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Effects of seasonal variations in vegetation and precipitation on catchment erosion rates along a climate and ecological gradient: Insights from numerical modelling

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Abstract. Precipitation in wet seasons influences catchment erosion and contributes to annual erosion rates. However, wet seasons are also associated with increased vegetation cover, which helps resist erosion. This study investigates the effect of present-day seasonal variations in rainfall and vegetation cover on erosion rates for four catchments along the extreme climate and ecological gradient (from arid to temperate) of the Chilean Coastal Cordillera (~26 °S – ~38 °S). We do this using the Landlab-SPACE landscape evolution model modified to account for vegetation-dependent hillslope-fluvial processes and hillslope hydrology. Model inputs include present-day (90 m) topography, and a timeseries (from 2000-2019) of MODIS-derived NDVI for vegetation seasonality; weather station observations of precipitation; and evapotranspiration obtained from GLDAS NOAH. Simulations were conducted with a step-wise increase in complexity to quantify the sensitivity of catchment scale erosion rates to seasonal variations in precipitation and/or vegetation cover. Simulations were conducted for 1,000 years (20 years of vegetation and precipitation observations repeated 50 times). After detrending the results for long-term transient changes, the last 20 years were analyzed. Results indicate that when vegetation cover is varied but precipitation is held constant, the amplitude of change in erosion rates relative to mean erosion rates ranges between 6.5% (humid-temperate) to 36% (Mediterranean setting). In contrast, in simulations with variable precipitation change and constant vegetation cover, the amplitude of change in erosion rates is higher and ranges between 13% (arid) to 91% (Mediterranean setting). Finally, simulations with coupled precipitation and vegetation cover variations demonstrate variations in catchment erosion of 13% (arid) to 97% (Mediterranean setting). Taken together, we find that precipitation variations more strongly influence seasonal variations in erosion rates. However, the effects of seasonal variations in vegetation cover on erosion are also significant (between 5-36%) and are most pronounced in semi-arid to Mediterranean settings and least prevalent in arid and humid-temperature settings.

Keywords: Landlab, vegetation, Chilean Coastal Cordillera, biogeomorphology, seasonality, precipitation.

1 Introduction

Catchment erosion rates vary spatially and temporally (e.g., Wang et al., 2021) and depend on topography (slope, Carretier et al., 2018) vegetation cover and type (e.g., Zhang et al., 2011; Starke et al., 2020; Schaller and Ehlers, 2022) and precipitation rates (e.g., Cerdà, 1998; Tucker and Bras, 2000). Over annual timescales, temporal variations in catchment erosion occur in response to seasonal variations in precipitation and vegetation cover. For example, previous work has found that a significant fraction of annual erosion occurs during wet seasons, with high runoff rates (Hancock and Lowry, 2021; Leyland et al., 2016; Gao et al., 2021; Wulf et al., 2010). However, this increase in precipitation during wet seasons also promotes vegetation growth, which in turn influences erosion rates (Langbein and Schumm, 1958; Zheng, 2006; Schmid et al., 2018). Seasonality, and longer-term, changes in both precipitation and vegetation cover plays a crucial role in intra-annual changes in erosion rates (Istanbulluoglu and Bras, 2006; Yetemen et al., 2015; Schmid et al., 2018; Sharma et al., 2021). The intensity, frequency, and seasonality of precipitation and vegetation cover change within a year depend on the climate and ecological conditions of the area of interest (Herrmann and Mohr, 2011). One means of investigating the effects of seasonality in precipitation and (or) vegetation cover on erosion rates is through landscape evolution modeling (LEM), which can be parameterized for variations in vegetation-dependent hillslope and fluvial processes over seasonal time scales.

Previous modeling and observational studies have investigated the effects of seasonality in precipitation and vegetation on catchment erosion. Bookhagen et al., (2005), Wulf et al., (2010), and Deal et al., (2017) investigated the effects of stochastic variations in precipitation on erosion and sediment transport in the Himalayas. They found that high variability in rainstorm days (>80% of MAP) during the wet season (summer monsoon) caused high variability in the suspended sediment load. Work by Chakrapani (2005) identifies the control of mean local relief and seasonality in precipitation on sediment load in rivers. Similar seasonality in sediment loads was reported in a field study in Iran, using sediment traps and erosion pins. These authors concluded that wet seasons have maximum erosion rates (>70% of annual), which decreases in the dry season (<10% of annual) (Mosaffaie et al., 2015). Field observations in the heavily vegetated Columbian Andes concluded that soil erosion and nutrient losses are significantly influenced by precipitation seasonality (Suescún et al., 2017). In contrast, work by Steegen et al., (2000) in a loamy agricultural catchment in central Belgium found suspended sediment concentrations in streams were lower during summer (wet) rather than winter (dry) months due to the development in vegetation cover in the wet season. Other workers have found a dependence of seasonal erosion on ecosystem type. For example, Istanbulluoglu et al., (2006) found a reduction in soil loss potential to storm frequency in humid ecosystems compared to arid and semi-arid regions. Work by Wei et al., (2015) documented that differences in vegetation cover may contribute to long-term erosion and sedimentation. However, seasonal variations in runoff and sediment yield are mainly influenced by intra-annual rainfall variations. Finally, previous work in a Mediterranean environment (Gabarrón-Galeote et al., (2013) described rainfall intensity as the main factor in determining hydrological erosive response, regardless of the rainfall depth of an event.

When looking at seasonal vegetation changes in more detail, several different studies suggest these changes are important for catchment erosion. For example, Garatuza-Payán et al., (2005) emphasized that seasonal patterns in erosion are strongly influenced by plant phenology demonstrated by the changes in vegetation cover (as measured by NDVI). A similar study on the Loess Plateau, China, by Zheng (2006) documented decreasing soil erosion as vegetation cover increases during the wet season. Work conducted in a forested setting (Zhang et al., 2014) documented the importance of tree cover as an effective filter for decreasing the effects of rainfall intensity on soil structure, runoff, and sediment yield. Numerical modeling studies have also found a significant impact of vegetation on erosion. For example, Zhang et al., (2019) found that when precipitation is kept constant, the effect of vegetation cover change on sediment yields is significant (20-30% of the total flux). Also, during the early to the mid-wet season, the richness and evenness of plant cover play an essential role in reducing erosion rates during low rainfall events (Hou et al., 2020). However, in the case of high-intensity rainfall events at the start of a wet season, when vegetation cover is low, the duration and intensity of rainfall were found to significantly affect erosion rates (Hancock and Lowry, 2015). Other work conducted in a Mediterranean environment points to the coincidence of peak rainfall erosivity in low vegetation cover settings, leading to an increased risk of soil erosion (Ferreira and Panagopoulos, 2014). Despite potentially conflicting results in the previous studies, what is clear is that seasonality in precipitation and vegetation covers are co-conspire to influence catchment erosion, although which factor (precipitation or vegetation) plays the dominant role is unclear.

This study complements the previous work by applying a Landscape Evolution Model (LEM) to investigate seasonal transients in catchment erosion due to variations in precipitation and vegetation. We do this for four locations in the extreme climate and ecological gradient (i.e., arid, semi-arid, Mediterranean, and humid temperate) of the Chilean Coastal Cordillera. Our efforts are focused on testing two hypotheses: (1) if precipitation is the first-order driver of seasonal erosion rates, then the influence of seasonal changes in vegetation cover would be of low significance, and (2) catchment erosion in arid and semi-arid regions is more sensitive to seasonality in precipitation and vegetation than the Mediterranean and humid temperate regions. To test the above hypotheses, we conduct a sensitivity analysis of fluvial and hillslope erosion over four Chilean study areas to investigate the individual effects of seasonal changes in vegetation cover and precipitation compared to simulations with

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coupled variations in precipitation and vegetation cover. We do this using a two-dimensional LEM (the Landlab-SPACE software), which explicitly handles bedrock and sediment entrainment and deposition. We build upon the approach of Sharma et al., (2021) with the additional consideration of soil-water infiltration. Our model setup is focused on present conditions in the Chilean Coastal Cordillera (Fig. 1) and use as input present day topography from SRTM DEMs (90 m) for four regions with different climate/ecological settings. Simulations in these different ecosystems are drive by observed variations vegetation cover from MODIS NDVI (between 2000 – 2019) and observed precipitation rates over the same time period from neighboring weather stations.

2 Study Areas

This section summarizes the geologic, climate, and vegetation settings of the four selected catchments (Fig. 1) investigated in the Chilean Coastal Cordillera. These catchments (from north to south) are located in the Pan de Azúcar National Park (arid, ~26°S), Santa Gracia nature preserve (semi-arid, ~30°S), and the La Campana (mediterranean, ~33°S) and Nahuelbuta (temperate-humid, ~38°S) national parks. Together, these study areas span ~1,300 km distance of the Coastal Cordillera. These study areas are chosen for their steep climate and ecological gradient from North (arid environment with small shrubs) to South (humid temperate environment with evergreen mixed forests) (Schaller et al., 2020). The study areas are part of the German-Chilean priority research program EarthShape (www.earthshape.net) and ongoing research efforts within these catchments.

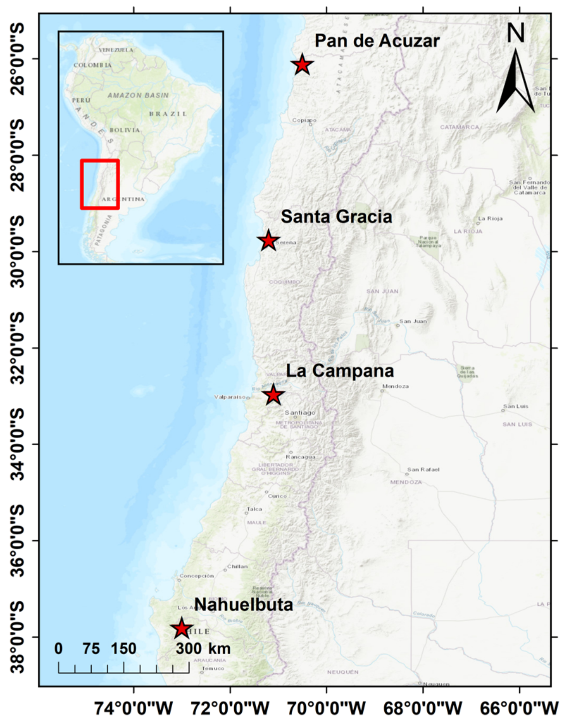

Figure 1. Study areas in the Coastal Chilean Cordillera ranging from an arid environment in the North (Pan de Azúcar), semi-arid (Santa Gracia), Mediterranean (La Campana), and humid temperate environment in the South (Nahuelbuta). The above map is obtained from the Environmental System Research Institute (ESRI) map server (https://services.arcgisonline.com/ArcGIS/rest/services/World_Topo_Map/MapServer, last access: 25 April 2022).

