion rates, which predominantly capture "natural background" erosion rates before agricultural intensification, with sediment fluxes measured over more recent agricultural times (e.g., 1–10+ years). Hewawasam et al. (2003) and Vanacker et al. (2007) used such an approach to show that deforestation has dramatically increased erosion rates in the highlands of Sri Lanka (presently dominated by tea plantations) and the Andes of Ecuador (dominated by mixed cropland and pasture). Vanackar et al. (2007) also found that increases in vegetation cover returned catchment erosion rates to background values.

Without additional comparative studies such as these, it is difficult to assess whether and how land degradation depends on the setting and the type of agricultural activity in mountain environments. In particular, terracing is widely used in mountain agriculture, especially for subsistence agriculture in the Himalaya, but its effects on soil losses remain to be completely understood. In this study, we focus on the Middle Hills of the Nepal Himalaya, where detailed plot-erosion investigations have suggested that traditional terracing practices are associated with relatively low rates of soil loss (Gardner and Gerrard, 2003; Smadja, 1992; Tiwari et al., 2009). It is unclear how the results from these plot studies relate to degradation at the wider landscape scale in the Middle Hills (Hamilton, 1987), and the concept of dwindling Himalayan soil resources and the associated "Theory of Himalayan Environmental Degradation" (Eckholm, 1975; Ives and

Messerli, 1989) remain widely discussed (e.g., Asia Development Bank and ICIMOD, 2006; Sitaula et al., 2005).

To shed new light on the problem of soil degradation associated with agriculture in the Himalaya, here we present new cosmogenic $^{10}\mathrm{Be}_{\mathrm{qtz}}$ data from well-studied agricultural catchments in the Nepal Middle Hills, and we compare these data with previously determined sediment yields, soil loss rates, and mass wasting fluxes. By comparing two catchments with varying extents of agricultural land use, and by setting our results in the context of other $^{10}\mathrm{Be}_{\mathrm{qtz}}$ and sediment flux data from Nepal, we gain additional insight into the extent of agricultural reworking of the Himalayan landscape.

2 Study site

The focus of this study is on the Likhu Khola valley, an east-west trending river valley in central Nepal that lies immediately north of the Kathmandu valley (at approximately 27°50′ N, 85°20′ E; Fig. 1). The proximity of the Likhu valley to the city of Kathmandu (∼ 50–60 km distance) has led to intense population pressure on this rural environment. The Likhu Khola itself is a tributary of the Trisuli River, which flows via the Narayani River to the Ganges. The elevation of the Likhu drainage basin ranges from 600 to 1850 m. The bedrock is composed of Kathmandu Complex gneisses and schists, overlain by a deep weathered zone (several meters depth) and loamy soils up to 2–3 m thickness, with typical A-horizons 10–40 cm thick and B-horizons 10–220 cm thick (Shrestha, 1997). Slopes in the Likhu are steep, at 10–45°. The Likhu fault, a geologic structure associated with but distinct from the Main Central Thrust (MCT), runs with an east-west strike through the bottom of the valley (Fig. 1). Annual rainfall is approximately 2500 mm, as measured at the Kakani meteorology station on the ridge that defines the southern watershed boundary of the Likhu.

Agricultural practices in the Nepal Middle Hills include rain-fed bari terraces, which have sloping surfaces and are used primarily for maize production, and irrigated khet terraces which are flooded and used primarily for rice production. In the Likhu, the majority of agriculture during the study period was in the form of khet terraces (30.6 % total catchment area), with some bari (16.6 % area) and grassland (15.4 %). The remainder of land was forest (14.5 %) and scrubland (Gerrard and Gardner, 2002).

We focus specifically on the Bore Khola, a subcatchment of the Likhu Khola with total catchment area 4.82 km^2, of which 60 % remains forested (Fig. 2). The main Bore Khola has two first-order headwaters: the 1st-order Bore (catchment area 2.01 km^2), and the Chinnya Khola (area 0.60 km^2), both of which are predominantly forested (> 80 %). For comparison, we also consider the larger Likhu Khola basin (catchment area 166.4 km^2) just upstream of its confluence with the Trisuli (shown in Fig. 1).

3 Methods

3.1 Short-term, anthropogenic erosion rates

Data on short-term (annual to decadal) erosion rates were assembled from previously published measurements of soil loss from plots, quantification of sediment transported by streams, and mapping of the distribution and volumes of landslides, slumps, and debris flows.

3.2 Measurement of $^{10}\text{Be}_{\text{qtz}}$

Rates of natural background erosion were calculated from the concentration of in-situ produced ^{10}Be in quartz ($^{10}\text{Be}_{\text{qtz}}$) separated from stream sediments. Sediment samples (~ 5 kg each) were collected from material in active transport in the streambed, from the 1st-order Bore Khola, the Chinnya Khola, and the Likhu Khola main stem (Figs. 1 and 2). Samples were returned to the UK and sieved to size fractions of < 0.25 mm, 0.25–0.71 mm, 0.71–2.0 mm, and 2.0–4.0 mm. Quartz grains in the < 0.25 mm fraction are too small to determine the concentrations of ^{10}Be in quartz. The other 3 size fractions were analyzed separately for the Bore and Chinnya samples. There was little coarse-grained material in the Likhu main stem sample, so only the 0.25–0.71 mm fraction was processed. Sample processing and ^{10}Be analysis was completed at the Cosmogenic Nuclides National Laboratory (LN2C) and the French national AMS facility ASTER at CEREGE (Aix-en-Provence, France). Samples were leached in HF to separate quartz and to remove meteoric contamination (Kohl and Nishiizumi, 1992). AMS analyses were calibrated against NIST SRM 4325 based on a $^{10}\mathrm{Be}/^{9}\mathrm{Be}$ ratio of $(2.79 \pm 0.03) \times 10^{-11}$ and a ^{10}Be half-life of $(1.36 \pm 0.07) \times 10^{6}$ years (Nishiizumi et al., 2007).

