Comments to the Author:

I've now read the two reviews and the responses to these. For the most part, I am happy with the responses of the authors and think this is close to being ready to proceed to ESURF. The main component that I think still needs work is the sensitivity analysis. Both reviewers asked for this, and the authors responded by adding a section that shows the influence of single parameter values with all else held constant. I think this is work in the right direction, but more could be done to explain to readers how confident the authors are in the result. I suggest adding a few more sentences about how uncertain the input parameters are (temperature, precipitation and erosion) and how changing these parameters within the limits of their uncertainty modifies the results. This is more work, but I do hope that the authors have the model running and wiggling the parameters will not represent a major challenge. Doing this will give readers more confidence that the authors have correctly identified the mechanism for generating the observed pattern of terraces.

I would like to thank the editor for the comments. They have certainly helped improve the quality of the manuscript. We have done a more thorough sensitivity analysis for each parameter. This is presented in figure 9 and in the revised text. Uncertainties and sensitivities for the soil model are presented in Norton et al., 2014, so we focused this analysis on the resulting sediment transport capacity and sediment load at two location along the river profile; on the plateau at 30km downstream and near the coastal plains at 100km downstream. These represent the two distinct endmember settings of the Rio Pisco. We have also shuffled this analysis to just before the discussion as it removes some early references to results/discussion in the model set up and it allows for better flow.

Lined comments:

Page 2 line 7: "Dominant control on escarpment rivers": this is awkward phrasing. I would say dominant control on the geometry of these rivers, or on the incision of such rivers.

Changed to: "In this paper, we suggest that weathering is a dominant control on river form in escarpment settings as it is responsible for the production of sediment through the formation of regolith."

Page 2, line 12: Reference should be italic. Also, say “Since chemical weathering”.

Changed.

Page 3, line 28: Ending with “point of view” is slightly awkward .Consider rephrasing.

Changed to: ” While this scenario is logical, the ability of sediment delivery from hillslopes to control fluvial transport has not been tested.”

Page 4: Line 17 and thereafter: The mentions of the parameters in the text should have the same format as in the equations, so on this line the parameters need to be italic and have their subscripts. Check throughout to make sure there are no other typos of this kind.

Changed and fixed 2 other non-italicized parameters.

Page 4, line 23: The Heimsath 1997 paper is from a landscape in northern California that is not that similar to the landscapes studied here. Arjun has calculated this scalar in a number of places and I suggest adding a sentence to explain the range of these values and why you selected the one that you did. I also think in the discussion you should mention that this number can change as a function of climate change. If it is relatively easy to run the transport model, I would also suggest doing a sensitivity check of this parameter (I suspect it has only a small effect but it might be nice to demonstrate).

Added: “Globally, α has been measured between 0.017 and 0.042 cm-1 (Heimsath et al., 2001; 2005). The highest values result in slightly thinner soils that are equivalent within error to the modelled soil thicknesses using α = 0.03 cm-1 (see Norton et al., 2014). Lower values of α result in significantly thicker soils which would enhance river sediment loads during rapid soil stripping.”

Page 5, section 3.1. I think this needs a bit of work. First of all, the caption to figure 5 could include some more detail. It should explain that the curves show the predicted soil thicknesses if only the listed variables change. Secondly, this plot doesn’t really tell us how certain the authors are of the predicted soil thicknesses. I think there should be a second plot that shows how the predicted curve will vary based on the maximum and minimum values of reconstructed precipitation and temperature. Also, I would mention on line 5 where the temperature effect comes from (that is, restate that it affects the maximum soil production rate).

This has been reworked.

We have added: “In the model, temperature and precipitation influence the maximum soil production rate (Equation 1), while erosion determines the overall mass balance (Equation 3). Recent work by Heimsath et al. (2012) indicated that SPRmax may also be affected by erosion rate such that faster erosion results in faster soil production.” To section 3.1.

We have added: “The light grey line shows predicted soil thickness in the downstream direction using all parameters. We then held all other variables constant and allowed the temperature (medium grey line), precipitation (black line), and erosion (dashed line) to change downstream.” to the figure caption.

The uncertainties in soil thickness were discussed in Norton et al 2014 so we have put in a new sensitivity analysis of the coupled model in Figure 9 as it is more pertinent to this paper.

Page 5, line 29: A citation is needed here for the modern precipitation rate.

Added reference to Agteca, 2010 dataset.

Page 6, line 3: “Steady state is unclear in this context: if the denudation rate is increasing, how can things be steady state? Please explain.

Added: “We consider steady state to be the case where the soil production response time is significantly shorter than the timescale over which long-term climate changes (i.e. soil transitions smoothly between steady state thicknesses).”

Page 6, lines 15-16: The authors are running long term models but the variability of precipitation is from a 20 year dataset. The authors should mention how much precipitation rates are likely to have changed in the past.

Added: “Garraud et al. (2003) used an atmospheric transport which excluded ocean dynamics model to estimate glacial-interglacial climate on the Altiplano. Their ~10-20%

modelled glacial-interglacial precipitation variability through the Late Quaternary matches the ~16-18% inter-annual variability on the Altiplano from the Agteca (2010) dataset. As such, we assume that the 20 year data are at least broadly representative of long-term precipitation and use the relationship between absolute precipitation rate and relative variability (Figure 7b) to test the sensitivity of the model and propagate errors."

Page 7, line 2: I would use the word "homogenous" rather than "invariable".

Changed.

Page 7, line 16: The authors say equation 5 is fit to the Rio Pisco, but what was fit? They then say that the b exponent is "usually" 0.5. Was 0.5 used here or was that parameter fit to field observations?

We have fixed this. It was a holdout from the old version of the model. We scale width empirically to catchment area and include the variables and a figure now.

We scale channel width to catchment area using the empirical geometry relationship, $W = aQ_w^b$(e.g. Yalin, 1992) fit to the Rio Pisco, where a is 0.015 and b is 0.95 (Figure 7).

Page 10 line 4: It is not clear what distinction the authors are trying to make here. Are we supposed to understand there is some different sediment in the bedload compared to the total bedload? Are the CRN concentrations different in the bedload and in the terraces? A few extra sentences of explanation would be useful here.

We also acknowledge that the terrace sediments represent primarily the bedload flux while the cosmogenic nuclide-derived sediment flux is total load (i.e. dissolved, suspended, and bedload). This is because cosmogenic nuclides record total landsurface lowering, whether through chemical or physical weathering and terraces are by necessity built only of the physical load.

Page 10 line 5: typo delete "if".

Deleted.

Page 11, line 1: It seems, based on the discussion below, that the soil response time has been calculated so I think it would be better if the response time is stated explicitly here.

We added: "This is the case for the ~104 yr climate intervals in western Peru. For the Rio Pisco knickzone, modern erosion rates range from ~50-250 mm ky-1 (Abbühl et al., 2011) with annual precipitation between ~100 and 400 mm (Agteca, 2010). This results in soil response times (90% of the steady state value) of 5.3 - 25kyr (Norton et al., 2014)."