The bedrock of the four study areas is composed of granitoid rocks, including granites, granodiorites, and tonalites in Pan de Azúcar, La Campana, and Nahuelbuta, respectively and gabbro and diorites in Santa Gracia (Oeser et al., 2018). The soil types

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in each catchment were identified as a sandy loam in three northern catchments (with high bulk density: 1300 – 1500 kg m^{-3}) and sandy clay loam in Nahuelbuta (with lower bulk density: 800 kg m^{-3}) (Bernhard et al., 2018). The western margin of Chile along the latitudes of the different study areas is characterized by a similar tectonic setting whereby an oceanic plate (currently the Nazca plate) has been subducting under the South American plate since the Palaeozoic. Despite this common tectonic setting along, slight differences in modern rock uplift rates are documented in the regions surrounding the three northern catchments (i.e., < 0.1 mm yr^{-1} for ~ 26 °S to ~33 °S) (Melnick, 2016) and the southern catchment (i.e., 0.04 to > 0.2 mm yr^{-1} for ~38 °S over the last 4±1.2 Ma) (Glodny et al., 2008; Melnick et al., 2009). Over geologic (millennial) timescales, measured denudation rates in the region range between ~0.005 to ~0.6 mm yr^{-1} (Schaller et al., 2018). To facilitate a comparison between the study areas and focus on erosion variations from seasonal changes in precipitation and vegetation, we assume a uniform rock uplift rate of 0.05 mm yr^{-1} for this study. This rate is broadly consistent with the range of previously reported values.

The climate gradient in the study areas ranges from an arid climate in Pan de Azúcar (north) with mean annual precipitation (MAP) of ~11 mm yr^{-1} to semi-arid in Santa Gracia (MAP: ~ 88 mm yr^{-1}), the Mediterranean in La Campana (MAP: ~350 mm yr^{-1}), and a temperate-humid climate in Nahuelbuta (south) with a MAP of 1400 mm yr^{-1} (Ziese et al., 2020). The observed mean annual temperatures (MAT) also vary with latitude ranging from ~20°C in the north to ~5°C in the south (Übernickel et al., 2020). The previous gradients in MAP and MAT and latitudinal variations in solar radiation result in a southward increase in vegetation density (Bernhard et al., 2018). The vegetation gradient evident from mean MODIS Normalized Difference Vegetation Index (NDVI) values range from ~0.1 in Pan de Azúcar (north) to ~0.8 in Nahuelbuta (south) (Didan, Kamel, 2015). In this study, NDVI values are used as a proxy for vegetation cover density, similar to the approach of Schmid et al. (2018).

This gradient in climate and vegetation cover from north to south in the Chilean Coastal Cordillera provides an opportunity to study the effects of seasonal variations in vegetation cover and precipitation on catchment-scale erosion rates in different environments.

3 Methods

This section comprises a description of model inputs (section 3.1), estimation of runoff rates (section 3.2), model setup (section 3.3), and initial and boundary conditions (section 3.4). This is followed by an overview of simulations conducted (section 3.5) and a brief description of how detrending the model results was conducted to remove long-term transients (section 3.6).

3.1 Data used for model inputs

In contrast to previous modeling studies (Schmid et al., 2018; Sharma et al., 2021) in the same regions, we used present-day topography as the initial condition for simulations instead of a synthetic topography produced during a model spin-up phase in LandLab. Initial topography for the four selected catchments was obtained by cropping the SRTM digital elevation model (DEM) in rectangular shapes encapsulating the catchment of interest (Fig. 1). These catchments are same as those investigated with previous soil, denudation, and geophysical studies (e.g., Bernhard et al., 2018; Oeser et al., 2018; Schaller et al., 2018; Dal Bo et al., 2019)/ The DEM has a spatial resolution of 90 m and is the same as the cell size used in the model (dx and dy) (SRTM data set of Earth Resources Observation And Science (EROS) Center, 2017). Maximum relief of ~1852 m is observed in La Campana (~33 °S), followed by ~1063 m in Santa Gracia (~30 °S), ~809 m in Nahuelbuta (~38 °S) and ~623 m Pan de Azúcar (~26 °S). Catchment sizes considered vary between ~64 km^2 in Pan de Azúcar, ~142.5 km^2 in Santa Gracia, ~106.8 km^2 in La Campana and ~68.7 km^2 in Nahuelbuta. We note that present-day topography as the initial condition in simulations can introduce an initial transient in erosion rates due to model erosional parameters (e.g., erodibility, hillslope diffusivity) differing from actual parameters within the catchment, we address this issue through a detrending of model results described later.

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Precipitation data applied over each study area (Fig. 3b) was acquired from the Global Precipitation Climatology Centre (GPCC) for the period 01/03/2000 to 31/12/2019 (DD/MM/YEAR). The data has a spatial resolution of 1° (~111 km) and a 1-day temporal resolution and comprises daily land-surface precipitation from rain gauges built on Global Telecommunication System-based and historic data (Ziese et al., 2020). The previous data was augmented with daily precipitation weather station data from 01/02/2020 to 28/02/2020 obtained from Übernickel et al., (2020). We do this to include all the seasons between 2000 to 2019, i.e., from the Austral Autumn of 2000 to the Austral Summer of 2019. The periods (months of a year) of specific seasons in the Chilean Coastal Cordillera are illustrated in Table 1. Seasonal precipitation rates were calculated by summing up daily precipitation rates at three-month intervals. The seasonality and intensity of precipitation in the wet season (winter) increases from the arid (Pan de Azúcar) to humid temperate (Nahuelbuta) region.

Table 1. Months of a year corresponding to specific seasons in the Chilean Coastal Cordillera

Seasons	Months
Summer[d*]	December - February
Autumn[w*]	March - May
Winter[w*]	June - August
Spring[d*]	September - November

*d: dry season, w: wet season

NDVI derived from remote sensing imagery has been proven as an effective tool to estimate seasonal changes in vegetation cover density (Garatuza-Payán et al., 2005). Normalized difference vegetation index (NDVI) values were obtained from MODIS (Didan, Kamel, 2015) satellite data and were used as a proxy for changes in vegetation cover in the catchments. The NDVI data were acquired for 20 years (01/03/2000 – 28/02/2020), with a spatial resolution of 250 m and temporal resolution of 16 days. For application within the model simulations, the vegetation cover dataset was resampled to match the spatial resolution (90 m) of SRTM DEM and temporal resolution of 3 months. To summarize, season variations in precipitation rate and vegetation cover were applied to the simulations between 01/03/2000 and 28/02/2020 and encompass a 20-year record of observation variations in these factors.

Additional aspects of the catchment hydrologic cycle were determined using the following approaches for the same time period previously mentioned. First, evapotranspiration (ET) data was obtained from Global Land Data Assimilation System (GLDAS) Noah version 2.1, with a monthly temporal resolution and spatial resolution of 0.25° (~28 km) (Beaudoing et al., 2020; Rodell et al., 2004). The data was obtained from March-2000 to February-2020. Due to the coarse resolution of the dataset, ET is assumed to be uniform over the entire catchment area. No higher resolution datasets were available over the 20-year time-period of interest.

Soil properties such as the grain size distribution (sand, silt, and clay fraction) and bulk density were adapted from Bernhard et al., (2018) to estimate soil water infiltration capacity in each study area. Based on these soil properties, the soils have been classified as a sandy loam (in Pan de Azúcar, Santa Gracia, and La Campana) and sandy clay loam (Nahuelbuta). Average bulk density values of 1300 kg m^{-3}, 1500 kg m^{-3}, 1300 kg m^{-3}, and 800 kg m^{-3} were used for Pan de Azúcar, Santa Gracia, La Campana, and Nahuelbuta, respectively (Bernhard et al., (2018).

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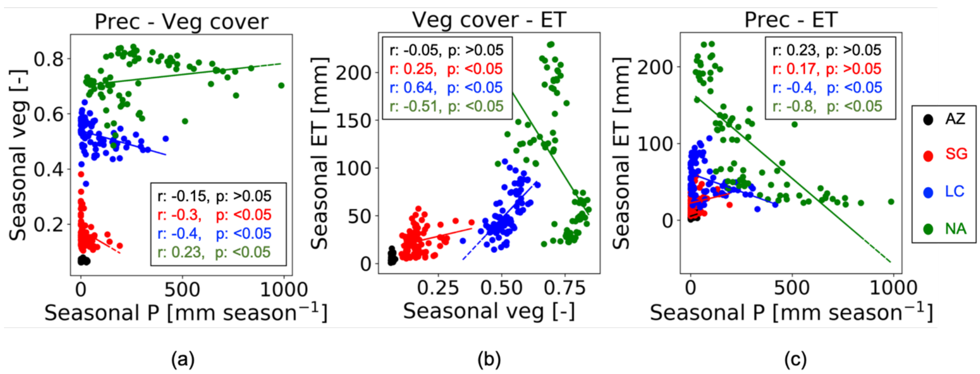

Figure 2. Parameter correlation for model input data (i.e., seasonal precipitation, vegetation cover and evapotranspiration) including: (a) seasonal precipitation [mm season^{-1}] and fraction of vegetation cover [-], (b) fractional seasonal vegetation cover [-] and evapotranspiration [mm], and (c) seasonal precipitation [mm season^{-1}] and evapotranspiration [mm]. The plots represent observations corresponding to Autumn of 2000 to Summer of 2019. Each data point represents one season and are color coded by study area (AZ: Pan de Azúcar, SG: Santa Gracia, LC: La Campana, and NA: Nahuelbuta).

Figure 2 shows correlations between the model input data, such as variable climatic or hydrologic cycle metrics (i.e., precipitation and evapotranspiration) and vegetation cover for each study area investigated. The relationships, and regression lines, shown for each area in different climate-ecological zones the general seasonal relationships over the 20 years (i.e., Autumn of 2000 – Summer of 2019) of data. For example, the correlation between seasonal precipitation and vegetation cover (Fig. 2a) illustrates a moderate negative correlation ($r > -0.4$) in the semi-arid (SG) and Mediterranean (LC) regions. In contrast, vegetation in the humid temperate region (NA) is positively correlated (r: 0.23). ET and vegetation cover are positively correlated (Fig. 2b) in the semi-arid (SG) and Mediterranean regions (LC). However, the correlations are negative in the humid-temperate region (NA). The correlation between seasonal precipitation and ET (Fig. 2c) is slightly positive (r: ~0.2) in the semi-arid region (SG) and moderately negative (r: -0.4) in the Mediterranean (LC) study area. However, we observe a strong negative correlation (r: -0.8) between precipitation and ET in humid-temperate and Mediterranean regions (LC and NA, Fig. 2c). This negative correlation is owed to the steep negative gradient in temperature (e.g., ~2.5 °C in NA) and solar radiation (Übernickel et al., 2020) during winters (wet season) in southern latitudes (LC and NA).