3.3 Inferring long-term denudation rates from $^{10}\mathrm{Be}_{\mathrm{qtz}}$

The widely used approach to determining denudation rates from $^{10}\mathrm{Be}_{\mathrm{qtz}}$ (e.g., von Blanckenburg, 2006; Dunai, 2010; Granger and Riebe, 2007; Portenga and Bierman, 2011) assumes that erosion occurs at steady state from the Earth's surface, such that (see the Methods Supplement for more details):

$$C_{\mathrm{sed}} = \sum_i \frac{P_i(0)}{\lambda + \rho\varepsilon/\Lambda_i} \quad (1)$$

where C_{sed} is the measured ^{10}Be concentration in river sediment quartz, i denotes each cosmogenic production pathway of ^{10}Be, $P_i(0)$ is the production via pathway i at the surface (i.e., where depth $z = 0$), λ is the ^{10}Be decay constant, ρ is the density of eroding rock (we use $\rho = 2.6\,\mathrm{g\,cm^{-3}}$), ε is the steady-state denudation rate, and Λ_i is the attenuation length associated with production pathway i. We use two terms in Eq. (1), one term for production by neutron spallation and another for muonic production. For neutrons, we use $\Lambda_n = 160\,\mathrm{g\,cm^{-2}}$ (a widely adopted value; cf. Goethals et al., 2009) and P_n calculated for the mean latitude, longitude, and elevation of each catchment based on scaling of a sea level high latitude spallation production rate of $4.49\,\mathrm{at\,g^{-1}\,yr^{-1}}$ (Stone, 2000; using code of Balco et al., 2008). For muons, we use $\Lambda_m = 4200\,\mathrm{g\,cm^{-2}}$ (the median value from the compilation of Braucher et al., 2013) and $P_m(0)$ calculated for the mean elevation of each catchment based on scaling of a sea level high latitude muonic production rate of 0.028 at g^{-1} yr^{-1} (Braucher et al., 2011, 2013).

Steady-state denudation rate is found by inverting Eq. (1) for ε (see Table 2 for the Likhu sample results). Adopting a mean catchment elevation and latitude for production rate calculations provides a close approximation of catchment-wide production in most catchments (von Blanckenburg, 2006). Uncertainties are estimated based on the 16th and 84th percentiles of the Monte Carlo distributions derived from repeating the inversion taking into account 1σ measurement error on C_{sed} (Table 1), 10 % uncertainty on P_m (0) and P_n (0), and uncertainties of 10 and 500 g cm^{-2} on Λ_n and Λ_m, respectively.

3.4 Additional data

Additional data from other catchments in Nepal were assembled from the literature, to provide wider context for the measurements from the Likhu Khola reported here. In all cases, calculated denudation rates (in mm yr^{-1} average surface lowering) were converted to erosional fluxes (in t km^{-2} yr^{-1}) based on density of 2.6 g cm^{-3}, because rock density controls the amount of sediment production over depths measured by $^{10}Be_{qtz}$ denudation rates. The denudation rates and fluxes calculated from $^{10}Be_{qtz}$ reflect long-term losses via both physical erosion and chemical weathering.

4 Erosion rate results

4.1 Long-term background rates from the Likhu Khola

Natural background denudation rates (Table 1) inferred from $^{10}Be_{qtz}$ assuming the steady state relation in Eq. (1) range from $0.28+0.05/-0.04$ to $0.42+0.11/-0.08$ mm yr^{-1} in the 1st-order Bore and Chinnya catchments, which are only minimally affected by agricultural land use. These rates represent 728 ± 140 to 1092 ± 276 t km^{-2} yr^{-1} sediment yield. At these erosion rates, $^{10}Be_{qtz}$ integrates over timescales of ∼ 1600–2500 years. The inferred erosion rates are identical for all size fractions of the river sediment from the Chinnya catchment. In the Bore catchment, rates in the 0.25–0.71 mm and 0.71–2.0 mm size fractions of river sediment were identical, while best estimate rates in the 2–4 mm fraction were 50 % higher but not quantitatively distinguishable within analytical error. There is no statistically significant difference between rates in the Bore and Chinnya. Calculated steady-state denudation rates at the Likhu main stem site were $0.51+0.17/-0.11\ \mathrm{mm\,yr^{-1}}$, or $1326 \pm 429\ \mathrm{t\,km^{-2}\,yr^{-1}}$, higher than in either of the smaller sub-catchments for the equivalent grain size range of river sediment.

4.2 Anthropogenically perturbed rates from the Likhu Khola

Suspended sediment yields in the Bore Khola, measured at the outlet of the larger catchment that comprises both the Bore and Chinnya headwaters and includes significant (∼ 40 %) agricultural area (Fig. 2), totaled $341\text{–}1527\ \mathrm{t\,km^{-2}}$ during the monsoon season of 1992 (Table 3). The wide range in these estimates is attributable to the different methods of calibrating the field measurements (Brasington and Richards, 2000). This range provides a reasonable estimate of the total annual sediment yield, since over 90 % of rainfall and the majority of sediment removal takes place during the monsoon season (Gerrard and Gardner, 1999). However, measured suspended sediment fluxes in this system are probably sensitive to the runoff in any given year of observation (Brasington and Richards, 2000).

Plot studies from bari terraces yield soil loss rates from 270 to $1290\ \mathrm{t\,km^{-2}}$ during the monsoon seasons in 1992 and 1993 (Gardner and Gerrard, 2003), with a mean of $560 \pm 340\ \mathrm{t\,km^{-2}}$ ($n = 14$). Soil loss rates on grassland and natural forest were lower, $\sim 50\ \mathrm{t\,ha^{-1}}$, but rates on degraded forest were substantially higher, $\sim 1000\text{–}2000\ \mathrm{t\,ha^{-1}}$ (Gardner and Gerrard, 2001; Gerrard and Gardner, 2002).