Figure 2: I suggest adding a sentence of explanation for the erosion rate curve in panel d.

Added: "Downstream erosion rates were estimated by spatially interpolating the erosion rate data of Abbühl et al. (2011) and extracting the long-profile."

Figure 6: An extra sentence or two of explanation for panels e and f are needed.

Added: "The steady state model (e) calculates the sediment load Qs as the sum of sediment delivered by erosion (erosion rate x timestep x local area) at each node. To model transient hillslope stripping, we remove the entire soil thickness (soil thickness x timestep x local area) at each node. These model setups provide endmember scenarios for hillslope response to changing climate."

On the potential for regolith control of fluvial terrace formation in semi-arid escarpments

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Abstract

Cut-fill terraces occur throughout the western Andes where they have been associated with pluvial episodes on the Altiplano. The mechanism relating increased rainfall to sedimentation is however not well understood. Here, we apply a hillslope sediment model and reported cosmogenic nuclide concentrations in terraces to examine terrace formation in semi-arid escarpment environments. We focus on the Rio Pisco system in western Peru in order to determine probable hillslope processes and sediment transport conditions during phases of terrace formation. Specifically, we model steady state and transient hillslope responses to increased precipitation rates. The measured terrace distribution and reconstructed sediment loads measured for the Rio Pisco agree with the transient model predictions, suggesting strong climatic control on the cut-fill sequences in western Peru primarily through large variations in sediment load. Our model suggests that the ultimate control for these terraces is the availability of sediment on the hillslopes with hillslope stripping supplying large sediment loads early in wet periods. At the Rio Pisco, this is manifest as an approximately 4x increase in erosion rates during pluvial periods. We suggest that this mechanism may also control terrace occurrence in other semi-arid escarpment settings.

1 Introduction

High elevation plateaus are commonly associated with either passive margins (e.g. Africa, Sri Lanka, Australia) or large convergent mountain systems (e.g. Himalaya, Andes). In either case, erosion on the plateau edge leads to the formation of rapidly eroding escarpments adjacent to the more slowly eroding plateaus (*Kober et al.*, 2006; *Matmon et al.*, 2002; *Seidl et al.*, 1996; *van der Beek et al.*, 2002; *Vanacker et al.*, 2007; *von Blanckenburg et al.*, 2004; *Weissel and Seidl*, 1997). In this paper, we suggest that weathering is a dominant control on river form in escarpment settings~~escarpment rivers~~ as it is responsible for the production of sediment through the formation of regolith. The antiquity of most of these plateaus suggests that they erode through parallel retreat (*Schlunegger et al.*, 2006) with somewhat constant topographic profiles. These large topographic gradients often result in orographic precipitation on the escarpment (e.g. *Bookhagen and Strecker*, 2008). Since chemical weathering is at least partially dependent on water supply (e.g. *White and Blum*, 1995a), regolith formation is also likely to be enhanced on the plateau, especially during wet phases.

Quaternary climate change has led to fluctuations in the available precipitation on both the plateaus and adjacent valleys. The fluvial cut and fill terrace systems, which are common in these settings, are typically attributed to this climate variability (*Bookhagen et al.*, 2006; *Steffen et al.*, 2009). Using a climate-dependent regolith production algorithm (*Norton et al.*, 2014) coupled with simple sediment transport laws (e.g. *Tucker and Slingerland*, 1997), we investigate the effects of climate change in the form of precipitation variation on the hillslope system and propose that hillslope regolith production and stripping may control cut and fill sequences during the Late Quaternary.

2 Setting

We focus on the Rio Pisco drainage basin, situated on the western Andean margin at c. 17° S, central Peru. This stream flows from its headwaters at ~4000 m asl across the Altiplano Plateau before plunging into a deeply incised canyon. This region marks a broad knickzone, which connects the mostly non-incised Miocene Altiplano Plateau to the flat, low-lying coastal plains (Figure 1). The high elevation plateau is characterized by high precipitation rates and low erosion rates, while the knickzone exhibits lower precipitation rates but much faster erosion (Figure 2). The knickzone is interpreted to maintain its slope while eroding headward due to low erosion rates at the plateau margin (*Abbühl et al*., 2011). Above the

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knickzones, the streams are still graded to the Miocene baselevel. This high elevation plateau could be the result of dynamic reorganization of river channels (*Willett et al.*, 2014) and/or the uplift of the western Andes (e.g. *Schlunegger et al*., 2006, *Schildgen et al.*, 2007). Along the knickzone, the Rio Pisco is currently under sediment capacity as evidenced by the narrow modern channel where the stream cuts into valley fill and bedrock. The upper river reaches are primarily bedrock channels, while lower reaches are alluvial. Downstream of the knickzone, the floodplain widens and the river becomes braided, attesting to an excess of sediment.

A series of cut-fill terraces and debris flow deposits fill the widening channel to within ~40km from the coast (e.g. *Steffen et al.*, 2009; *Bekaddour et al.,* 2014). These valley fills consist of both fluvial conglomerates and hillslope-derived debris flow breccias, which could indicate phases of landsliding (e.g. *McPhillips et al*., 2014). We proceeded according to *Litty et al.* (2015) and measured the exposed thickness and extent of >100 terraces in the Pisco Valley (Figure 3). These were classified as fluvial (composed of moderately-well sorted, well-rounded clast-supported cobbles) or colluvial (composed of poorly sorted, angular to sub-rounded, matrix-supported clasts; Figure 4). The terraces were correlated based on elevation and composition.

Steffen et al. (2009) dated the Late Quaternary terraces, which are abundant in the lower reaches downstream of the knickzone, from ~40 to 120 km downstream distance. The ages of the terrace accumulation correspond with well-known wet periods in the western Andes (e.g. Minchin, 47.8-36 ka and Tauca, 26-14.9 ka, *Baker et al.,* 2001a, 2001b; *Fritz et al*., 2004; *Placzek et al.*, 2006). As documented by *Steffen et al.* [2009], regolith is shed over ca. 10-15 ky timescales from the hillslopes as debris flows during these pluvial periods. These authors suggested that increased rainfall resulted in increased erosion and thereby increased sediment supply to the river, causing a phase of deposition in the valley, starting generally with debris flows from the hillslopes. They argued that as hillslopes became depleted of sediment, the river begins to incise again while discharge remains high. While this scenario is logical, the ability of sediment delivery from hillslopes to control fluvial transport ~~it~~ has not been tested ~~from a sediment transport oriented point of view~~. In this contribution, we present a model linking the production of sediment through weathering with a sediment transport model to explore the conditions leading to the formation of the Rio Pisco terraces.