3.2 Estimation of runoff rates

The precipitation rates [m season^{-1}] are subjected to soil-water infiltration [m season^{-1}] and evapotranspiration [m season^{-1}] to estimate the seasonal runoff rates [mm season^{-1}]. The runoff rates (R) at every time step (t) are calculated using actual soil-water infiltration (I_a) and evapotranspiration (ET) as follows,

$$R(t) = P(t) - I_a(t) - ET(t) \quad (1)$$

where, *P* is the precipitation amount in a season. This relationship was applied in the model grid cells with non-zero sediment thickness.

The soil-water infiltration rate was estimated by applying the Green-Ampt equation (Green and Ampt, 1911; Julien et al., 1995):

$$f(t) = K_e\left(1 + \frac{\psi \cdot \Delta\theta}{F}\right) \quad (2)$$

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where f(t) is the infiltration rate [m s^{-1}] at time t, K_e is the effective hydraulic conductivity [m s^{-1}], F is the cumulative infiltration [m], Ψ is the suction at the wetting front [m], and Δθ is the difference between saturated and initial volumetric moisture content [m^3 m^{-3}]. Effective hydraulic conductivity is highly variable and anisotropic; hence, it was considered to be uniform with a value of 1×10^{-6} m s^{-1} for each catchment.

Following the approach of Istanbulluoglu and Bras, (2006) for loamy soils, the soil-water infiltration was modified to account for variable vegetation cover in each grid cell, as follows:

$$I_c(t) = f(t)(1 - V(t)) + 4f(t)(V(t)) \quad (3)$$

$$I_a(t) = Min[P(t), I_c(t)] \quad (4)$$

where I_c is the infiltration capacity and V is the vegetation cover (between 0 and 1) in a model grid cell at time-step *t*. Values used in the simulations for the parameters in equations 2-4 are provided in appendix Table A1.

3.3 Model setup

We applied the Landlab landscape evolution model (Hobley et al., 2017), combined with the SPACE 1.0 module of Shobe at al. (2017). The SPACE module allows coupled detachment-transport limited fluvial processes with simultaneous bedrock erosion and sediment entrainment/deposition. The Landlab-SPACE programs were modified for vegetation-dependent hillslope processes (Johnstone and Hilley, 2014) and vegetation-dependent overland flow and fluvial erosion using the approach described in Schmid et al. (2018) and Sharma et al. (2021). In addition, the geomorphic processes considered involve weathering and regolith production (Barnhart et al., 2019) and infiltration of surface water into soil (Rengers et al., 2016) based on the Green-Ampt method (Green and Ampt, 1911), and runoff modeling.

The model parameters (Table. A1) are calibrated to the distinct climate and ecological settings in the Chilean Coastal Cordillera observations of Schaller et al., (2018). The model state parameters (i.e., erosion, diffusion, lithology, tectonic rock uplift rate, etc.) in the simulations are adapted from Sharma et al., (2021). The model was simulated at a seasonal scale (time step of three months) from the Autumn of 2000 (01/03/2000) to the Summer of 2019 (28/02/2020). Simulations were conducted for a total time of 1000 years with a time-step of 1 season (3 months) with 20 years (2000 – 2019) of observations in vegetation and precipitation. These 20-years of observations were repeated (looped) 50 times, to identify, and detrend, long-term transient trends in catchment erosion rates due to potential differences in assumed erosional parameters such as the hillslope diffusivity or fluvial erodibility. The combined effect of temporally variable (at seasonal scale) precipitation and vegetation cover (also spatially variable) on catchment-scale erosion rates was therefore the primary factors influencing predicted erosion rates.

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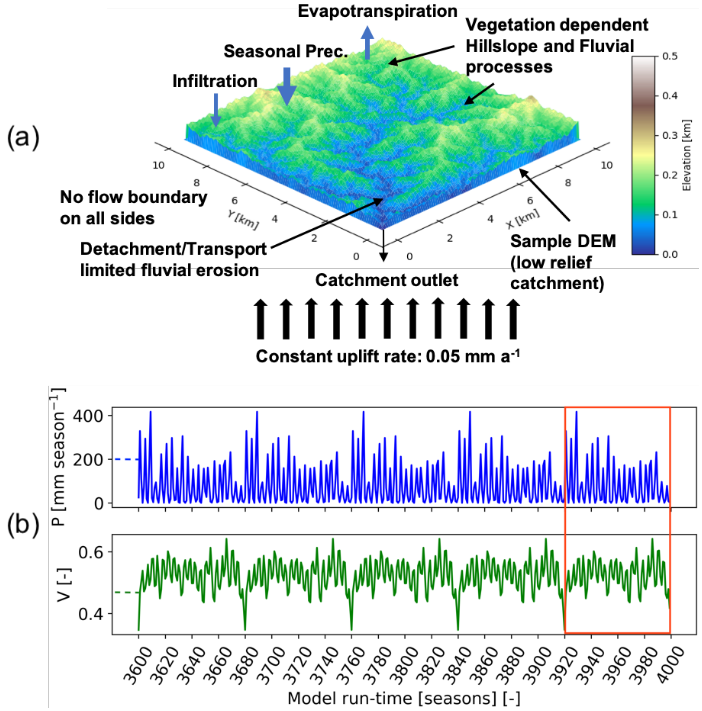

Figure 3. Schematic of the model geometry and seasonal precipitation and vegetation forcings used in this study. (a) Model setup representing sample DEM (low relief catchment) with no flow boundaries on all sides and a single catchment outlet. The model involves vegetation-dependent seasonal hillslope and fluvial processes and rainfall-infiltration-runoff modeling. (b) Seasonal precipitation and vegetation cover dataset (Mediterranean, La Campana, setting) for the last five iterations of model simulations. The results of highlighted iterations (after detrending for long-term transients) are analyzed in consecutive sections.

3.4 Boundary and initial conditions

The boundaries are closed (no flow) on all sides, with a single stream outlet at the point of minimum elevation at boundary nodes (Fig. 3). Initial sediment cover thickness is considered uniform across the model domain, and was approximated based on observations by Schaller et al., (2018) and Dal Bo et al., (2019). The sediment thickness used are 0.2 m in arid (AZ), 0.45 m in semi-arid (SG), 0.6 m in the Mediterranean (LC), and 0.7 m in humid temperate (NA) catchments. The initial rock uplift rate is kept constant throughout the entire model run as 0.05 mm yr^{-1}, adapted from a similar study (Sharma et al., 2021).

3.5 Overview of simulations conducted

The simulations were designed to identify the sensitivity of erosion rates to seasonal variations in either precipitation rates or vegetation cover, as well as the more realistic scenario of coupled seasonal variations in both vegetation cover and precipitation. We evaluated this sensitivity with a step-wise increase in model complexity. Three sets of simulations were designed for the four selected study areas, which are as follows,

1. Scenario 1: Influence of constant (mean seasonal) precipitation with seasonal variations in vegetation cover catchment-scale erosion rates.
2. Scenario 2: Influence of seasonal variation in precipitation and constant (mean seasonal) vegetation cover on catchment-scale erosion rates.

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3. Scenario 3: Influence of coupled seasonal variations in both precipitation and vegetation cover on catchment-scale erosion rates.

The results for scenarios 1 – 3 are illustrated in sections 4.1, 4.2, and 4.3, respectively.

3.6 Detrending of results for long term transients

Model simulations were conducted for 1,000 years using 20 years [March-2000 – Feb-2020] of observations in vegetation cover, and precipitation and were repeated 50 times for a total simulation duration of 1000 years. Simulations presented here were conducted on the present-day topography to allow for the application of observed time series of precipitation and vegetation change in different ecosystems and study areas. This choice of setting comes with the compromise that the erosional parameters (e.g., diffusivity, erodibility, etc.) used in the model are likely not the same as those that led to the present-day catchment topography. As a result, a long-term transient in erosion rates is expected as the model tries to reach an equilibrium with assumed erosional parameters. To correct for any long-term transients in erosion influencing our interpretations, we conducted a linear detrending of the results to remove any long-term variations. Hence, the detrended model results for the last 20 years were analyzed and discussed in sections 4 and 5.

4 Results

In the following sections, we focus our analysis on the mean catchment erosion rates over seasonal (3 months) time scales (see Table. 1). In all scenarios, the rock uplift rate was kept constant at 0.05 mm yr^{-1} following the approach of Sharma et al. (2021). For simple representation, the results of the last five years of the last cycle of transient simulations starting from Autumn-2015 to Summer-2019 are displayed in Fig. 4, 6, and 8 (after detrending, see section 3.6). The results for the entire time series (Autumn-2000 – Summer-2019) are available in the supplement (Fig. 1 – 3). The precipitation and erosion rates are shown with the units [mm $season^{-1}$].

4.1 Scenario 1: Influence of constant precipitation and seasonal variations in vegetation cover on erosion rates

In scenario 1, vegetation cover (MODIS NDVI from March 2000 to February 2020) fluctuates seasonally (Fig. 4b), and precipitation rates are kept constant at the seasonal mean (i.e., MAP divided by the number of seasons in a year) during the entire time-series (Fig. 4a) (Ziese et al., 2020). The range of seasonal vegetation cover variations (and mean seasonal precipitation rates) are observed as 0.06 – 0.08 [-] (3.92 mm $season^{-1}$), 0.1 – 0.4 [-] (20.16 mm $season^{-1}$), 0.35 – 0.65 [-] (79 mm $season^{-1}$), and 0.5 – 0.85 [-] (292 mm $season^{-1}$) for the Pan de Azúcar, Santa Gracia, La Campana and Nahuelbuta study areas (Fig. 1), respectively.

The predicted mean catchment seasonal erosion rates range between $0 - 6 \times 10^{-4}$ mm $season^{-1}$, $0 - 9.4 \times 10^{-4}$ mm $season^{-1}$, $0 - 2.3 \times 10^{-3}$ mm $season^{-1}$, and $1.2 \times 10^{-3} - 4 \times 10^{-3}$ mm $season^{-1}$ in Pan de Azúcar, Santa Gracia, La Campana, and Nahuelbuta, respectively (Fig. 4c). The mean catchment seasonal erosion rates have an inverse linear relationship with seasonal vegetation cover for arid, semi-arid, and Mediterranean settings (Fig. 5). However, this relationship is positive in the humid-temperate setting, i.e., erosion increases with an increase in vegetation cover with a relatively lower gradient (3×10^{-3}).

The maximum gradient between vegetation cover and erosion rates is observed in the Mediterranean region (La Campana, gradient: -6×10^{-3}). The slopes in the vegetation cover – erosion rate relationship (Fig. 5) represent the sensitivity of each catchment to changes in seasonal vegetation cover, which indicates that the Mediterranean region (La Campana) is ~4.5 times more sensitive than the semi-arid region (Santa Gracia). Due to very low precipitation in the arid region (Pan de Azúcar), no significant range in erosion rates is observed (e.g., Pearson r: 0.17; p: >0.05). The results (Fig. 4 and 5) suggest a high sensitivity in erosion in the Mediterranean setting to changes in seasonal vegetation cover (i.e., erosion rates decrease with an increase in

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vegetation cover). The erosion rates are low (e.g., <0.005 mm season-1) due to low mean precipitation rates subjected to infiltration and evapotranspiration.