Gerrard and Gardner (1999, 2002) estimated an average denudation rate from mass wasting of $0.325\ \mathrm{mm\,yr^{-1}}$ for the Likhu basin as a whole (note their 1999 paper reports rates that are 10× too high due to a conversion error, but this is corrected in the 2002 paper). They measured lower rates ($\sim 0.05\,\mathrm{mm\,yr^{-1}}$) for the Bore sub-catchment and suggested that this lower value is more representative of the southern slopes of the Likhu, based on aerial images (Gerrard and Gardner, 1999). The difference in denudation rate between southern and northern slopes, also seen in the analysis of Shrestha et al. (2004), may be due in part to relatively more land degradation on northern slopes (as suggested by Gerrard and Gardner, 1999, 2002), but may also be influenced by the presence of the Likhu fault that runs east-west through the middle of the valley (Fig. 1). If this fault accommodates deformation, for example associated with the Main Central Thrust (MCT), then higher tectonically-driven denudation rates might be expected on the northern slopes (cf. Godard et al., 2014; Wobus et al., 2005). Activity of the Likhu fault could help to explain the higher $^{10}\mathrm{Be}_{\mathrm{qtz}}$-derived long-term denudation rate for the Likhu mainstem compared to the Bore and Chinnya, which sit on the southern slopes of the valley. Notably, the $^{10}\mathrm{Be}_{\mathrm{qtz}}$ denudation rates in the Bore and Chinnya are similar to other denudation rates in the Middle Hills of Nepal, while the rates for the Likhu Khola as a whole approach the higher rates observed in association with more rapid tectonic uplift in the Nepal High Himalaya (Godard et al., 2014; Wobus et al., 2005). The northern slopes of the Likhu do not have obviously different relief structure (e.g., river channel steepness), as might be expected for a different uplift and erosion regime (Godard et al., 2014; Scherler et al., 2014). However, non-linearity in such relationships mean that differences in topographic parameters associated with the $\sim 2\times$ difference in denudation rate might not be easy to identify across the Likhu.

4.3 Comparative data from Middle Hills region of Nepal

Other than our study in the Likhu, we are not aware of any other data pairing short-term, present-day erosion rates with $^{10}\mathrm{Be}_{\mathrm{qtz}}$-derived long-term denudation rates where both data have been collected a the same site in the Himalayan Middle Hills. However, there are some additional erosion rate data from a variety of different sites in Nepal, some in the Middle Hills region.

Long-term, $^{10}Be_{qtz}$-derived denudation rates from other small catchments in Nepal have been reported from 0.10±0.01 to 1.81±0.49 mm yr^{-1} (Godard et al., 2014; Wobus et al., 2005; see Supplement Table S1). The large range has been attributed to variable tectonic position, with significantly higher denudation rates in the more rapidly uplifting High Himalaya (Godard et al., 2014; Wobus et al., 2005). Data that are comparative to the region of the Likhu Khola are those restricted to catchments south of the MCT, and south of the physiographic and denudational transition that may demarcate blind thrusting (Wobus et al., 2005). The data from these catchments yield mean denudation rates of 0.19 ± 0.1 mm yr^{-1} from the 4 small catchments (< 25 km^2 catchment area) sampled by Wobus et al. (2005) and 0.22 ± 0.12 mm yr^{-1} from the 16 medium-sized catchments (25–110 km^2 area) sampled by Godard et al. (2014). Averaging all of these data, the overall long-term mean denudation rate for the Nepal Middle Hills is 0.22 ± 0.11 mm yr^{-1}, equivalent to 572 ± 286 t km^{-2} yr^{-1} sediment yield, and similar to the $^{10}Be_{qtz}$-derived denudation rates we have measured in the Bore and Chinnya. These rates from Nepal are also similar to those observed in the lower-elevation regions of the Garwhal Himalaya in India (Scherler et al., 2014). Previously reported rates were not all calculated with the same $^{10}Be_{qtz}$ production scheme that we use, and application of the same production scheme may be expected to bring results even closer together. As noted above, the rates we measure for the Likhu mainstem are higher, and approach rates found in the High Himalaya, perhaps because of higher denudation rates on the northern slopes of the Likhu valley, north of the Likhu fault. It is also possible that other effects – such as reworking of cosmogenically shielded alluvial by the Likhu mainstem – contribute to the higher inferred denudation rate at this site.

Additional data on short-term soil loss from agricultural lands in Nepal provide widely varying erosion rates, with plot study data ranging from < 10 to > 10 000 t km^{-2} yr^{-1} (as compiled by Chalise and Khanal, 1997; Jha and Paudel, 2010). This variability may be partly attributable to variable background denudation rate but also reflects different land use practices at the different sites that have been studied. Such variation is consistent with observations in the Likhu Khola of varying plot-level soil loss, depending on the type of land use.

The data most immediately comparable to the river sediment $^{10}\mathrm{Be}_{\mathrm{qtz}}$ denudation rates are river sediment fluxes that integrate across multiple land use types. Many of the rivers monitored for suspended sediment in Nepal have very large catchment areas that drain significant High Himalayan regions (e.g., data in Andermann et al., 2012), while others drain significant portions of the lowland Terai floodplain. Since the High Himalaya generally have higher denudation rates, and the Terai are expected to have relatively low denudation rates, the sediment yields from the large river basins do not provide a robust comparison to the long-term rates for the Middle Hills. Considering only sediment yields from rivers with catchment areas restricted to the Middle Hills, suspended sediment fluxes range from 173 to 5300 $\mathrm{t\,km^{-2}\,yr^{-1}}$ (as reported by Chalise and Khanal, 1997; see Supplement Table S2). The distribution of rates is significantly positively skewed, with a median value (±5th–95th percentile; $n = 8$) of $1338 + 3948/-1165\,\mathrm{t\,km^{-2}\,yr^{-1}}$. This value should be interpreted with caution since sediment yields calculated by Andermann et al. (2012) for some of the same gauging stations yield significantly different values, in some cases lower by 2× or more (Supplement Table S2).

5 Discussion

5.1 Short-term vs. long-term erosion rates

To first-order, the $^{10}\mathrm{Be}_{\mathrm{qtz}}$-derived, natural background erosion rates measured for the 1st-order Bore and Chinnya are remarkably similar to the present-day sediment fluxes (Table 1, Fig. 3). Denudation rates from $^{10}\mathrm{Be}_{\mathrm{qtz}}$ reflect removal in both solid and dissolved form, potentially complicating direct comparison with sediment fluxes, which do not include removal in dissolved form. However, dissolved fluxes are low relative to the total denudation at this site (dissolved fluxes are less than ~ 10 % of the total denudation flux; West et al., 2002), so this is not a major factor in our analysis.