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3 Hillslope Regolith

The mechanisms and rates of weathered regolith production are commonly expressed in the context of erosion rates such that slower erosion rates are associated with thicker soil cover (e.g. *Heimsath et al.*, 1997). The Western Andean margin of Peru provides a setting in which weathered regolith is thick on the slowly eroding plateau, but nearly absent at low elevations despite even lower erosion rates. This seeming contradiction is best explained by gradients in the governing climatic variables. *White and Blum* (1995b) showed that solute fluxes from a global compilation of granitic watersheds approach 0 as precipitation approaches 0. In order to best model this gradient in soil thickness, we apply the climate dependent regolith production model of *Norton et al* (2014), which was based on the temperature and precipitation dependent weathering data of *White and Blum* (1995b). The model predicts time-transgressive or steady state soil production rates and soil thicknesses for a given mean annual temperature and mean annual precipitation, and mean erosion rate. Temperature (*T*), precipitation (*P*), and silicate mineral activation energy (E_a) set the maximum soil production rate (SPR_{max}):

$$SPR_{max} = a_0 P e^{\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)}, \qquad (1)$$

where R is the gas constant, T_0 is 5°C, and a_0 = 0.42 is a precipitation scaling factor tuned to the Pisco soil dataset (*Norton et al.*, 2014). The instantaneous soil production rate (*SPR*) and change in soil thickness are calculated as a function of soil depth (*H*);

$$SPR = SPR_{max} e^{-\alpha H}, \qquad (2)$$

and local mass balance;

$$\frac{dH}{dt} = a_0 P e^{\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)} e^{-\alpha H} - D, \qquad (3)$$

where α = 0.03 cm^{-1} is the soil depth scalar ~~(e.g. *Heimsath et al.*, 1997)~~ (e.g. *Heimsath et al.*, 1997) determined as the best fit to the Pisco dataset (*Norton et al.*, 2014) and *D* is the denudation rate. Globally, α has been measured between 0.017 and 0.042 cm^{-1} (*Heimsath et al.*, 2001; 2005). The highest values result in slightly thinner soils that are equivalent within error to the modelled soil thicknesses using α = 0.03 cm^{-1} (see *Norton et al.*, 2014). Lower values of α result in significantly thicker soils which would enhance river sediment loads during rapid soil stripping. Rapid soil production rates and thick soils are predicted for high

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Formatted: Not Superscript/ Subscript temperatures and precipitation amounts. Erosion rates are the ultimate control on the output soil thickness and system response time.

3.1 Regolith thickness in the Rio Pisco drainage basin

We test the sensitivity of the *Norton et al.* (2014) model to the different input variables by allowing one variable to change while holding the other two at the plateau value (Figure 5). In the model, temperature and precipitation influence the maximum soil production rate (Equation 1), while erosion determines the overall mass balance (Equation 3). Precipitation and erosion have the largest individual control on the calculated steady-state regolith thickness. The temperature effect is much smaller. As such, variations in temperature (both intra- and inter-annual) are negligible compared to other parameters. If regolith thicknesses were dependent on temperature alone, ~~our~~ the model predicts a more or less uniform blanket over the entire catchment, increasing slightly towards the coast as temperatures get warmer. In contrast, regolith depth would decrease rapidly towards the coast in a solely precipitation-dependent state, approaching 0 at ~100 km from the headwaters. Finally, if erosion were the sole process controlling and limiting regolith thicknesses, the value of this variable would be expected to decrease in the rapidly eroding knickzone, but to thicken again farther downstream. We note that in all cases, a positive dependence of the maximum soil production rate SPR_{max} on erosion, as proposed by *Heimsath et al*. (2012), would result in thicker soil cover over a wider range of erosion rates, but should not change the overall distribution of soils from the model. The modeled regolith depths generally match the sparse measured depths from ridgetops in the Pisco Valley (e.g. *Norton et al.*, 2014). Ridgetops were sampled for soil depth as the hillslopes throughout the escarpment tend to be stripped bare of weathered material in the modern climate. Additionally, the rugged terrain, poor access and lack of drillings precluded the collection of further data.

3.2 Hillslope sediment delivery mechanisms

Sediment supply to the river was calculated by combining the climate dependent soil production model (*Norton et al.*, 2014) with cosmogenic nuclide-derived denudation rates (*Abbühl et al*., 2010, 2011; *Bekaddour et al.*, 2014). To determine modern sediment supply, we allow the Pisco river to erode at its long-term rate as determined by cosmogenic nuclides, assuming no hillslope storage (an assumption vital to the cosmogenic nuclide methods as well; e.g. *von Blanckenburg*, 2006). The modern discharge is taken as the basin integrated precipitation rate (*Agteca*, 2010), which decreases down river which yields an average discharge of 20 m^3/s along the coastal section. As such, we ignore the effects of evapotranspiration and infiltration, but still capture a more realistic discharge for the Pisco, which is c. 23 m^3/s as measuring at the gauging station of Letrayoc (*Bekaddour et al.*, 2014).

We model two potential responses to increased rainfall during pluvial periods: steady state increase in denudation rate, and transient stripping of hillslope sediment (Figure 6). We consider steady state to be the case where the soil production response time is significantly shorter than the timescale over which long-term climate changes (i.e. soil transitions smoothly between steady state thicknesses). Based on cosmogenic nuclide concentrations from the Piura River in northwestern Peru, *Abbühl et al*. (2010) showed that, at steady state, denudation rates increase exponentially with increasing precipitation rates below the plateau edge but are independent of precipitation on the plateau. Our first model assumes this relationship to hold in time as well as space. We therefore hold the denudation rate constant on the plateau throughout time, but vary the denudation rate below the plateau edge as $D_2 = D_1 * \exp^{cP}$ (where D_2 and D_1 are the predicted and initial denudation rate (mm yr^{-1}), respectively, P is the mean annual precipitation (mm) and c = 0.0041 is empirically derived for the Western Andes; *Abbühl et al*., 2010) up to the limit of soil thickness (i.e. the maximum allowable erosion rate is the soil production rate). ~~This steady state model predicts a small but continuous increase in sediment load over the duration of the pluvial period (e.g. Figure 6, 8b). Precipitation variability is modelled from the 20 year averages for the rainfall stations in the immediate vicinity (Figures 1 and 7; *Agteca*, 2010). The largest inter-annual variability occurs on the plateau where annual rainfall is the highest. Relative rates are, however, highest near the coast where large single events can more than double the annual averages (Figure 7b). *Garraud* et al. (2003) used an atmospheric transport which excluded ocean dynamics model to estimate glacial-interglacial climate on the Altiplano. Their ~10-20% modelled glacial-interglacial precipitation variability through the Late Quaternary matches the ~16-18% inter-annual variability on the Altiplano from the *Agteca* (2010) dataset. As such, we assume that the 20 year data are at least broadly representative of long-term precipitation and use the relationship between absolute precipitation rate and relative variability (Figure 7b) to test the sensitivity of the model and propagate errors.~~

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Temperatures during the Last Glacial Maximum are estimated to have been 5-9C lower on the Altiplano (Baker et al., 2001).