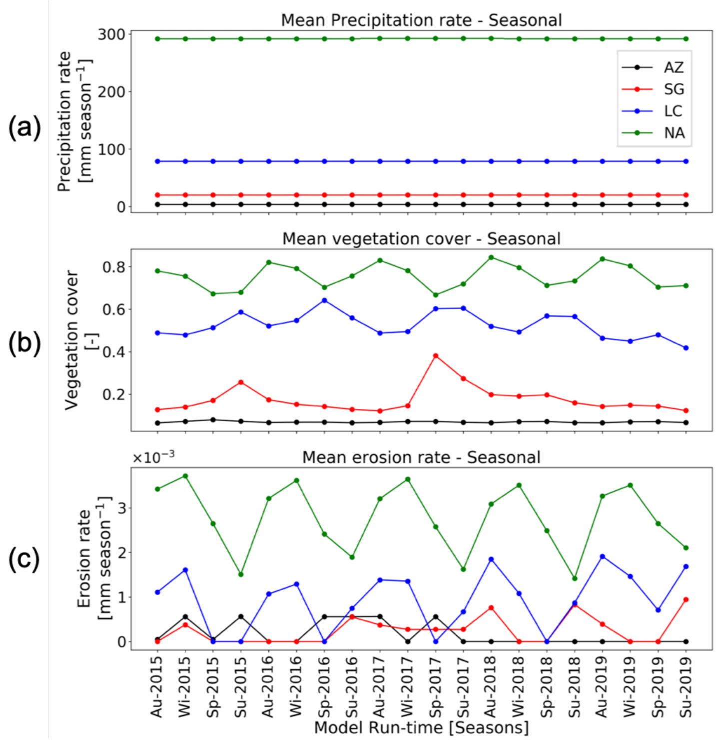

Figure 4. Results of simulations with constant seasonal precipitation and variable vegetation over last 5 years (Autumn-2015 – Summer-2019) of last cycle of transient-state model run representing: (a) mean catchment seasonal precipitation rates [mm season^{-1}], (b) mean catchment seasonal vegetation cover [-], and (c) mean catchment seasonal erosion rates [mm season^{-1}].

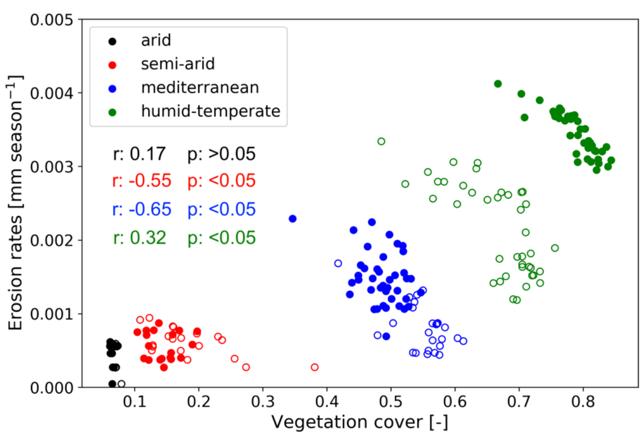

Figure 5. Correlation of vegetation cover [-] and erosion rates [mm season^{-1}] obtained from simulations with constant seasonal precipitation and variable vegetation over the last cycle of the transient state model run (Autumn-2000 – Summer-2019). Hollow circles: dry season; filled circles: wet season. Each individual circle represents one predicted season within the timeseries.

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4.2 Scenario 2: Influence of seasonal variations in precipitation and constant vegetation cover on erosion rates

In scenario 2, vegetation cover (MODIS NDVI from Mar-2000 – Feb-2020) is kept constant at the mean seasonal vegetation cover (Fig. 6b) and precipitation rates vary seasonally (Mar-2000 – Feb-2020) (Fig. 6a). The range of seasonal precipitation rate variations are observed in the range of 0 – 32.42 mm season^{-1}, 0 – 191.66 mm season^{-1}, 0.03 – 417 mm season^{-1}, and 26 – 987 mm season^{-1} for Pan de Azúcar, Santa Gracia, La Campana and Nahuelbuta, respectively.

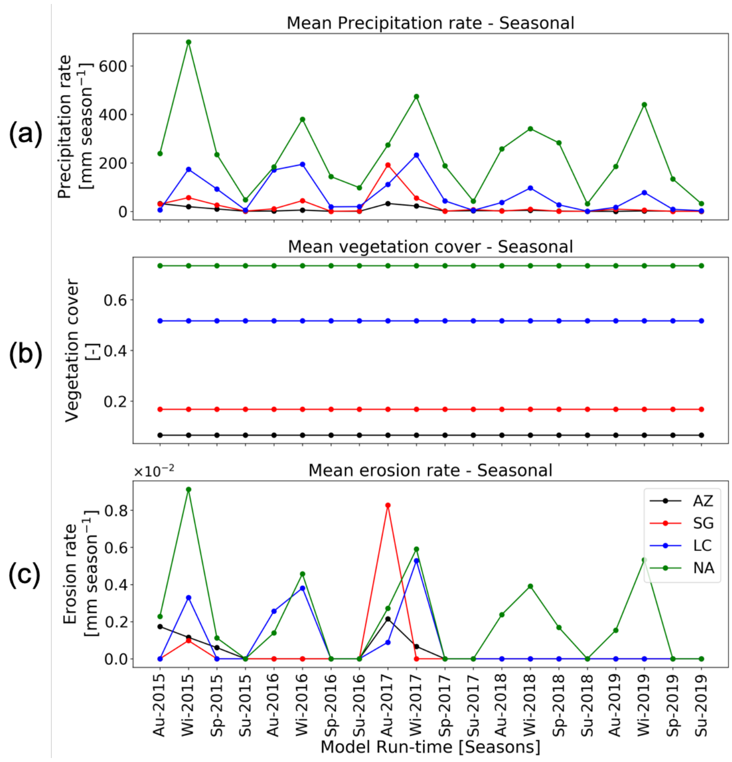

Figure 6. Results of simulations with variable seasonal precipitation and constant vegetation over last 5 years (Autumn-2015 – Summer-2019) of last cycle of transient-state model run representing: (a) mean catchment seasonal precipitation rates [mm season^{-1}], (b) mean catchment seasonal vegetation cover [-], and (c) mean catchment seasonal erosion rates [mm season^{-1}].

The simulated mean catchment seasonal erosion rates are observed in the range of $0 - 2 \times 10^{-3}$ mm season^{-1}, $0 - 8.3 \times 10^{-3}$ mm season^{-1}, $0 - 1.37 \times 10^{-2}$ mm season^{-1}, and $0 - 1.3 \times 10^{-2}$ mm season^{-1} in Pan de Azúcar, Santa Gracia, La Campana, and Nahuelbuta, respectively (Fig. 6c). The mean catchment seasonal erosion rates are positively correlated with seasonal precipitation rates (Fig. 7), with a maximum gradient in the arid region (AZ, gradient: ~1.3×10^{-4}).
The gradients in the precipitation – erosion rate relationship (Fig. 7) indicate the sensitivity of each catchment to changes in seasonal precipitation rates, such that that the arid region (AZ) is ~2.7, ~3.2, and ~8 times more sensitive than semi-arid (SG), Mediterranean (LC) and humid-temperate region (NA), respectively. The results (Fig. 6 and 7) suggest a high sensitivity of erosion in the arid and semi-arid settings to changes in seasonal precipitation rates (i.e., erosion increases at relatively higher rates with an increase in precipitation). The erosion rates are higher than in scenario 1 (e.g., 0 – 0.014 mm season^{-1}) due to higher precipitation rates in scenario 2.

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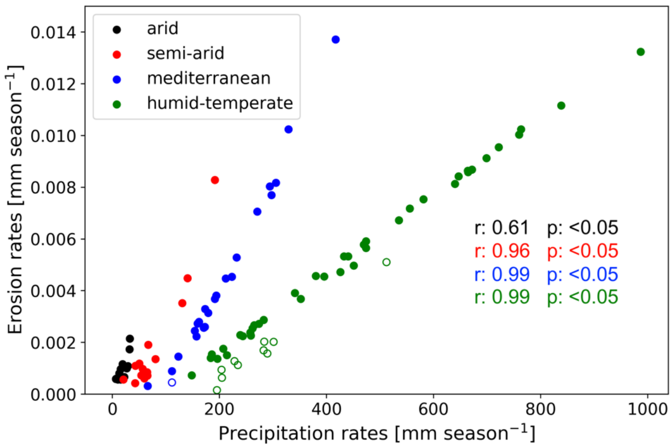

Figure 7. Correlation of precipitation rates [mm season^{-1}] and erosion rates [mm season^{-1}] obtained from simulations with variable seasonal precipitation and constant vegetation over the last cycle of the transient state model run (Autumn-2000 – Summer-2019). Hollow circles: dry season; filled circles: wet season. Each individual circle represents one predicted season within the timeseries.

4.3 Scenario 3: Influence of coupled seasonal variations in both precipitation and vegetation cover on erosion rates

In this scenario, coupled variations in seasonal vegetation cover (MODIS NDVI from Mar-2000 – Feb-2020) (Fig. 8b) and precipitation rates are presented for the years 2000 - 2019 (Fig. 8a). The range of seasonal precipitation rates (and seasonal vegetation cover, V) variations are 0 – 32.42 mm season^{-1} (V= 0.06 – 0.08 [-]), 0 – 191.66 mm season^{-1} (0.1 – 0.38 [-]), 0.03 – 417 mm season^{-1} (0.35 – 0.65 [-]), and 26 – 987 mm season^{-1} (0.5 – 0.85 [-]) for Pan de Azúcar, Santa Gracia, La Campana and Nahuelbuta, respectively.

The mean catchment seasonal erosion rates are observed in the range of $0 - 2 \times 10^{-3}$ mm season^{-1}, $0 - 1 \times 10^{-2}$ mm season^{-1}, $0 - 1.4 \times 10^{-2}$ mm season^{-1}, and $0 - 1.4 \times 10^{-2}$ mm season^{-1} in Pan de Azúcar, Santa Gracia, La Campana, and Nahuelbuta, respectively (Fig. 8c). Similar to scenario 2, mean catchment seasonal erosion rates are observed to be positively correlated with seasonal precipitation rates (Fig. 9), with a maximum gradient in an arid region (AZ, gradient: ~1.3×10^{-4}). The slopes in the precipitation – erosion rate relationship (Fig. 9) represent the sensitivity of each catchment to coupled variations in seasonal precipitation rates and vegetation cover. The results (Fig. 8 and 9) indicate that the arid region (AZ) is ~2.3, ~3, and ~8 times more sensitive than the semi-arid (SG), Mediterranean (LC), and humid-temperate region (NA), respectively. The similarity in results obtained from scenarios 2 and 3 suggest the first-order control of seasonal precipitation changes on erosion rates (e.g., Pearson $r > 0.6$ for arid setting, Fig. 9a), with less significance to changing vegetation cover (Pearson $r < -0.19$ for semi-arid setting, Fig. 9b).