The long-term denudation rates for the Bore and the Chinnya are indistinguishable from the soil loss rates from plots on well-maintained bari terraces and lie in the middle of the range of river suspended flux estimates for the Bore. The similarity of long-term and present-day erosion rates that we observe in the agricultural Likhu Khola contrasts with the significantly higher present-day vs. long-term fluxes measured in agricultural catchments in Sri Lanka and Ecuador (Fig. 3). If long-term rates in the Likhu are compared to soil loss observed on degraded forests and pastureland (Table 3), a stronger land use effect becomes apparent in Nepal. However, these soil losses are plot-level rather than catchment-integrated values, and the difference (~ 3× increase) is still not close to the > 10× erosional flux increase observed in some of the Sri Lanka and Ecuador catchments when comparing short- and long-term rates.

5.2 How representative are the short-term flux measurements?

The short-term data on stream sediment flux and soil loss from plots in the Likhu were all collected from a short time window (over 1–3 years) in the early 1990s. Erosion over longer (e.g., decadal or even centennial) timescales is most relevant for soil degradation, reservoir sedimentation, and similar environmental concerns. Rainfall and runoff were slightly lower than the longer-term average during the observational period in the 1990s in the Likhu, so the measured fluxes may underestimate actual erosion rates over decadal timescales (Brasington and Richards, 2000). Moreover, short-term measurements can inherently underestimate longer-term denudation rates if they miss episodic high-magnitude, low-frequency events (e.g., Covault et al., 2013; Kirchner et al., 2001). The similarity between short- and long-term rates that we observe might be an artifact of measurement, if decadal sediment fluxes are actually significantly elevated relative to the long-term rates but the measured sediment fluxes were simultaneously underestimated during our observational period. Sediment fluxes have been measured over a much longer period of time in the Trisuli River, downstream of the

Likhu Khola, with calculated sediment yields of 970 $\mathrm{t\,km^{-2}\,yr^{-1}}$ (Chalise and Khanal, 1997; unknown number of samples and time interval) and 542 $\mathrm{t\,km^{-2}\,yr^{-1}}$ (Andermann et al., 2012; based on 665 measurements between 1973–1979). These values are similar to the 341–1527 $\mathrm{t\,km^{-2}\,yr^{-1}}$ observed in the Bore Khola (Table 3). The Trisuli basin ($\sim$ 4500 $\mathrm{km^2}$ area) covers a much larger area than the Likhu and includes significant portions of the High Himalaya, so comparing rates from these two catchments is not straightforward. The High Himalaya generally produce higher long-term background erosion rates than the Middle Hills (Gabet et al., 2008; Godard et al., 2014), so if anything we might expect the Trisuli erosion rates to be higher than in the Likhu over similar time windows. The similarity of the Trisuli sediment fluxes to those measured in the Likhu provides a first-order indication that the Likhu fluxes are not grossly underestimated.

5.3 How representative are the background denudation estimates?

The long-term, background denudation rates calculated from $^{10}\mathrm{Be}_{\mathrm{qtz}}$ using Eq. (1) assume steady state, which may be perturbed in settings such as the Likhu over the long-term by mass wasting (e.g., Niemi et al., 2005; Puchol, 2013; West et al., 2014; Yanites et al., 2009), and in the short term by anthropogenic soil reworking (e.g., von Blanckenburg et al., 2004; Brown et al., 1998). We consider the importance of these non-steady state processes for calculated rates in the Likhu by modeling the perturbation to the concentration-depth profiles (see details in the Supplement). In brief summary:

- Observed mass wasting fluxes in the Bore and the Chinnya are low (Table 3), so we expect that landslide activity does not strongly bias our calculated steady-state denudation rates for these sites (see Supplement Section S2). This is supported by the lack of significant grain-size dependency of $^{10}\mathrm{Be}_{\mathrm{qtz}}$ for the Bore and Chinnya samples, since significant landslide contributions have been found to generate large grain size differences (e.g., Aguilar et al., 2014; Belmont et al., 2007; Brown et al., 1995; Puchol, 2013). However, such grain size variations are not universally observed (Clapp et al., 2002; Kober et al., 2012; Safran et al., 2005), so this cannot be taken as absolute confirmation that landslides are unimportant, but the combination of low present-day landslide fluxes and similarity across grain sizes suggests mass wasting processes probably do not strongly bias our estimated rates.

- Landslide occurrence is greater in the Likhu mainstem, and is high enough to theoretically introduce significant uncertainty in our calculations. The Likhu catchment area is sufficiently large ($> 100\,\mathrm{km}^2$) that it may be expected to effectively average mass wasting inputs that occur stochastically in time and space across the catchment area (cf. model predictions of Niemi et al., 2005; Yanites et al., 2009), although episodic events may bias denudation rates estimates to some extent even in large catchments (West et al., 2014). In any case, the denudation rates we infer for the Likhu mainstem are presented only for wider context and are not the primary reference for comparison to present-day sediment yields.

- The uncertainty introduced because of anthropogenic reworking of soils due to agricultural activity (e.g., von Blanckenburg et al., 2004; Brown et al., 1998) depends significantly on (i) the depth of agricultural reworking, and (ii) the depth of natural background soil mixing (see Supplement Section S3). We anticipate that the depth of reworking is not significantly greater than the depth of the mixed layer, since Likhu soils are on steep slopes and typically in the range of 0.5–2 m thickness. In this case, agricultural reworking would have no significant influence on denudation rates calculated from $^{10}\mathrm{Be}_{\mathrm{qtz}}$ (Granger and Riebe, 2007). However, if the depth of reworking exceeded the mixing depth by ~ 0.5 m, for example via rill formation (e.g., von Blanckenburg et al., 2004) the actual long-term denudation rates could be as much as ~ 50 % lower than those we infer from Eq. (1). For the 1st-order Bore and the Chinnya samples, which provide the reference for comparison to the short-term erosion rates, agricultural reworking is expected to be minimal since the upstream areas are predominantly forested (Fig. 2).