The transient model is based on the widespread presence of debris flow deposits in the terraces and the rapid accumulation rates suggested by OSL dating (*Steffen et al*., 2009). These observations suggest that sediment is rapidly eroded from the hillslopes during pluvial periods, resulting in a sediment pulse into the basin. To model this transient sediment delivery, we assume complete hillslope stripping downstream of the knickzone (where slopes are steep) upon initiation of the pluvial period followed by negligible erosion after the hillslopes become bare of sediment (e.g. Figure 6, 8c). We compare the longitudinal sediment transport capacity/sediment load ratios to the existing terrace distribution in the Pisco valley.

4 Fluvial transport

The eroded material delivered to the channels will either be deposited or transported, depending on the transport capacity of the stream. Channel flow and potential incision in these streams are typically expressed in terms of shear stress and sediment transport equations, and flow is driven by temporally variable (but spatially invariablehomogeneous) precipitation.

We begin by coupling the weathering-dependent model with an algorithm that describes sediment transport in channels and apply it to the long profile of the Rio Pisco. Sediment transport capacity T_c is calculated using the Bagnold equation (e.g. *Tucker and Slingerland*, 1994; 1997):

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$$T_c = \frac{BW}{(\rho_s - \rho_w)\rho^{1/2} g}(\tau - \tau_c)(\tau^{1/2} - \tau^{1/2}{}_c) \qquad (4)$$

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where B is a constant equal to 10 (e.g. *Hancock and Anderson*, 2002), W is channel width, ρ_s and ρ_w are the densities of sediment and water, respectively, g is gravity, τ is the applied bed shear stress, and τ_c is the critical shear stress for the entrainment of the D_{50}, which is the 50th percentile grain size. Note that here we calculate sediment transport capacity, and the actual sediment discharge is dependent on the sediment yield of the basin. We scale channel width to discharge catchment area A using the empirical downstream hydraulic geometry relationship, $W = aA^b$ (e.g. Yalin, 1992) fit to the Rio Pisco, :

$$W = aQ_w^{\ b} \qquad (5)$$

where a is a constant0.015 and b is usually assumed to be 0.595 (*Tucker and Slingerland*, 1997) (Figure 7x).

Shear stress is calculated as:

$$\tau = \rho_w g \left(\frac{Q_w}{W}\right)^{3/5} n^{3/5} S^{7/10} \qquad (65)$$

(after *Hancock and Anderson*, 2002) where Q_w is the water discharge, n is Manning's n, and S is the channel gradient. Critical shear stress is calculated as

$$\tau_c = 0.047(\rho_s - \rho_w) g D_{50} \qquad (76)$$

(e.g. Leopold et al., 1964) where D_{50} is the 50th percentile grain size, here taken to be the mean grain size measured in the Pisco Valley terraces, 0.02 m (*Litty et al.*, 2015). We applied a Shield's parameter of 0.047, which is consistent with the suggetions proposed by *Meyer-Müller* (1948) and *Heller and Paola* (1992) for these streams.

The cumulative sediment supply is calculated as the sum of the upstream hillslope erosional fluxes contributing to point n along the channel:

$$Q_s = \sum_{i=1}^{n} D_i A_i \qquad (87)$$

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and water discharge is likewise calculated as the sum of the upstream area and precipitation amount,

$$Q_w = \sum_{i=1}^{n} c P_i A_i \qquad (~~9~~8)$$

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where A_i is the lateral contributing hillslope area (m^2) to point i in the channel, P_i is precipitation (mm yr^{-1}) and D_i is erosion (mm ky^{-1}) from this area, and c is a runoff coefficient. The runoff coefficient accounts for losses due to evapotranspiration and infiltration. Because of a lack of data we assume in this study that $c=1$, however, it is likely that the coefficient is smaller as evapotranspiration (e.g., *Bloschl et al.*, 2013) and infiltration in the lower reaches of the Rio Pisco lead to lower discharge downstream. In this case, T_c will decrease more rapidly downstream.

The fluvial transport model, while simple in its approach, provides a first order estimate of river response in this system. The 1-D model is not capable of representing changes in fluvial transport style or changing hydraulic parameters. This is especially noticeable in our treatment of hydraulic geometry and shear stress which are calculated using empirical relationships (e.g. *Hancock and Anderson*, 2002*; Shields*, 1936). We adopted this approach as a more formal treatment of roughness and skin friction (e.g. *Ferguson*, 2007) would require knowledge of flow velocity or depth which are lacking for the Rio Pisco. Despite these limitations, the shear stress approach has been shown to adequately model strath terrace formation which involves both erosion and deposition in the fluvial system (*Hancock and Anderson*, 2002).

4.1 Coupled hillslope-river model

We apply the 1-D coupled sediment transport - weathering dependent soil model to the Rio Pisco using 1 km node spacing (Figure 6e, f). All dependent variables are free to change at each node (e.g. spatially variable denudation rates, precipitation rate, and temperature). We take precipitation rates from the Global Historical Climatology Network compilation of *Agteca* (2010), which are based on 493 individual rain gauges measured over 10 to 85 years (mean 20 years) within Peru. For the Rio Pisco model inputs (Figure 2), we use the long-

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profile trend of precipitation based on an interpolation of the 17 rain gauges that are within 25 km of the catchment. The largest inter-annual variability occurs on the plateau where annual rainfall is the highest. Relative rates are, however, highest near the coast where large single events can more than double the annual averages (Figure 8b). *Garraud* et al. (2003) used an atmospheric transport which excluded ocean dynamics model to estimate glacial-interglacial climate on the Altiplano. Their ~10-20% modelled glacial-interglacial precipitation variability through the Late Quaternary matches the ~16-18% inter-annual variability on the Altiplano from the *Agteca* (2010) dataset. As such, we assume that the 20 year data are at least broadly representative of long-term precipitation and use the relationship between absolute precipitation rate and relative variability (Figure 8b) to test the sensitivity of the model and propagate errors. Both sediment transport capacity and sediment load are dependent on precipitation. Decreased precipitation on the plateau could lead to transport limited streams through decreased sediment transport capacity (Figure 9). Otherwise, within realistic limits, precipitation does not significantly change our results.

Temperature is determined for each node assuming an atmospheric lapse rate of 6° C/km, and the mean annual temperature of 12.8° C of Cusco, Peru at 3204m elevation a.s.l. For the Rio Pisco model inputs (Figure 2), we use the long profile trend of precipitation based on an interpolation of the 17 rain gauges that are within 25 km of the catchment.Temperatures during the Last Glacial Maximum are estimated to have been 5-9°C lower on the Altiplano (Baker et al., 2001). The sensitivity of the coupled model to temperature is tested within the glacial/interglacial variability. As temperature only affects the maximum soil production rate it has no effect on the transport capacity or the sediment load on the plateau where erosion rates are held constant (Figure 9).

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Denudation rates for the Rio Pisco have been measured by *Abbühl et al.* (2010) and complemented by *Bekaddour et al.* (2014). We use a tensioned spline (weight 0.1) to interpolate denudation rate values for each point along the river profile. Denudation rates reach a maximum of ~250 mm/ky in the knickzone and are much lower on both the plateau and near the coast at ~11 mm/ky. We exclude one sample (Pis 11) from the dataset of *Abbühl et al.* (2011) as it is most likely heavily influenced by recycling of shielded sand from the ~50ky conglomerate terraces and therefore does not represent the basin-wide denudation rate at this point. These long-profile values are used as inputs to calculate soil depths along the

Pisco Valley and to determine sediment delivery to the channel. Sediment load is controlled by erosion rate in the model. At very rapid erosion rates, the sediment loads may exceed transport capacity on the plateau (Figure 9). In all other scenarios, erosion variation does not change our results.