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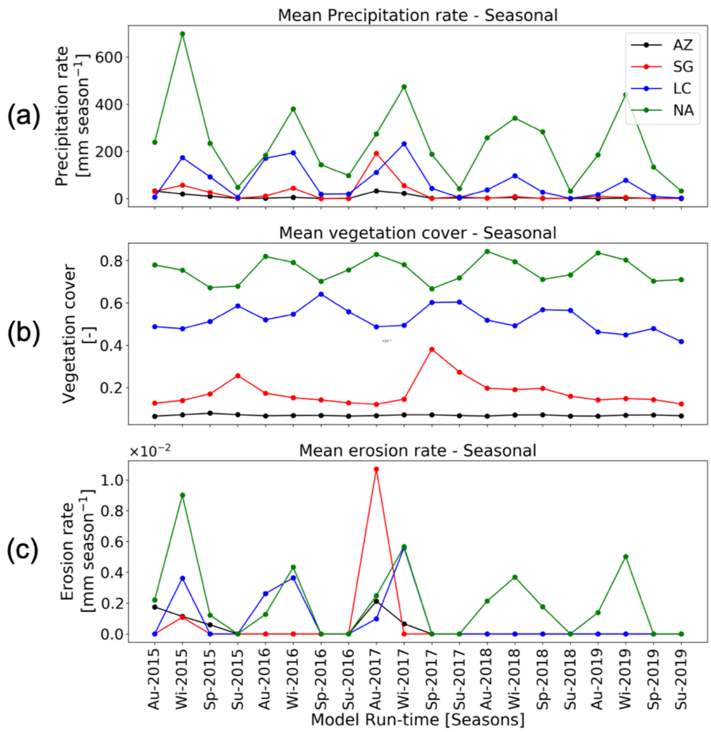

Figure 8. Results of simulations with coupled variations in seasonal precipitation and vegetation over the last five years (Autumn-2015 – Summer-2019) of the last cycle of transient-state model run representing: (a) mean catchment seasonal precipitation rates [mm season^{-1}], (b) mean catchment seasonal vegetation cover [-], and (c) mean catchment seasonal erosion rates [mm season^{-1}].

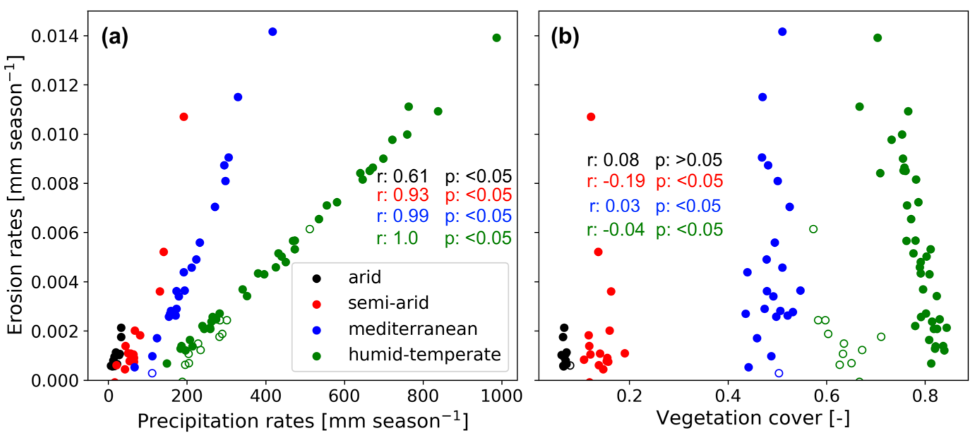

Figure 9. Correlation between (a) precipitation rates [mm season^{-1}] and (b) vegetation cover and erosion rates [mm season^{-1}] obtained from simulations with coupled variations in seasonal precipitation and vegetation over the last cycle of the transient simulation (Autumn-2000 – Summer-2019). Hollow circles: dry season; filled circles: wet season. Each individual circle represents one predicted season within the timeseries.

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5 Discussion

This section discusses the relationship between variations in seasonal precipitation and vegetation cover with erosion rates (section 5.1). This is followed by a discussion of the effect of variable vegetation and precipitation rates on seasonal erosion rates (section 5.2). Following this, we present the synthesis of catchment scale erosion rates variability over wet and dry seasons (section 5.3). Finally, we compare our results with previously published studies (section 5.4) and discuss model limitations (section 5.5).

5.1 Synthesis of the amplitude of change in erosion rates for model scenarios 1-3

The amplitude of change of mean catchment erosion rates [in percentage] varies at a seasonal scale (Fig. 10) between the study areas. The amplitude of change in erosion rates to their respective mean values was estimated (Fig. 10) using the coefficient of variation in percent (standard deviation divided by the mean of a dataset). The coefficient of variation is a statistical tool to compare multiple variables free from scale effects, i.e., it is a dimensionless quantity (Brown, 1998). This comparison represents the sensitivity of each catchment to changing seasonal weather for all three model scenarios (section 4.1 – 4.3).
In scenario 1, with seasonal variations in vegetation cover and constant seasonal precipitation (Fig. 10a), the amplitude of change in erosion rates ranges between 6.5% in the humid-temperate setting and 36% in Mediterranean setting. The above results support the findings of Zhang et al. (2019), which observed 20-30% of the total change in sediment yield with constant precipitation and variable vegetation cover. The above study used the soil and water assessment tool (SWAT) based on NDVI and climate parameters. In addition, a 5.5% change in amplitude in erosion rates is observed in the arid setting (Fig. 10a). However, due to the weak correlation between vegetation cover and erosion rates (i.e., Pearson r: 0.17 and $p>0.05$, Fig. 5) and negligible vegetation cover ($V < 0.1$), it is unclear if these changes in erosion rates are due to changes in vegetation cover alone.

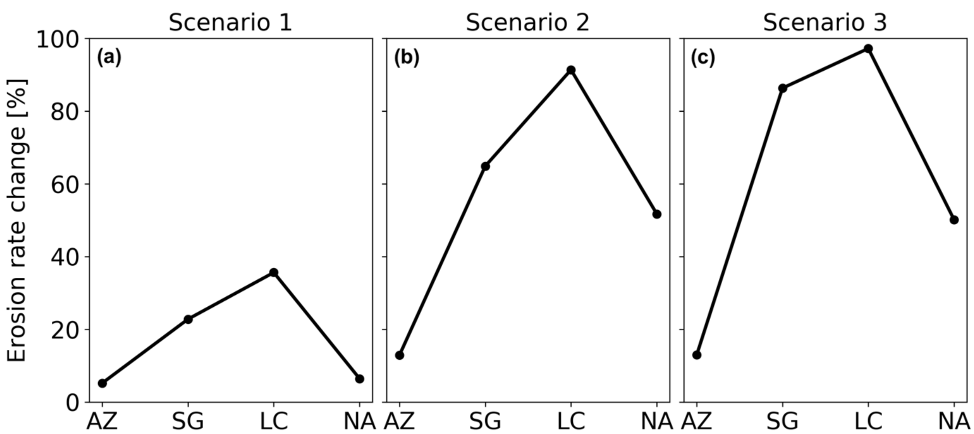

Figure 10. The amplitude of change in seasonal erosion rates (relative to their respective means) in (a) scenario 1: with variable vegetation cover and constant precipitation rates, (b) scenario 2: with constant vegetation cover and variable precipitation rates, and (c) scenario 3: with coupled variations in vegetation cover and precipitation rates.

In scenario 2, with constant vegetation cover and variable precipitation rates (Fig. 10b), the amplitude of change in erosion rates ranges from 13% in the arid setting (AZ) to 52%, 65%, and 91% in humid-temperate (NA), semi-arid (SG) and Mediterranean (LC) settings, respectively. A similar trend is observed in scenario 3 with coupled variations in vegetation cover and precipitation rates (Fig. 10c), with the amplitude of change in erosion rates between 13% in the arid setting up to 50%, 86%, and 97% in the humid-temperate, semi-arid and Mediterranean settings, respectively. The magnitude of erosion rate changes is amplified in scenario 3, especially in the semi-arid setting (e.g., ~21% increase in the amplitude of change from

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scenario 2 to scenario 3). This amplification could be owed to the 35% change in vegetation cover in the semi-arid setting (Fig. 8). Overall, these observations indicate a high sensitivity of erosion in semi-arid and Mediterranean environments compared to arid and humid-temperate settings.

The pattern of erosion rate changes in scenarios 1-3 implies a predominant control of precipitation variations (rather than vegetation cover change) on catchment erosion rates at a seasonal scale. This interpretation is consistent with previous observational studies. For example, a plot-scale study by Gabarrón-Galeote et al. (2013) in the Mediterranean environment in Belgium concluded that rainfall intensity was the main factor in determining the observed seasonal soil hydrological and erosive response. Another field study by Suescún et al. (2017) in the Columbian Andes highlighted the significant influence of precipitation seasonality (over vegetation cover seasonality) on runoff and erosion rates. An observational catchment-scale study in the semi-arid Chinese Loess Plateau by Wei et al. (2015) indicated that intra-annual precipitation variations were a significant contributor to monthly runoff and sediment yield variations.

5.2 Synthesis of catchment erosion rates over wet and dry seasons

In this section, we discuss the ratio of MAP (Fig. 11a) and mean annual erosion (MAE) (Fig. 11b) during different seasons (i.e., autumn – summer) in a year, averaged over the entire time series (2000 – 2019). This analysis is performed for the simulation results of scenario 3 for different climate and ecological settings (i.e., arid to humid-temperate). We do this specifically with scenario 3 results to capture the trends in erosion rates with coupled variations in model input (i.e., precipitation and vegetation cover).