Although we cannot conclusively rule out some non-steady state bias in our calculation of background denudation rates, additional confidence in our inferred steady-state rates comes from comparison to long-term rates observed in other studies in the Nepal Middle Hills (Fig. 3; Supplement Table S1). Calculated steady-state denudation rates are similar across a wide range of catchments, despite differences in land use and catchment size; larger variability in steady-state rates from one catchment to another would be expected if $^{10}\mathrm{Be}_{\mathrm{qtz}}$-derived denudation rates were significantly influenced by land use or mass wasting in this environment. Moreover, the spatially consistent rates across the Nepal Middle Hills are also temporally consistent with long-term exhumation rates determined from thermochronology (Godard et al., 2014), suggesting that the inferred rates provide a reasonable estimate of actual long-term denudation.

5.4 Comparison of short- vs. long-term rates across Nepal

Additional short- and long-term erosion rate data from similar sites elsewhere in Nepal help provide more information to assess whether the short- vs. long-term comparison in the Likhu data is representative. The significant variability and uncertainty in the wider Nepal sediment flux data (e.g., compare data calculated by two different methods in Supplement Table S2) makes it difficult to directly compare the short-term fluxes measured at other sites with the long-term rates from the Likhu, and none of the other short- and long-term data are paired from the same sites. However, considering the distribution of denudation rates across the Nepal Middle Hills, the picture is consistent with the Likhu data (Fig. 3). Overall, there may be a hint of a slight increase of short-term fluxes compared to long-term, and this may reflect a slight anthropogenic enhancement of erosion. Nonetheless, there is no evidence to support a large systematic difference, and this is consistent with the similarity of short and long-term erosion rates observed for the Likhu.

One other intensively studied site in Nepal, the Khudi Khola, also shows similar long-term denudation rates and sediment fluxes, with both short- and long-rates erosion measured over a period of several years (Gabet et al., 2008; Niemi et al., 2005; Puchol, 2013). The Khudi catchment encompasses areas north of the MCT with very high total denudation rates (~ 2–$3\,\mathrm{mm\,yr^{-1}}$ for the catchment as a whole). These high rates are thought to be largely dominated by landslides, so the Khudi represents a significantly different geomorphic regime when compared to the Likhu, but again in this case the data do not suggest a dominant anthropogenic imprint on total erosional fluxes in the Nepal Himalaya.

5.5 Implications: sediment delivery, mass wasting, and soil production

The implications of our results are that most of the sediment carried by the Likhu Khola, and by other similar rivers draining the Nepal Middle Hills, does not come from agricultural land degradation but rather from naturally high rates of landscape denudation. This suggests that soil management efforts should not necessarily be expected to dramatically reduce sediment delivery to downstream reservoirs and floodplains.

However, the lack of differences between short- and long-term erosion rates in Nepal cannot be taken on their own as evidence that land use is not affecting soil loss and hastening potential degradation of soil resources. This is because it is difficult to use catchment-scale fluxes to tease apart land use effects if total erosion is dominated by gullies, landslides, debris flows, and analogous mass wasting sources. Where these processes are important, the observed catchment-scale rates – both short- and long-term – become dominated by the mass wasting supply, rather than by soil erosion, and small changes in erosion from soils become indistinguishable at the catchment scale. The comparison of short- and long-term rates then would not, on its own, reveal the extent to which agricultural land use degrades soil resources in the Middle Hills.

Mass wasting does not appear to dominate the erosion fluxes in the Bore and the Chinnya, but we can assess more thoroughly the relative importance of different erosion processes using data collected on mass wasting volumes and associated supply of sediment to rivers. For a steady state natural erosion system in the absence to agricultural activity, the difference between the long-term denudation rate (from $^{10}\mathrm{Be}_{\mathrm{qtz}}$) and the denudation rate driven by mass wasting should be the average rate of soil production on hillslopes (Heimsath et al., 2012). If the present-day mass wasting rates measured in the Likhu are assumed to reflect background natural fluxes from mass wasting, then the implied soil production rates (Fig. 4) would be 920 ± 429 $\mathrm{t\,km^{-2}\,yr^{-1}}$ for the Likhu catchment (1326 ± 429 $\mathrm{t\,km^{-2}\,yr^{-1}}$ total denudation minus 406 $\mathrm{t\,km^{-2}\,yr^{-1}}$ mass wasting) and 671 ± 101 $\mathrm{t\,km^{-2}\,yr^{-1}}$ for the Bore sub-catchment (728 ± 101 $\mathrm{t\,km^{-2}\,yr^{-1}}$ total denudation and 57 $\mathrm{t\,km^{-2}\,yr^{-1}}$ mass wasting). These inferred soil production rates, which are equivalent to ~ 0.26–0.35 $\mathrm{mm\,yr^{-1}}$, are similar for the Likhu and the Bore despite the very different rates of total denudation. These rates are probably minimum estimates, because the present-day mass wasting estimates may be enhanced due to land use (Gerrard and Gardner, 2002). If actual long-term mass wasting fluxes are lower, the inferred soil production rates would be higher.