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4.2 Sediment load and transport

Calculated modern sediment transport capacity and sediment flux (determined from ^{10}Be derived denudation rates (*Abbühl et al*., 2010) show that the transition from supply limit to transport limit coincides with the upstream appearance of terraces (Figure 10~~8~~). Note that supply and transport limits refer in this case to excess transport capacity and sediment load, respectively. We also acknowledge that the terrace sediments represent primarily the bedload flux while the cosmogenic nuclide-derived sediment flux is total ~~bed~~load (i.e. dissolved, suspended, and bedload). This is because cosmogenic nuclides record total ~~landsurface~~land surface lowering, whether through chemical or physical weathering and terraces are by necessity built only of the physical load. As such, our estimated sediment loads are likely a maximum. Even ~~if~~ with this caveat, the stream is supply limited in the upper bedrock-floored sections, and transport limited further down where cut-fill terraces are abundant, and the modern river flows over a wide floodplain made up of gravelly sediments. In the case that the Rio Pisco basin maintains steady-state (e.g. the response time of the weathering system is faster than the rate of climate change), the main response to a doubling of precipitation rates (using eq. ~~9~~ 8 for water flux, and eq. ~~8~~ 7 for the erosional flux) from modern is for the stream to aggrade over a relatively short ~20 km long section below the knickzone (Figure 10~~8~~b). During drier climates, the sediment transport capacity in this zone exceeds the loads as denudation rates are low. According to this simulation of wet and dry steady-states, extensive cut-and-fill terraces should only be common in a narrow band near the knickzone. Farther downstream, sediment flux exceeds sediment transport capacity both during wet and dry phases and the stream primarily aggrades.

A transient stripping scenario is suggested by the results of *Steffen et al*. (2009). According to Figure 3 in their paper, the transition towards a more humid climate resulted in an episodic phase of erosion, where regolith was rapidly stripped from hillslopes below the plateau over ~10-15 ky, supplying large volumes of sediment to the trunk stream. These phases of fluvial aggradation are followed by waves of incision travelling back up valley. This suggests that an episodic phase of rapid hillslope stripping occurs, resulting in a large sediment pulse to the rivers, followed by a rapid drop off of hillslope-derived sediment as the hillslope reservoirs are emptied. We model this transient response towards a more humid climate as a two-step process. Upon initiation of the wet period, all weathered regolith (calculated from the model) below the plateau is stripped from the hillslopes and supplied to the stream. In the second step, the bare hillslopes are unable to contribute new sediment to the stream. This is exacerbated by potentially faster erosion rates during the wet phases that inhibit the formation of a significant regolith cover. In this scenario, sediment supply to the stream during this step is controlled solely by inputs from the plateau, with little to no sediment being supplied from below the plateau. This pulsed-transient case necessitates that sufficient time has elapsed between wet periods for the weathered regolith to build up to the steady state values (*Bekaddour et al.*, 2014). This is the case for the ~10^4 yr climate intervals in western Peru. For the Rio Pisco knickzone, modern erosion rates range from ~50-250 mm ky-1 (*Abbühl et al.*, 2011) with annual precipitation between ~100 and 400 mm (*Agteca*, 2010). This results in soil response times (90% of the steady state value) of 5.3 - 25kyr (*Norton et al.*, 2014). This is the case for the ~10^4 yr climate intervals in western Peru (e.g. *Norton et al.*, 2014). The result of this simulation is that sediment accumulates over the entire downstream reach of the stream as regolith is rapidly stripped from the hillslopes. Once this material is exhausted, however, the bedrock-alluvial transition moves approximately 100 km upstream, incising the valley fill (Figure 810c). This scenario is more consistent with the observed occurrence of terraces in the Rio Pisco (Figure 3). This scenario is also supported by ^{10}Be-derived paleodenudation rates (Figure 911; *Bekaddour et al.*, 2014). The first sediments deposited during each wet phase are debris flow breccias with high ^{10}Be concentrations (lower palaeodenudation rates), indicative of long residence time on the hillslopes. The subsequent fluvial gravels are derived from sediment with shorter residence times (higher palaeodenudation rates). The continued contribution of fluvial sediment with high palaeodenudation rates suggests that reality most likely lies between the steady-state and pulsed-transient cases. However, these end-member scenarios can be informative for understanding terrace formation in escarpment environments

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5 Discussion and Conclusion

Fluvial aggradation in the Rio Pisco has been associated with wet periods (*Steffan et al.*, 2009). This has important consequences for regolith production on the Western Escarpment. On the plateau, where precipitation rates are ~1000 mm/yr and denudation rates ~10 mm/ky, the response time of soils is > 100 ky (*Norton et al.*, 2014). In the knickzone, precipitation is ~100-400 mm/yr and denudation rates are 100-250 mm/ky. This results in soil response times of ~< 10ky. More importantly, the knickzone reach lies in a special climatic and denudational setting in which small decreases in precipitation or increases in denudation can push the system into a state where regolith production rates are unable to keep up with denudation. Once conditions become amenable to regolith formation again, cover can reform on millennial timescales on the hillslopes due to the rapid response times (*Norton et al.*, 2014).

When applied to the modern Rio Pisco the model suggests transient behavior. On the long term, knickzone migration is eroding into the plateau as the river adjusts to a lower baselevel. In addition to the direct control that baselevel has on the river, undercutting can dramatically change the rates and style of hillslope response (*Roering et al.*, 2015; *Bilderbach et al.*, 2015). In the Pisco Valley case, little sediment is available in the knickzones and response may resemble the Waipaoa catchment in New Zealand where baselevel lowering generated abundant deep-seated landslides (*Bilderbach et al.*, 2015). Such a response is partially supported by the presence of large boulders in the channels and coarse-angular clasts in the debris flow deposits. On the short term, hillslopes are quickly stripped of sediment, decoupling hillslope regolith from the incising channel. Key to both of these processes is that the timescale of hillslope stripping (as implied by the occurrence of debris flows) is less than the timescale of regolith production. For instance, an increase in precipitation rates can lead to a temporary increase in denudation rates (*Tucker and Slingerland*, 1997) until the hillslopes are stripped of sediment, exposing bedrock (*Carson and Kirkby*, 1972). The regolith is then regenerated during intermediate climates. An additional complication, recently suggested by *Heimsath et al*. [2012], is that the maximum regolith production rate may also be dependent on erosion rates such that faster erosion rates yield faster production rates. While we have not built this relationship into this study; we note that such a relationship would lead to enhanced regolith thickness in the knickzones and have no effect on the slowly eroding plateau or coastal plains.