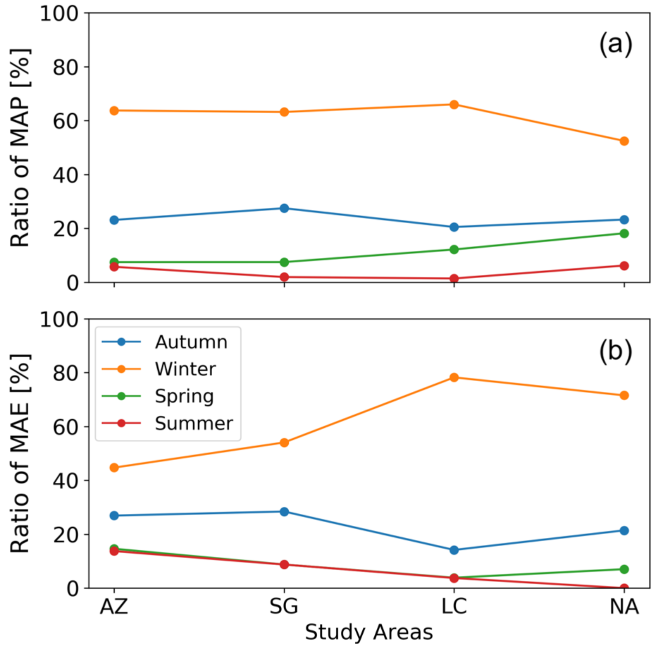

Figure 11. The ratio of model variables to annual means during all the seasons in a year for simulation results from scenario 3 (coupled seasonal variations in precipitation and vegetation cover). The plots correspond to (a) ratio of MAP per season [%] and (b) ratio of MAE per season [%] of the mean values averaged over the last 20 years of the simulations (2000 - 2019). Each point represents the ratio for each ecological setting i.e., arid (Pan de Azúcar, AZ), semi-arid (Santa Gracia, SG), Mediterranean (La Campana, LC), and humid-temperate settings (Nahuelbuta, NA).

The values for the ratio of MAP during different seasons (Fig. 11a) depicts winter (June-August) and summer (December-February) as the wettest and driest seasons of the year, respectively. For example, all study areas receive >50% and <6% of MAP during winters and summers. The same is reflected in Fig. 11b with 45%, 55%, 78%, and 71% of MAE in the arid, semi-arid, Mediterranean, and humid-temperate settings, respectively, during winters. On the contrary, during summers the share of MAE decreases from 14% in the arid setting to 1% in the humid-temperate setting. The Autumn (March-May) receives lower precipitation amounts that range from 20–30% of MAP in the study areas. Arid and semi-arid settings experience a relatively higher share of MAE (e.g., ~30%) than the Mediterranean and humid temperate settings (e.g., ~15-20%). The Spring season experiences relatively higher erosion rates despite a smaller share of MAP in arid and semi-arid settings. For example, the arid and semi-arid settings experience 10-14% of the MAE for ~7% of MAP. At the same time, the Mediterranean and humid-temperate settings experience 5-7% of MAE for ~12-18% of MAP during Spring. Overall, we find that arid and semi-arid settings experience <15% and ~50% of MAE during the wet (winter) and dry (summer) seasons. The above relationship is amplified for the Mediterranean and humid-temperate settings with <5% and >70% of MAE occurring during wet and dry seasons, respectively. The latter is in agreement with an observational study by Mosaffaie et al., (2015) in a Mediterranean catchment in Iran. More specifically, Mosaffaie et al., (2015) used field observations from 2012-2013 to conclude that maximum erosion rates (>70%) are observed during the wet season, which decreases in the dry season (<10%).

5.3 Comparison to previous studies

In this section, we relate the broad findings of this study to the previously published observational studies. In an observational study in an agrarian drainage basin in the Belgian Loam Belt, Steegen et al., (2000) evaluated sediment transport over various time scales (including seasonal). They observed lower sediment fluxes during the seasons with high vegetation cover. In addition, an observational study by Zheng (2006) investigated the effect of vegetation changes on soil erosion in the Loess Plateau, China, and concluded that soil erosion was significantly reduced (up to ~50%) after vegetation restoration. Another observational study in semi-arid grasslands in Loess Plateau, China, by Hou et al., (2020) highlighted a considerable reduction in erosion rates due to the development of richness and evenness of the plant community in the early to the mid wet season. Our results from scenario 1 (seasonal variations in vegetation cover with constant precipitation rates) support the findings of the above studies whereby a negative correlation (Pearson r: ~ –0.6 and $p < 0.05$) was found between vegetation cover and erosion rates for the semi-arid and Mediterranean settings. More specifically, we found erosion rates decrease with an increase in vegetation cover in Santa Gracia (semi-arid) and La Campana (Mediterranean) (see Fig. 5). However, a positive correlation (Pearson r: ~0.3 and $p<0.05$) is observed in the humid-temperate setting from dry season to wet season (see Fig. 5).

A catchment-scale observational study in Baspa Valley, NW Himalayas (Wulf et al., 2010), analyzed seasonal precipitation gradients and their impact on fluvial erosion using weather station observations (1998 – 2007). The study observed a positive correlation between precipitation and sediment yield variability, demonstrating the summer monsoon's first-order control on erosion processes. An observational study by Wei et al., (2015) in Loess Plateau, China, evaluated erosion and sediment transport under various vegetation types and precipitation variations. They found that significant changes in vegetation cover might contribute to long-term soil dynamics. However, seasonal variations in runoff and sediment yield were mainly influenced by rainfall seasonality. In comparison to the results of this study, we find the similarity in the patterns of erosion rates in scenario 2 (variable precipitation and constant vegetation cover) and scenario 3 (coupled variations in precipitation and vegetation) are consistent with the findings of Wei et al., (2015). For example, the amplitude of change in erosion rates (Fig. 10) in scenarios 2 and 3 differ by 0%, 6%, and –2% in the arid, Mediterranean, and humid-temperate settings, respectively. However, this difference is enhanced in the semi-arid region (i.e., ~23%) due to a relatively high degree of variation (~25%) in seasonal vegetation cover change.

Finally, an observational study in the Columbian Andes by Suescún et al., (2017) assessed the impact of seasonality on vegetation cover and precipitation and found higher erosion rates in regions with steeper slopes. Another study by Chakrapani

(2005) emphasized the direct impact of local relief and channel slope on sediment yield in natural rivers. The broad findings of the above studies agree with our results from scenarios 1-3, as we find higher erosion rates in the Mediterranean and humid-temperate regions with steeper topography (mean slope ~20 deg), which encounter high seasonality (and intensity) in precipitation.

5.4 Model Limitations

The model setup used in this study was designed to quantify the sensitivity of erosion rates in different climate and ecological settings with variations in precipitation rates and vegetation cover at seasonal scales. We represent the degree of variations in erosion rates in terms of change amplitude (with respect to the mean) for different model scenarios (see sections 4.1 – 4.3). This study was intended to introduce temporal downscaling (from millennial to seasonal time scales) to the approach of previous similar modeling studies (e.g., Schmid et al., 2018; Sharma et al., 2021).

Our modeling approach used several simplifying assumptions that warrant discussion and potential investigation in future studies. For example, model results presented here successfully capture the major surface processes, including vegetation-dependent erosion and infiltration, sediment transport, and surface runoff. However, groundwater flow is not considered in the current study, and how the reentry of groundwater into streams over seasonal scales would influence downstream erosion. The reason is that groundwater flow modeling includes a high amount of heterogeneity and anisotropy and requires much finer grid sizes (<1m) and smaller time steps (in seconds to hours). Thus, due to the large grid-cell size (90 m), timescales (monthly), and high uncertainty in subsurface hydrologic parameters we were unable to evaluate the effects of groundwater flow on our results. Furthermore, this study assumed uniform lithological and hydrological parameters (e.g., vertical hydraulic conductivity, initial soil moisture, evapotranspiration, erodibility, etc.) over the entire catchment. As said earlier, these properties are subjected to a high level of uncertainty and heterogeneity, the best fitting parameters, based on previously published literature (e.g., Schaller et al., 2018; Bernhard et al., 2018; Schmid et al., 2018; Sharma et al., 2021) are used for the model simulations. However, the heterogeneity in vegetation cover and related soil-water infiltration per grid cell is used in this study. For the heterogeneity in vegetation cover, we use MODIS-derived NDVI as a proxy of vegetation cover. According to Garatuza-Payán et al. (2005), NDVI is assumed as an effective tool for estimating seasonal changes in vegetation cover density. However, the spatial resolution (250 m) of the NDVI dataset is lower than that of the SRTM DEM (90 m) used in the study. Nevertheless, the difference in spatial resolution of vegetation cover and topography might introduce ambiguity in the model results.

A final limitation stems from several generalized model parameters (e.g., rock uplift rate, erodibility, diffusivity, etc.) applied to the SRTM DEM (as initial topography). We did this to capture the effects of seasonality in precipitation and vegetation cover in modern times (2000 - 2019). However, the current topography might not have evolved with the same tectonic and lithological parameters. To address this limitation, we simulated the model for 50 iterations and detrended the model results to remove those transient effects (see section 3.6). This limitation can be handled in future studies by parameterizing the model to the current topography using stochastic (e.g., Bayesian) techniques (e.g., Stephenson et al., 2006; Avdeev et al., 2011). As this study was aimed to capture the control of seasonal precipitation and (or) vegetation changes on the relative variability of erosion rates, the above limitation may not pose a problem in the model results.

6 Summary and Conclusions

In this study, we applied a landscape evolution model to quantify the impact of seasonal variations in precipitation and vegetation on catchment averaged erosion rates. We performed this in regions with varied climate and ecology including: arid, semi-arid, Mediterranean, and humid-temperate settings. Three sets of simulations were designed to model erosion rates for (a) scenario 1: constant precipitation and variable vegetation cover, (b) scenario 2: variable precipitation and constant

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vegetation cover, and (c) scenario 3: coupled variations in precipitation and vegetation cover. The main conclusions derived from this study are as follows:

1. Scenario 1, with variable vegetation cover and constant precipitation (Fig. 4), resulted in small variations in seasonal erosion rates (<0.02 mm yr^{-1}) in comparison to the other scenarios. The amplitude of change in seasonal erosion rates (relative to the mean) is the smallest in humid-temperate setting and maximum in the Mediterranean setting (Fig. 10a). For example, it ranges from 6.5% in humid-temperate setting (Nahuelbuta) to 23% and 36% in semi-arid (Santa Gracia) and Mediterranean settings (La Campana), respectively.
2. Scenario 2, with constant vegetation cover and variable precipitation (Fig. 6), results in relatively higher seasonal erosion rates (<0.06 mm yr^{-1}) in comparison to scenario 1. The amplitude of change in seasonal erosion rates (relative to the mean) is smallest in the arid setting and the largest in the Mediterranean setting (Fig. 10b). For example, it ranges from 13% in the arid setting (Pan de Azúcar) to 52%, 65%, and 91% in humid-temperate (Nahuelbuta), semi-arid (Santa Gracia), and Mediterranean settings (La Campana), respectively.
3. Scenario 3, with coupled variations in vegetation cover and precipitation (Fig. 8), results in similar seasonal erosion rates (<0.06 mm yr^{-1}) to scenario 2. Similarly, the amplitude of change in seasonal erosion rates (relative to the mean) is the smallest in the arid setting and the largest in the Mediterranean setting (Fig. 10c). For example, it ranges from 13% in the arid setting (Pan de Azúcar) to 50%, 86%, and 97% in humid-temperate (Nahuelbuta), semi-arid (Santa Gracia), and Mediterranean settings (La Campana), respectively. A significant increase (from scenario 2) in variation in erosion rates (~21%) is owed to the ~25% variation in vegetation cover in semi-arid settings.
4. All study areas experience maximum and minimum erosion during wet and dry seasons, respectively (Fig. 11b). However, the difference (in maximum and minimum) is amplified from the arid (~30%) to the Mediterranean and humid-temperate settings (~70-75%). This is owed to the range of amplitude of precipitation rate change (Fig. 7) increasing from the arid (e.g., ~9 mm) to humid-temperate settings (e.g., ~543 mm) in wet and dry seasons.