Our minimum estimated soil production rates for the Likhu are relatively high in the global context but reasonable for mountain environments (cf. Heimsath et al., 2012; Larsen et al., 2014). They suggest that the natural conversion of bedrock to soil is expected to yield relatively high sediment fluxes from hillslopes. Thus erosional losses from agricultural soils in the Middle Hills should not inherently be a cause for alarm on their own, although very high rates of soil loss, for example from degraded or abandoned lands, should be of concern. The inferred soil production rates can be compared to plot-scale soil losses to estimate the agricultural soil budget (Fig. 5). For degraded forests and scrubland, the deficit that results from anthropogenic modification is significant, in the range of 500–1500 $\mathrm{t\,km^{-2}\,yr^{-1}}$, or ~ 0.2–0.6 $\mathrm{mm\,yr^{-1}}$ excess soil removal. This rate of removal could rapidly deplete soil resources (i.e., in comparison to A-horizon depths of ~ 10–40 cm in the Likhu). Data on soil loss rates are not available for khet terraces, but for bari terraces, the resulting deficit from soil erosion is insignificant, suggesting that these terraces are effective at retaining soil. However, this result should be treated cautiously. For example, slumping of terrace risers is frequently observed (e.g., Gerrard and Gardner, 2000) and if such damage is not repaired it could lead to longer-term enhanced erosion. Moreover, modeling of soil erosion in the Likhu suggests that rainfed bari terrace soil losses may be significantly higher than the measured rates used in Fig. 5, while degraded forest losses may be lower (Shrestha, 1997). If bari terraces loss rates are in the range of 1000 s of $\mathrm{t\,km^{-2}\,yr^{-1}}$, as suggested by the model results, associated soil deficits would be much larger for this land use type than shown in Fig. 5.

In any case, the budgets shown in Fig. 5 provide a useful context for considering how soil loss from agricultural land use compares to the long-term rates of soil production. One important consideration in such budgets is that the calculated soil production rates represent catchment-wide average values, and site-specific soil production rates are expected to vary significantly within the catchment, e.g., as a function of soil depth (Heimsath et al., 1997, 2012) which typically varies with topographic position. The deficits calculated for specific land use types provide a broad landscape perspective but are not expected to apply to all individual soil sites. It is also important to recognize that soil development and thickening is expected to take place in the short term where the soil erosion budget is positive under a given land use type, but over the long time scales of landscape evolution, these soils are likely to be disturbed by episodic losses, e.g., by slumping or other hillslope failure.

6 Conclusions

Data on denudation rates from the agriculturally modified Middle Hills of Nepal show no measurable increases in short-term erosion rates, determined from river sediment fluxes and plot soil loss rates, compared to long-term "natural" background denudation rates, determined from cosmogenic $^{10}\mathrm{Be}_{\mathrm{qtz}}$. The measured long-term cosmogenic rates are independent of the grain size analyzed for the catchments studied. The only significantly different long-term denudation rate is for the Likhu Khola mainstem, which may be associated with enhanced denudation from activity on the Likhu fault, but also may be influenced by the greater portion of agricultural land use in the catchment area and/or by alluvial reworking of sediments with low $^{10}\mathrm{Be}_{\mathrm{qtz}}$ by the larger river.

The similarity of short- and long-term rates in the Likhu Khola, and more widely in the Nepal Middle Hills, is in notable contrast to the large enhancement of short-term fluxes observed in other montane agricultural catchments. The Nepal data suggest that:

1. much of the sediment carried by rivers out of the Nepal Middle Hills is derived from natural erosion, comprising a combination of mass wasting and soil production from hillslopes, and does not result from soil degradation as a result of agriculture;
2. as suggested in previous research, well maintained terraced agricultural practices in the Nepal Middle Hills appear to prevent very rapid acceleration of erosion that may take place under other mountain agriculture; and
3. since overall erosion rates and rates of soil production are high, the loss of soil may not be unsustainable from well-maintained terraces, although less well managed lands may be subject to rapid soil depletion relative to soil production.

The sustainability of soil resources with respect to natural rates of hillslope soil production in the Himalayan Middle Hills depends on how lands are maintained. Poor land management indeed leads to unsustainable deficits of soil loss, while well-maintained terraces effectively mitigate such degradation. Additional data from longer time intervals that includes higher magnitude erosional events would be important for confirming these observations. It is also important to recognize that the results from this study only concern the physical rates of soil loss and do not capture other potential aspects of environmental degradation associated with intensive agricultural land use, such as nutrient losses from soils and impacts on aquatic systems (e.g., Schreier et al., 2006).

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Table 1. ^{10}Be in river sediment from the Likhu Khola basin in the Nepal Middle Hills.

Sample	Name	Date collected	Sample Lat/Long	Sample elevation (m)	Mean catchment elevation* (m)	Catchment area (km^2)	Grain size (mm)	^{10}Be$_{qtz}$ (10^3 at g^{-1} ±1σ)
CT71	Likhu Khola	9 May 2002	27.8975° N, 85.2212° E	533	1366	166.4	0.25–0.71	13.51 ± 3.13
CT84	Chinnya Khola	16 May 2002	27.8413° N, 85.3072° E	960	1308	0.6	0.25–0.71	22.85 ± 2.79
							0.71–2	22.33 ± 1.91
							2-4	21.87 ± 5.40
CT85	Bore Khola	16 May 2002	27.8411° N, 85.3076° E	962	1646	2.0	0.25–0.71	29.73 ± 2.51
							0.71–2	29.10 ± 3.80
							2–4	19.60 ± 3.56

* Mean elevation calculated from 30 m DEM, with catchment areas delineated using flow-routing algorithm in Grass GIS.

Table 2. Cosmogenic production rates and inferred denudation rates for Likhu Khola samples.

Sample	Catchment	Grain size (mm)	P_n (0)[a] (at g^{-1} yr^{-1})	P_m (0)[b] (at g^{-1} yr^{-1})	Steady-state denudation rate[c] (mm yr^{-1})	Averaging timescale (yrs)	Inferred soil production rate[d] (mm yr^{-1})
CT71	Likhu Khola	0.25–0.71	9.81	0.051	**0.51** + 0.17/ − 0.11	1370	~ 0.35
CT84	Chinnya Khola	0.25–0.71	9.44	0.050	**0.29** + 0.05/ − 0.04	2410	~ 0.27
		0.71–2			**0.30** + 0.04/ − 0.04	2350	
		2–4			**0.30** + 0.11/ − 0.07	2310	~ 0.26
CT85	Bore Khola	0.25–0.71	11.87	0.058	**0.28** + 0.04/ − 0.03	2490	
		0.71–2			**0.28** + 0.05/ − 0.04	2440	
		2–4			**0.42** + 0.11/ − 0.08	1640	

[a] Catchment-average ^{10}Be production rate in quartz at $z = 0$ by neutron spallation (calculated based on Balco et al., 2008).