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The model clearly shows that regolith production on hillslopes has a large impact on sediment-flux in the river. The sequences of cut-fill terraces observed in the Rio Pisco are more consistent with transient hillslope stripping during wet phases, followed by incision once the hillslopes are bare of regolith. This can have significant consequences for the evolution of bedrock streams in particular, where incision rates are at least partially dependent on sediment flux (*Whipple and Tucker*, 2002). It is interesting to note that much the terraced zone does not adhere to the definition of a bedrock channel presented by *Turowski et al*. (2008) since much of the erosion is acting on previous fill. In this case, the bedrock/alluvial transition of *Tucker and Slingerland* (1996) is better defined as underload/overload with the result being local erosion or deposition of the substrate, be it bedrock or sediment. Large changes in sediment delivery will also result in significant changes in hydraulic geometry, channel gradient, and erosion regime both at-a-station and downstream. Deposition during high sediment load phases would flatten and widen the rivers, temporarily reducing driving stress. For the transient case presented here, this would enhance the modelled relationship leading to larger variation between erosional and depositional phases.

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The occurrence of cut-fill terraces in the Rio Pisco is best explained by a pulsed-transient response in which increased precipitation rates strip hillslopes of weathered material. The hillslopes remain bare until climate again becomes amenable to the preservation of weathered regolith. Such a scenario could be important in other escarpment settings.

Acknowledgements

The authors would like to thank M. Trauerstein and T. Bekaddour for assistance in the field. Two anonymous reviews and excellent editorial handling by Simon Mudd have improved the manuscript. This work was supported in part by a VUW Faculty of Science grant to KPN and SNF grant 200020_155892 awarded to FS.

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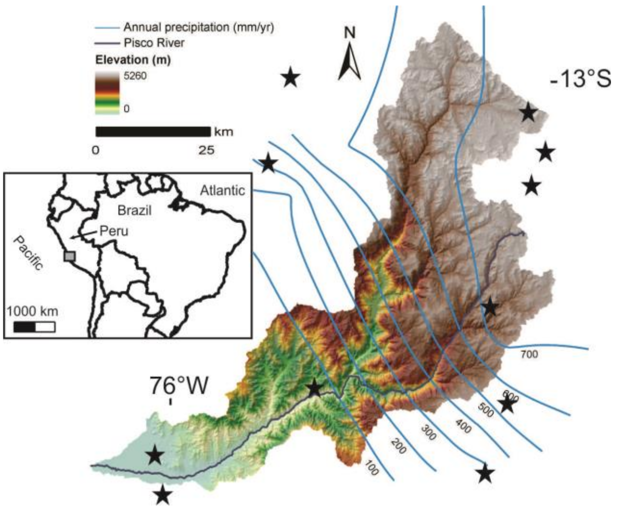

Figure 1. Setting and geomorphology of the Pisco River. Precipitation stations used to interpolate the annual rainfall are starred (*Agteca*, 2010).

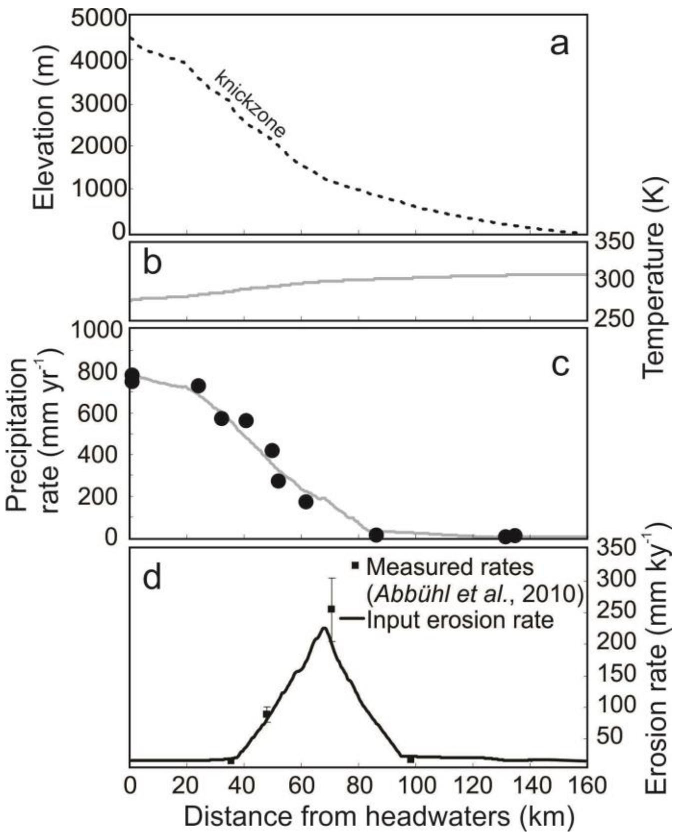

Figure 2. Geomorphic and climatic input parameters along the the Pisco River including: (a) river longitudinal profile, (b) temperature, (c) annual precipitation, and (d) erosion rate. Input rainfall stations (*Agteca*, 2010) projected along strike onto the Pisco River profile are shown by closed dots, input erosion rates with errors (*Abbühl et al.*, 201~~0~~1) are shown by closed squares. Downstream erosion rates were estimated by spatially interpolating the erosion rate data of *Abbühl et al.* (2011) and extracting the long-profile.

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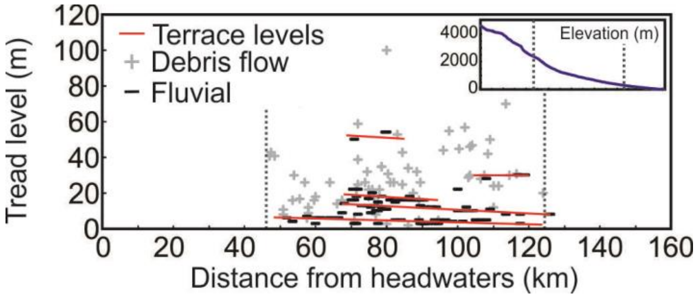

Figure 3. Locations of terraces along the Pisco River. The majority of terraces are concentrated in the zone from ~50 to 120 km downstream. Inset shows the location of the terraces (dashed lines) along the river profile.

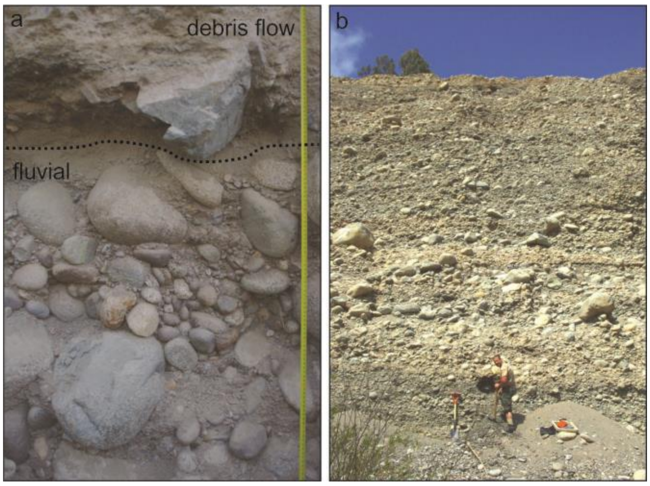

Figure 4. Rapid soil stripping in the Pisco valley is evidenced by abundant debris flow deposits (top, a) mixed with coarse, poorly sorted fluvial deposits (bottom, a and b, note person for scale).