Finally, this study was motivated by testing the hypotheses that (1) if precipitation variations primarily influence seasonal erosion, then the influence of seasonal vegetation cover changes would be less significant, and (2) catchment erosion in drier settings is more sensitive to seasonality in precipitation and vegetation, than wetter settings. With respect to hypothesis 1, we found that seasonal precipitation variations primarily drive catchment erosion and the effects of vegetation cover variations are secondary. Results presented here (Fig. 10b) support this interpretation with significantly high amplitude of change in erosion rates (with respect to means) ranging from 13 to 91% for scenario with constant vegetation cover and seasonal precipitation variations. However, the effect of seasonal vegetation cover changes is also significant (Fig. 10a) ranging between 5 – 36%. Hence, the first hypothesis is partially confirmed. Concerning hypothesis 2, we found that seasonal changes in catchment erosion are more pronounced in semi-arid and Mediterranean settings and less in arid and humid temperate settings. This interpretation is supported by Fig. 10c, with significantly high amplitude of change in catchment erosion in semi-arid (~86%) and Mediterranean (~97%) settings with relatively lower changes in humid temperate (~50%) and arid (~13%) settings, partially confirming the hypothesis.

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Appendix

Table A1. Input parameters with corresponding units for the landscape evolution model

Model Parameters	Values
Grid spacing (dx)	90 m
Model runtime (totalT)	1000 years (2000 – 2019 repeated over 50 times)
time-step (dt)	1 season (3 months)
Rock uplift rate (U)[1]	1.25 x 10^{-5} [m $season^{-1}$] (or 0.05 [mm a^{-1}])
Initial sediment thickness (H_initial)[2]	20 (AZ), 0.45 (SG), 0.6 (LC), 0.7 (NA) [cm]
Bedrock erodibility (Kr)[1]	2 x 10^{-9} [m^{-1}]
Sediment erodibility (Ks)[1]	2 x 10^{-8} [m^{-1}]
Reach scale bedrock roughness (H*)[1]	1 [m]
Porosity (φ)[1]	0.2 [-]
Fraction of fine sediments (Ff)[1]	0.2 [-]
Effective terminal settling velocity (Vs)[1]	2.5 [m $season^{-1}$]
m, n[1]	0.6, 1 [-]
Bedrock erosion threshold stream power (ω_cr)[1]	1.25 x 10^{-5} [m $season^{-1}$]
Sed. entr. threshold stream power (ω_cs)[1]	1.25 x 10^{-6} [m $season^{-1}$]
Bare soil diffusivity (K_b)[1]	2.5 x 10^{-4} [m^2 $season^{-1}$]
Exponential decay coefficient (α)[1]	0.3 [-]
Critical channel formation area (A_{crit})[3]	1 x 10^6 [m^2]
Reference vegetation cover (V_r)[3]	1 (100%)
Manning's number for bare soil (n_s)[3]	0.01 [-]
Manning's number for ref. vegetation (n_v)[3]	0.6 [-]
Sacling factor for vegetation influence (w)[3]	1 [-]
Soil bulk density (B)[4]	1300 (AZ), 1500 (SG), 1300 (LC), 800 (NA) [kg m^{-3}]
Soil type[4]	sandy loam (AZ, SG, LC); sandy clay loam (NA)
Initial soil moisture (s)[4]	0.058 (AZ), 0.02 (SG), 0.053 (LC), 0.15 (NA) [m^3 m^{-3}]

[1] Sharma et al. (2021), [2] Schaller et al. (2018), [3] Schmid et al. (2018), [4] Bernhard et al. (2018).

Code and data availability

The code and data used in this study are freely available upon request.

Author contributions

HS and TAE designed the initial model setup and simulation programs. HS and TAE conducted model modifications, simulation runs, and analysis. HS prepared the paper with contributions from TAE.

Competing interests

The authors declare that they have no conflict of interest.

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Preprint. Discussion started: 14 December 2022

Earth Surface Dynamics Discussions

References

Avdeev, B., Niemi, N. A., and Clark, M. K.: Doing more with less: Bayesian estimation of erosion models with detrital thermochronometric data, Earth Planet. Sci. Lett., 305, 385–395, https://doi.org/10.1016/j.epsl.2011.03.020, 2011.

Barnhart, K. R., Glade, R. C., Shobe, C. M., and Tucker, G. E.: Terrainbento 1.0: a Python package for multi-model analysis in long-term drainage basin evolution, Geosci. Model Dev., 12, 1267–1297, https://doi.org/10.5194/gmd-12-1267-2019, 2019.

Beaudoing, H., Rodell, M., and NASA/GSFC/HSL: GLDAS Noah Land Surface Model L4 monthly 0.25 x 0.25 degree, Version 2.1, https://doi.org/10.5067/SXAVCZFAQLNO, 2020.

Bernhard, N., Moskwa, L.-M., Schmidt, K., Oeser, R. A., Aburto, F., Bader, M. Y., Baumann, K., von Blanckenburg, F., Boy, J., van den Brink, L., Brucker, E., Büdel, B., Canessa, R., Dippold, M. A., Ehlers, T. A., Fuentes, J. P., Godoy, R., Jung, P., Karsten, U., Köster, M., Kuzyakov, Y., Leinweber, P., Neidhardt, H., Matus, F., Mueller, C. W., Oelmann, Y., Oses, R., Osses, P., Paulino, L., Samolov, E., Schaller, M., Schmid, M., Spielvogel, S., Spohn, M., Stock, S., Stroncik, N., Tielbörger, K., Übernickel, K., Scholten, T., Seguel, O., Wagner, D., and Kühn, P.: Pedogenic and microbial interrelations to regional climate and local topography: New insights from a climate gradient (arid to humid) along the Coastal Cordillera of Chile, CATENA, 170, 335–355, https://doi.org/10.1016/j.catena.2018.06.018, 2018.

Bookhagen, B., Thiede, R. C., and Strecker, M. R.: Abnormal monsoon years and their control on erosion and sediment flux in the high, arid northwest Himalaya, Earth Planet. Sci. Lett., 231, 131–146, https://doi.org/10.1016/j.epsl.2004.11.014, 2005.

Brown, C. E.: Coefficient of Variation, in: Applied Multivariate Statistics in Geohydrology and Related Sciences, Springer, Berlin, Heidelberg, 1998.

Carretier, S., Tolorza, V., Regard, V., Aguilar, G., Bermúdez, M. A., Martinod, J., Guyot, J.-L., Hérail, G., and Riquelme, R.: Review of erosion dynamics along the major N-S climatic gradient in Chile and perspectives, Geomorphology, 300, 45–68, https://doi.org/10.1016/j.geomorph.2017.10.016, 2018.

Cerdà, A.: The influence of aspect and vegetation on seasonal changes in erosion under rainfall simulation on a clay soil in Spain, Can. J. Soil Sci., 78, 321–330, https://doi.org/10.4141/S97-060, 1998.

Chakrapani, G. J.: Factors controlling variations in river sediment loads, Curr. Sci., 88, 569–575, 2005.

Deal, E., Favre, A. C., and Braun, J.: Rainfall variability in the Himalayan orogen and its relevance to erosion processes: RAINFALL VARIABILITY IN THE HIMALAYAS, Water Resour. Res., 53, 4004–4021, https://doi.org/10.1002/2016WR020030, 2017.

Didan, Kamel: MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006, https://doi.org/10.5067/MODIS/MOD13Q1.006, 2015.

Earth Resources Observation And Science (EROS) Center: Shuttle Radar Topography Mission (SRTM) Void Filled, https://doi.org/10.5066/F7F76B1X, 2017.

Ferreira, V. and Panagopoulos, T.: Seasonality of Soil Erosion Under Mediterranean Conditions at the Alqueva Dam Watershed, Environ. Manage., 54, 67–83, https://doi.org/10.1007/s00267-014-0281-3, 2014.

Gabarrón-Galeote, M. A., Martínez-Murillo, J. F., Quesada, M. A., and Ruiz-Sinoga, J. D.: Seasonal changes in the soil hydrological and erosive response depending on aspect, vegetation type and soil water repellency in different Mediterranean microenvironments, Solid Earth, 4, 497–509, https://doi.org/10.5194/se-4-497-2013, 2013.

Gao, P., Li, Z., and Yang, H.: Variable discharges control composite bank erosion in Zoige meandering rivers, CATENA, 204, 105384, https://doi.org/10.1016/j.catena.2021.105384, 2021.

Garatuza-Payán, J., Sánchez-Andrés, R., Sánchez-Carrillo, S., and Navarro, J. M.: Using remote sensing to investigate erosion rate variability in a semiarid watershed, due to changes in vegetation cover, IAHS Publ, 292, 144–151, 2005.

Glodny, J., Gräfe, K., Echtler, H., and Rosenau, M.: Mesozoic to Quaternary continental margin dynamics in South-Central Chile (36–42°S): the apatite and zircon fission track perspective, Int. J. Earth Sci., 97, 1271–1291, https://doi.org/10.1007/s00531-007-0203-1, 2008.

Green, W. H. and Ampt, G. A.: Studies on Soil Phyics., J. Agric. Sci., 4, 1–24, https://doi.org/10.1017/S0021859600001441, 1911.

Hancock, G. and Lowry, J.: Hillslope erosion measurement—a simple approach to a complex process, Hydrol. Process., 29, 4809–4816, 2015.

Hancock, G. and Lowry, J.: Quantifying the influence of rainfall, vegetation and animals on soil erosion and hillslope connectivity in the monsoonal tropics of northern Australia, Earth Surf. Process. Landf., 46, 2110–2123, https://doi.org/10.1002/esp.5147, 2021.

Herrmann, S. M. and Mohr, K. I.: A Continental-Scale Classification of Rainfall Seasonality Regimes in Africa Based on Gridded Precipitation and Land Surface Temperature Products, J. Appl. Meteorol. Climatol., 50, 2504–2513, https://doi.org/10.1175/JAMC-D-11-024.1, 2011.

https://doi.org/10.5194/esurf-2022-65
Preprint. Discussion started: 14 December 2022

Hobley, D. E. J., Adams, J. M., Nudurupati, S. S., Hutton, E. W. H., Gasparini, N. M., Istanbulluoglu, E., and Tucker, G. E.: Creative computing with Landlab: an open-source toolkit for building, coupling, and exploring two-dimensional numerical models of Earth-surface dynamics, Earth Surf. Dyn., 5, 21–46, https://doi.org/10.5194/esurf-5-21-2017, 2017.