[b] Catchment-average ^{10}Be production rate in quartz at $z = 0$ by muons (calculated based on Braucher et al., 2013).

[c] Denudation rate from Eq. (2) for steady state; errors reflect 16th and 84th percentiles of Monte Carlo distributions ($n = 10000$).

[d] Uncertainties not reported on soil production rates because they were not estimated for landslide fluxes.

* Bold values are medians of the distributions

Table 3. Present-day erosional sediment fluxes measured in the Likhu Khola.

Measurement	Source	Site	Sediment flux $\mathrm{t\,km^{-2}\,yr^{-1}}$
Suspended sediment flux	Brasington and Richards (2001)	Bore Khola	341–1527
Soil loss rate from plots	Gardner and Gerrard (2001, 2003)	Irrigated terraces	n.a.
		Rainfed terraces	560 ± 340
		Grassland	50
		Forest	50
		Degraded forest	1000–2000
Mass wasting flux by land use type	Gerrard and Gardner (2002)	Irrigated terraces	48
		Rainfed terraces	364
		Grassland	186
		Forest	80
		Degraded forest and scrubland	2395
Mass wasting flux by catchment	Gerrard and Gardner (1999, 2002)	Bore Khola	57
		Likhu Khola	551
		Likhu Khola*	406*
Flux from long term denudation	Table 1	Bore Khola	627–829
		Likhu Khola	897–1755

* Area-weighted average for Likhu catchment, based on estimated denudation rate of $0.325\,\mathrm{mm\,yr^{-1}}$ and landslide material density of $1.25\,\mathrm{g\,cm^{-3}}$, after Gerrard and Gardner (2002).

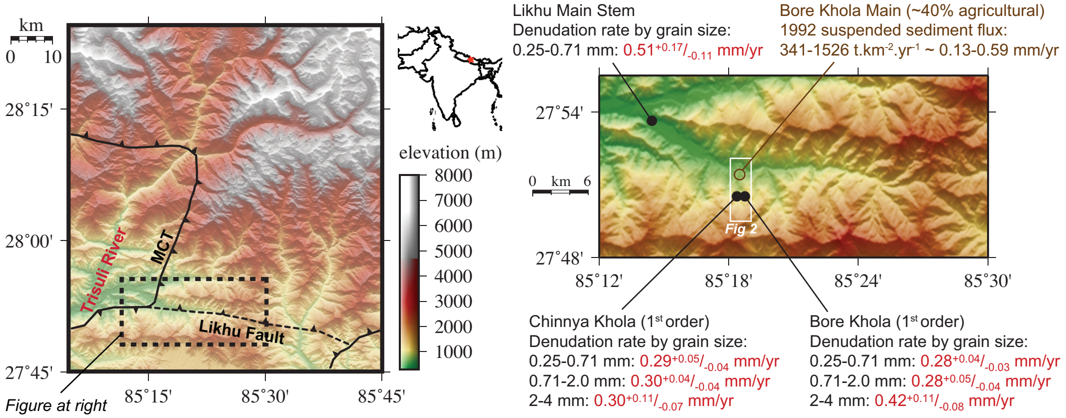

Figure at right

Likhu Main Stem
Denudation rate by grain size:
0.25-0.71 mm: $0.51^{+0.17}/_{-0.11}$ mm/yr

Bore Khola Main (~40% agricultural)
1992 suspended sediment flux:
341-1526 t.km^{-2}.yr^{-1} ~ 0.13-0.59 mm/yr

Chinnya Khola (1st order)
Denudation rate by grain size:
0.25-0.71 mm: $0.29^{+0.05}/_{-0.04}$ mm/yr
0.71-2.0 mm: $0.30^{+0.04}/_{-0.04}$ mm/yr
2-4 mm: $0.30^{+0.11}/_{-0.07}$ mm/yr

Bore Khola (1st order)
Denudation rate by grain size:
0.25-0.71 mm: $0.28^{+0.04}/_{-0.03}$ mm/yr
0.71-2.0 mm: $0.28^{+0.05}/_{-0.04}$ mm/yr
2-4 mm: $0.42^{+0.11}/_{-0.08}$ mm/yr

Figure 1. Map of the Likhu Khola study region. Map of central Nepal north of the Khatmandu Valley (left panel) and close-up map of the Likhu Khola (right panel), showing sampling sites for river sediment and corresponding $^{10}\mathrm{Be}_{\mathrm{qtz}}$-derived long-term denudation rates (see text). MCT: Main Central Thrust.

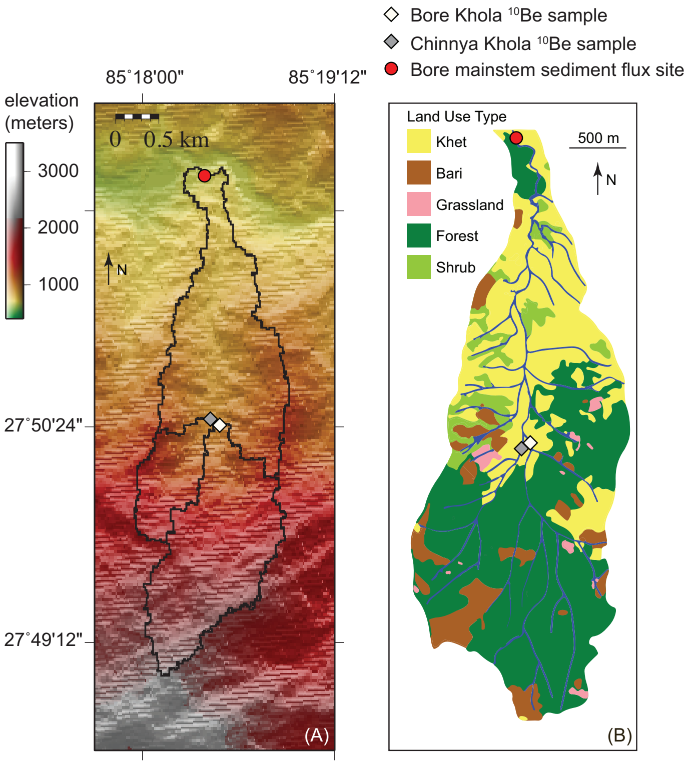

Figure 2. Detailed map of the Bore Khola study catchment. Maps of elevation **(A)** and land use **(B)** of the Bore Khola subcatchment of the Likhu Khola. The Bore Khole includes the 1st-order Bore and Chinnya headwater catchments that were sampled for determining long-term denudation rates from $^{10}\mathrm{Be}_{\mathrm{qtz}}$. Note that these first order catchments are predominantly forested with little agricultural land use, so they are expected to provide a robust background erosion rate. Land use map is adapted from Gerrard and Gardner (1999), with unknown projection that does not exactly match panel **(A)**. Bari are irrigated terraces; khet are rain-fed terraces.