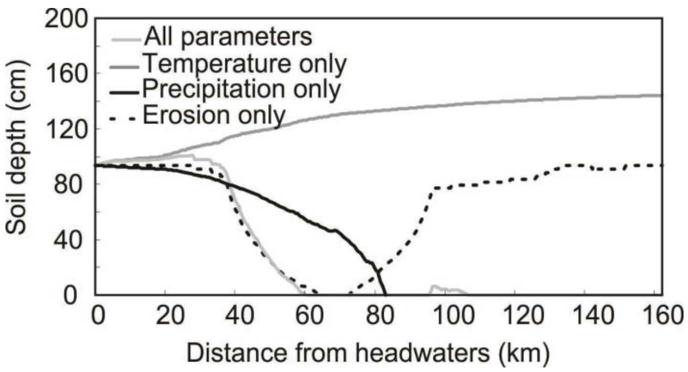

Figure 5. Sensitivity of the *Norton et al.* (2014) soil production model to each input parameter for the longitudinal profile of the Rio Pisco. The light grey line shows predicted soil thickness in the downstream direction using all parameters. We then held all other variables constant and allowed the temperature (medium grey line), precipitation (black line), and erosion (dashed line) to change downstream.

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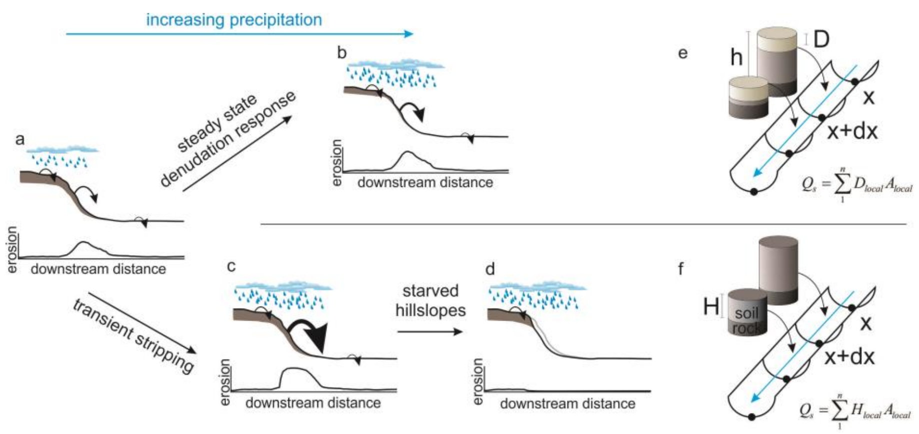

Figure 6. Conceptual model of two modes of hillslope response to increased precipitation in semi-arid environments. Arrow size represents the relative contribution of eroded hillslope sediment to the river. In the steady state case (a-b), increased precipitation results in increased hillslope erosion rates on steep hillslopes which are balanced by increased soil production (e.g. *Norton et al.*, 2014). In the transient case (a-c-d), increased precipitation results in rapid stripping of hillslope sediment as debris flows and shallow landslides (c), followed by negligible erosion on steep hillslopes once the soil mantle is eroded (d). The model set up for each of these scenarios is shown in e (steady state) and f (transient stripping). The steady state model (e) calculates the sediment load Qs as the sum of sediment delivered by erosion (erosion rate x timestep x local area) at each node. To model transient hillslope stripping, we remove the entire soil thickness (soil thickness x timestep x local area) at each node. These model setups provide endmember scenarios for hillslope response to changing climate.

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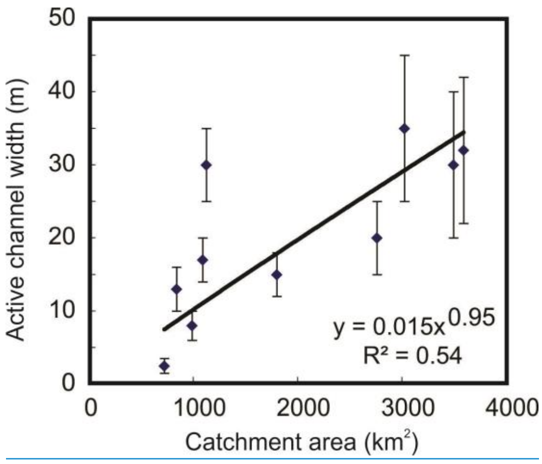

Figure 7. Active channel width/area scaling for the Rio Pisco.

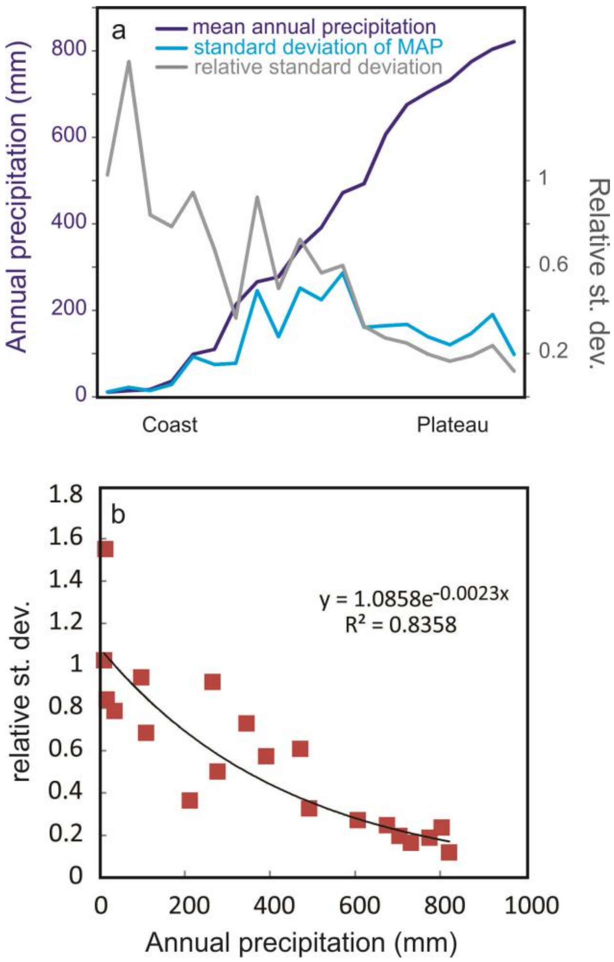

Figure 8~~7~~. Variation in annual precipitation calculated from 20 year monthly averages (*Agteca*, 2010). The relative interannual variability is largest near the coast where El Nino years bring increased precipitation (a). The relationship between relative variability and annual precipitation (b) was applied to the soil production and transport models and carried through as uncertainty (Figures 9 and ~~8~~10).