Hou, J., Zhu, H., Fu, B., Lu, Y., and Zhou, J.: Functional traits explain seasonal variation effects of plant communities on soil erosion in semiarid grasslands in the Loess Plateau of China, Catena, v. 194, 104743-, https://doi.org/10.1016/j.catena.2020.104743, 2020.

Istanbulluoglu, E. and Bras, R. L.: On the dynamics of soil moisture, vegetation, and erosion: Implications of climate variability and change, Water Resour. Res., 42, 2006.

Johnstone, S. A. and Hilley, G. E.: Lithologic control on the form of soil-mantled hillslopes, Geology, 43, 83–86, https://doi.org/10.1130/G36052.1, 2014.

Julien, P. Y., Saghafian, B., and Ogden, F. L.: RASTER-BASED HYDROLOGIC MODELING OF SPATIALLY-VARIED SURFACE RUNOFF1, JAWRA J. Am. Water Resour. Assoc., 31, 523–536, https://doi.org/10.1111/j.1752-1688.1995.tb04039.x, 1995.

Langbein, W. B. and Schumm, S. A.: Yield of sediment in relation to mean annual precipitation, Eos Trans. Am. Geophys. Union, 39, 1076–1084, https://doi.org/10.1029/TR039i006p01076, 1958.

Leyland, J., Hackney, C. R., Darby, S. E., Parsons, D. R., Best, J. L., Nicholas, A. P., Aalto, R., and Lague, D.: Extreme flood-driven fluvial bank erosion and sediment loads: direct process measurements using integrated Mobile Laser Scanning (MLS) and hydro-acoustic techniques: Direct measurement of flood-driven erosion using MLS and MBES, Earth Surf. Process. Landf., 42, 334–346, https://doi.org/10.1002/esp.4078, 2016.

Melnick, D.: Rise of the central Andean coast by earthquakes straddling the Moho, Nat. Geosci., 9, 401–407, https://doi.org/10.1038/ngeo2683, 2016.

Melnick, D., Bookhagen, B., Strecker, M. R., and Echtler, H. P.: Segmentation of megathrust rupture zones from fore-arc deformation patterns over hundreds to millions of years, Arauco peninsula, Chile: EARTHQUAKE SEGMENTATION AT ARAUCO, J. Geophys. Res. Solid Earth, 114, https://doi.org/10.1029/2008JB005788, 2009.

Mosaffaie, J., Ekhtesasi, M. R., Dastorani, M. T., Azimzadeh, H. R., and Zare Chahuki, M. A.: Temporal and spatial variations of the water erosion rate, Arab. J. Geosci., 8, 5971–5979, https://doi.org/10.1007/s12517-014-1628-z, 2015.

Oeser, R. A., Stroncik, N., Moskwa, L.-M., Bernhard, N., Schaller, M., Canessa, R., Brink, L. van den, Köster, M., Brucker, E., Stock, S., Fuentes, J. P., Godoy, R., Matus, F. J., Pedraza, R. O., McIntyre, P. O., Paulino, L., Seguel, O., Bader, M. Y., Boy, J., Dippold, M. A., Ehlers, T. A., Kühn, P., Kuzyakov, Y., Leinweber, P., Scholten, T., Spielvogel, S., Spohn, M., Übernickel, K., Tielbörger, K., Wagner, D., and Blanckenburg, F. von: Chemistry and microbiology of the Critical Zone along a steep climate and vegetation gradient in the Chilean Coastal Cordillera, CATENA, 170, 183–203, https://doi.org/10.1016/j.catena.2018.06.002, 2018.

Rengers, F. K., McGuire, L., Kean, J. W., Staley, D. M., and Hobley, D. E. J.: Model simulations of flood and debris flow timing in steep catchments after wildfire, Water Resour. Res., 52, 6041–6061, https://doi.org/10.1002/2015WR018176, 2016.

Rodell, M., Houser, P. R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J. K., Walker, J. P., Lohmann, D., and Toll, D.: The Global Land Data Assimilation System, Bull. Am. Meteorol. Soc., 85, 381–394, https://doi.org/10.1175/BAMS-85-3-381, 2004.

Schaller, M. and Ehlers, T. A.: Comparison of soil production, chemical weathering, and physical erosion rates along a climate and ecological gradient (Chile) to global observations, Earth Surf. Dyn., 10, 131–150, https://doi.org/10.5194/esurf-10-131-2022, 2022.

Schaller, M., Ehlers, T. A., Lang, K. A. H., Schmid, M., and Fuentes-Espoz, J. P.: Addressing the contribution of climate and vegetation cover on hillslope denudation, Chilean Coastal Cordillera (26°–38°S), Earth Planet. Sci. Lett., 489, 111–122, https://doi.org/10.1016/j.epsl.2018.02.026, 2018.

Schaller, M., Dal Bo, I., Ehlers, T. A., Klotzsche, A., Drews, R., Fuentes Espoz, J. P., and van der Kruk, J.: Comparison of regolith physical and chemical characteristics with geophysical data along a climate and ecological gradient, Chilean Coastal Cordillera (26 to 38\degree\,S), SOIL, 6, 629–647, https://doi.org/10.5194/soil-6-629-2020, 2020.

Schmid, M., Ehlers, T. A., Werner, C., Hickler, T., and Fuentes-Espoz, J.-P.: Effect of changing vegetation and precipitation on denudation – Part 2: Predicted landscape response to transient climate and vegetation cover over millennial to million-year timescales, Earth Surf. Dyn., 6, 859–881, https://doi.org/10.5194/esurf-6-859-2018, 2018.

Sharma, H., Ehlers, T. A., Glotzbach, C., Schmid, M., and Tielbörger, K.: Effect of rock uplift and Milankovitch timescale variations in precipitation and vegetation cover on catchment erosion rates, Earth Surf. Dyn., 9, 1045–1072, https://doi.org/10.5194/esurf-9-1045-2021, 2021.

Shobe, C. M., Tucker, G. E., and Barnhart, K. R.: The SPACE 1.0 model: A Landlab component for 2-D calculation of sediment transport, bedrock erosion, and landscape evolution, Geosci. Model Dev. Discuss., 1–38, https://doi.org/10.5194/gmd-2017-175, 2017.

https://doi.org/10.5194/esurf-2022-65
Preprint. Discussion started: 14 December 2022

Earth Surface Dynamics
Discussions
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Starke, J., Ehlers, T. A., and Schaller, M.: Latitudinal effect of vegetation on erosion rates identified along western South America, Science, 367, 1358–1361, https://doi.org/10.1126/science.aaz0840, 2020.

Steegen, A., Govers, G., Nachtergaele, J., Takken, I., Beuselinck, L., and Poesen, J.: Sediment export by water from an agricultural catchment in the Loam Belt of central Belgium, Geomorphology, 33, 25–36, https://doi.org/10.1016/S0169-555X(99)00108-7, 2000.

Stephenson, J., Gallagher, K., and Holmes, C.: A Bayesian approach to calibrating apatite fission track annealing models for laboratory and geological timescales, Geochim. Cosmochim. Acta, 70, 5183–5200, https://doi.org/10.1016/j.gca.2006.07.027, 2006.

Suescún, D., Villegas, J. C., León, J. D., Flórez, C. P., García-Leoz, V., and Correa-Londoño, G. A.: Vegetation cover and rainfall seasonality impact nutrient loss via runoff and erosion in the Colombian Andes, Reg. Environ. Change, 17, 827–839, https://doi.org/10.1007/s10113-016-1071-7, 2017.

Tucker, G. E. and Bras, R. L.: A stochastic approach to modeling the role of rainfall variability in drainage basin evolution, Water Resour. Res., 36, 1953–1964, https://doi.org/10.1029/2000wr900065, 2000.

Übernickel, K., Ehlers, T. A., Ershadi, M. R., Paulino, L., Fuentes Espoz, J.-P., Maldonado, A., Oses-Pedraza, R., and von Blanckenburg, F.: Time series of meteorological station data in the EarthShape study areas of in the Coastal Cordillera, Chile, https://doi.org/10.5880/FIDGEO.2020.043, 2020.

Wang, L., Zheng, F., Liu, G., Zhang, X. J., Wilson, G. V., Shi, H., and Liu, X.: Seasonal changes of soil erosion and its spatial distribution on a long gentle hillslope in the Chinese Mollisol region, Int. Soil Water Conserv. Res., 9, 394–404, https://doi.org/10.1016/j.iswcr.2021.02.001, 2021.

Wei, W., Chen, L., Zhang, H., and Chen, J.: Effect of rainfall variation and landscape change on runoff and sediment yield from a loess hilly catchment in China, Environ. Earth Sci., 73, 1005–1016, https://doi.org/10.1007/s12665-014-3451-y, 2015.

Wulf, H., Bookhagen, B., and Scherler, D.: Seasonal precipitation gradients and their impact on fluvial sediment flux in the Northwest Himalaya, Geomorphology, 118, 13–21, https://doi.org/10.1016/j.geomorph.2009.12.003, 2010.

Yetemen, O., Istanbulluoglu, E., Flores-Cervantes, J. H., Vivoni, E. R., and Bras, R. L.: Ecohydrologic role of solar radiation on landscape evolution, Water Resour. Res., 51, 1127–1157, https://doi.org/10.1002/2014wr016169, 2015.

Zhang, S., Li, Z., Hou, X., and Yi, Y.: Impacts on watershed-scale runoff and sediment yield resulting from synergetic changes in climate and vegetation, Catena, 179, 129–138, https://doi.org/10.1016/j.catena.2019.04.007, 2019.

Zhang, W., An, S., Xu, Z., Cui, J., and Xu, Q.: The impact of vegetation and soil on runoff regulation in headwater streams on the east Qinghai–Tibet Plateau, China, Catena, 87, 182–189, https://doi.org/10.1016/j.catena.2011.05.020, 2011.

Zhang, X., Yu, G. Q., Li, Z. B., and Li, P.: Experimental Study on Slope Runoff, Erosion and Sediment under Different Vegetation Types, Water Resour. Manag., 28, 2415–2433, https://doi.org/10.1007/s11269-014-0603-5, 2014.

Zheng, F. L.: Effect of Vegetation Changes on Soil Erosion on the Loess Plateau1 1Project supported by the Chinese Academy of Sciences (No. KZCX3-SW-422) and the National Natural Science Foundation of China (Nos. 9032001 and 40335050)., Pedosphere, 16, 420–427, https://doi.org/10.1016/S1002-0160(06)60071-4, 2006.

Ziese, M., Rauthe-Schöch, A., Becker, A., Finger, P., Rustemeier, E., and Schneider, U.: GPCC Full Data Daily Version 2020 at 1.0°: Daily Land-Surface Precipitation from Rain-Gauges built on GTS-based and Historic Data: Gridded Daily Totals (2020), https://doi.org/10.5676/DWD_GPCC/FD_D_V2020_100, 2020.