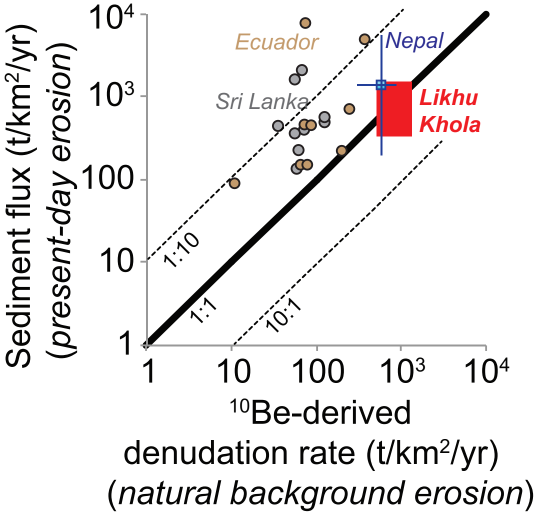

Figure 3. Comparison of short-term vs. long-term erosion rates for Nepal Middle Hills. Comparison of short-term erosion rates from sediment fluxes and long-term denudation rates from ^{10}Be concentrations in quartz from river sediment, from mountain catchments in different settings all with significant agricultural land use. Red box shows range of ^{10}Be$_{qtz}$-derived rates for Bore Khola determined in this study, compared to sediment fluxes from the Bore in 1992 (Brasington and Richards, 2001). Light blue point shows the mean (±standard deviation) ^{10}Be$_{qtz}$ denudation rate and the median (±5th and 9th percentiles) sediment flux from other catchments in the Nepal Middle Hills (note that these data are not from paired catchments and that the sediment fluxes are highly uncertain; see text and Supplement Tables S1 and S2). The Nepal data indicates little increase in present-day sediment fluxes about background denudation rates, in contrast to the large increases in present-day rates observed in many catchments in Sri Lanka (grey points; Hewawasam et al., 2004) and Ecuador (brown points; Vanackar et al., 2007).

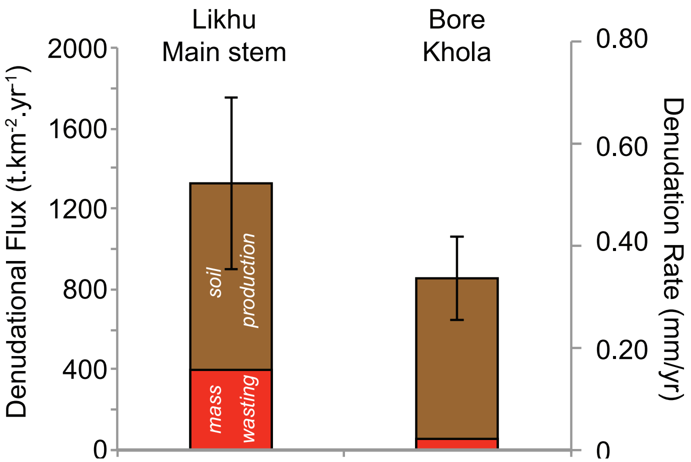

Figure 4. Inferred mass wasting and soil production for the Likhu Khola. Contribution to catchment-wide denudation from mass wasting (determined from present-day measurements) and hillslope soil production (inferred as difference between mass wasting and total measured denudation rates). If present-day catchment-wide mass wasting fluxes are assumed to represent the long-term average, then soil production rates are similar for the Likhu main catchment and the Bore sub-catchment. These values are minimum estimates for soil production since measured mass wasting values may be also enhanced by agricultural land use. Note that this partitioning yields a value for catchment-averaged soil production, and does not capture significant heterogeneity in soil production rates from one soil site to another within each catchment.

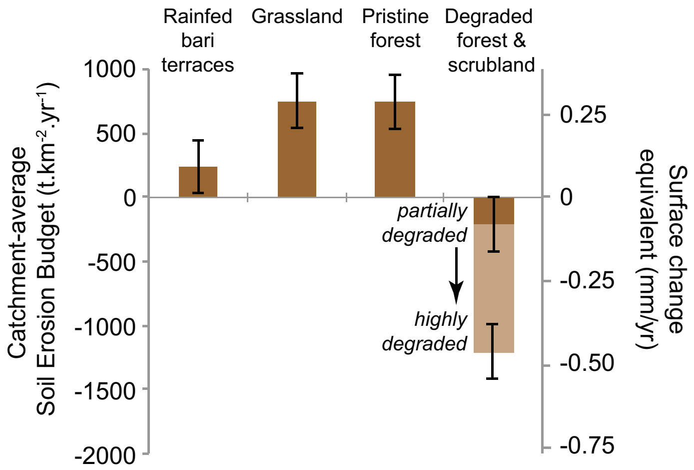

Figure 5. Net soil production/loss budget for different land use types in the Likhu Khola. Annual catchment-wide soil erosion budget based on inferred minimum soil production rates and measured soil losses from plots (Gardner and Gerrard, 2001, 2003). Site-specific soil production (and erosional loss) is likely to be highly variable, so the budget shown here will not apply to all soils. Nonetheless, the net budget illustrates that some land uses such as well-maintained terraces may have minimal effects on soil degradation, while other land uses may lead to highly unsustainable soil losses.