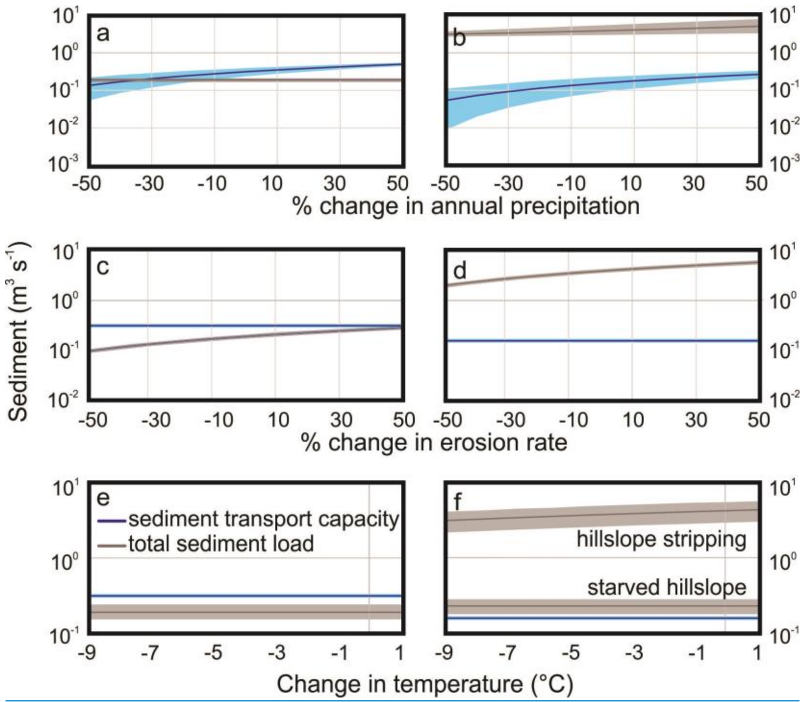

Figure 9. Response of sediment transport capacity (blue lines) and total sediment load (brown lines) to changes in annual precipitation (a, b), erosion rate (c, d), and temperature (e, f) for nodes on the plateau 30km downstream (a, c, e) and beyond the knickzone 100 km downstream (b, d, f). Each variable was changed within the estimated range for glacial/interglacial fluctuations (*Baker et al.*, 2001; *Garaud et al.*, 2003). The uncertainty for precipitation response (a, b) is propagated from the modern variability (*Agteca*, 2010; Figure 7). We assume an average 10% uncertainty in erosion rates (c, d) derived from cosmogenic nuclides and a 30% uncertainty in temperature (e, f) reflecting large uncertainties in the lapse rate. In all cases, the long-term variability does not likely change our model results. The exception to this is that sediment transport capacity on the plateau can drop below the sediment load at very low annual precipitation (a) or very fast erosion (c).

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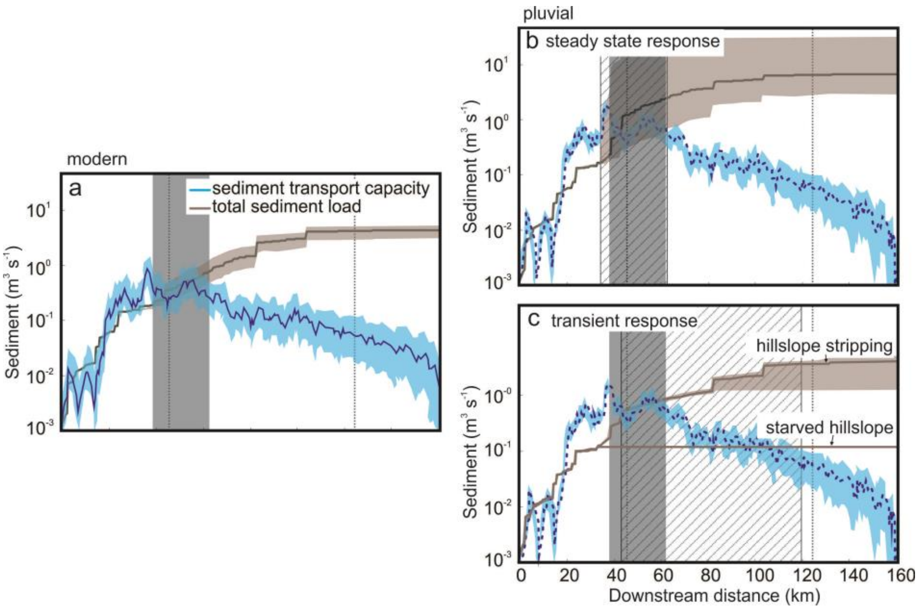

Figure ~~8~~10. Model of hillslope erosion through (a) steady state erosion and (b) transient hillslope stripping. In each graph, the solid grey area indictes the range of the modern bedrock/alluvial transition. The cross-hatched area indicates the endmember locations of the bedrock/alluvial transitions for each scenario. The grey stippled lines indicate the location of the Pisco River terraces. In the steady state case, the sediment load, Q_s, is proportional to the aerially summed upstream denudation rate, *D*, even if there is a thick regolith mantle, h. The result is a minimal shift in the bedrock/alluvial transition (the point at which sediment load exceeds sediment transport capacity; *Tucker and Slingerland*, 1997) between wet and dry phases (b). In the transient case, the entire modelled soil mantle (after *Norton et al.*, 2014) is stripped during a wet phase such that the sediment load, Q_s, is proportional to the aerially summed upstream regolith mantle, *H*, followed by a lack of sediment during the starved phase. The modelled result is a significant downstream shift in the bedrock/alluvial transition (c), which roughly corresponds to the observed occurance of terraces in the Pisco valley.

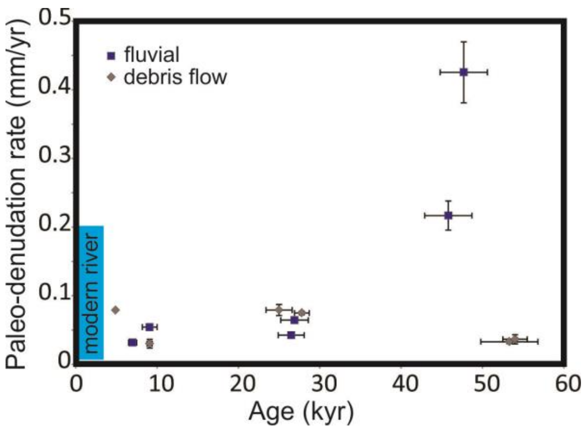

Figure 911. Accelerated erosion following initial deposition of debris flow material supports the idea of rapid stripping of a stable regolith mantle. The initial high concentrations (low paleo-denudation rates) for the debris flow deposits could represent long residence time on hillslopes while the low concentrations (high paleo-denudation rates) for the fluvial material could be the result of rapid removal of the regolith cover (data after *Abbühl et al.,* 2011 and *Bekaddour et al.,* 2014).