The effect of climate and vegetation on the topography of small – scale drainage basins in the Coastal Cordillera of South America

Master Thesis
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Eidesstattliche Erklärung

Hiermit versichere ich, dass ich die vorliegende Masterarbeit selbsständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

__________________________
Manuel Schmid
Abstract

Geologists have long recognized that the climatic conditions and the surface vegetation of a landscape have an effect on the morphological evolution (of mountain ranges?). In this study, we use remote sensing techniques to analyze 36 drainage basins from five different areas in the Coastal Cordillera of South America. The basins were characterized in terms of their topographic form (e.g., mean basin slope, basin total relief, basin hypsometry and mean basin channel steepness) and their climate setting (e.g., mean annual precipitation value and mean surface vegetation cover). The surface vegetation cover shows a high linear dependence on the annual precipitation until it reaches values up to 80% at precipitation values of 1100mm/y. Higher values of precipitation only show minor increases in surface vegetation cover. Catchment-mean slope and channel steepness data show a linear dependence with a Pearson correlation of 0.72, whereas mean $k_{sn}$ and total relief correlate with Pearson coefficient of 0.64. It is proposed that the morphometrics can be used as qualitative proxy for catchment-mean erosion rates. Mean slope, relief and steepness values show complex, non-linear relationship with increases in precipitation and vegetation surface cover. The highest morphometric values were identified at precipitation values of 1900 mm/y and 80% vegetation cover. Monte-Carlo least square fit analysis suggest coupling between vegetation cover and morphometric indices quadratic relationship and best goodness of fit ($r^2 = 0.71$) for mean basin slope. These findings substantiate the fact that climatic conditions and vegetation cover have impact on topographic evolution and correspond with other studies suggesting climatic regimes of different erosional efficiency.
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1. Introduction

The systems which describe the geomorphic processes on our planet are still an area of active research among the geoscientific community. The main controls which govern the evolution of topography are believed to be climate and tectonics (Burbank 2011; Abrahams & Ponczynski 1984; Langbein & Schumm 1958; Roe et al. 2002; Jeffery et al. 2014). Geomorphologists have focused on these two driving forces over the recent years, which has led to a better understanding of the sensitivity of landscapes to changes in the tectonic or climatic factors.

Nowadays a third endogenic control, the biological surface cover, gained significance in the focus of geoscience (Jiongxin 2005; Gyssels et al. 2005; Howard & Kerby 1983). Today there is a rising interest in the effects which vegetation has on soil parameters like shear stability, rainwater infiltration and rainfall interception (Gyssels et al. 2005; Wainwright et al. 2000; Reubens et al. 2007). Those factors are believed to be the underlying causes of topographic evolution due to vegetation change (Dietrich & Perron 2006; Istanbulluoglu & Bras 2005). This study aims to evaluate how a complex climatic system changes the vegetation cover within a drainage basin. Furthermore a method was tested for recognizing the signal that vegetation cover exerts on the controls of landscape evolution. This is done by the analysis of different landscape morphometrics.

There are many studies that looked at the relationships between vegetation/climate and erosion rates within a drainage area. Through this work, it is commonly accepted that changes in vegetation cover will also influence topographic patterns. This was determined using numerical modelling (Istanbulluoglu & Bras 2005; Wobus et al. 2006; Dietrich & Perron 2006) as well as the analysis of real, non-synthetic landscapes (Jiongxin 2005; Howard & Kerby 1983;
Abrahams & Ponczynski 1984; Horton 1945). Most of those studies use cosmogenic nuclides to determine millennial scale erosion rates in relation to the vegetational state of a drainage basin. The findings suggest a distinct coupling but no general, robust relationship has been found so far (Langbein & Schumm 1958; Wilson 1973).

Since many of those studies focus on either synthetic landscapes or tend to scrutinize only the climatic circumstances of one specific area (Jiongxin 2005; Snyder et al. 2000; DiBiase et al. 2010) there is a lack of studies that look at the overall, large-scale effects of vegetation changes across a climatic gradient in a distinct landscape form. In order to get an understanding of the sensitivity of landscapes to vegetation in a real setting, it is important to analyze the effects that directly show in landscapes with a common tectonic but different climatic history.

This study expands previous work by analyzing landscape morphometrics which are commonly utilized to examine tectonic processes. Yet, it enlarges the area over which this analysis is carried out. Our study basins are located along the Andean Coastal Cordillera. In order to get a better understanding of the sensitivity of landscapes to changes in climate/vegetation, we select basins with similar tectonic history and lithology. This isolates the effect of climate on the landscape evolution and therefore on the landscape morphometrics.
2. Methods

2.1. Data handling

This study uses a freely available 30 m resolution Digital Elevation Model (DEM) from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) mission, which was obtained using the official source of the NASA Jet Propulsion Laboratory (http://aster-web.jpl.nasa.gov/gdem.asp). From this DEM the industrial standard software packages of ArcGIS were used to calculate the landscape morphometrics described below. The stream profile data, including the normalized steepness index values, were extracted by using Mathworks MATLAB Software with an additional suite of scripts, already established in other publications (Wobus et al. 2006).

2.2. Derivation of topographic metrics

In this study, several topographic metrics were calculated, namely topographic slope, total relief and river steepness. Those metrics are used to characterize the erosional state of a basin. It is widely accepted that these metrics give information about how effective the hillslopes and rivers are able to detach and transport sediment. Therefore, a landscape with higher morphometric values would mostly correspond to higher rates of erosion. First, the average slope angle of each basin was extracted from the 30 m DEM by using ArcGIS (v10.1) implemented calculation routines which calculate the steepest gradient within a 3x3 pixel moving window. Second, the total relief of each basin was calculated by extracting the minimum and maximum physical elevation of each basin:
\[ \text{Relief}_{\text{tot}} = E \text{le}_{\text{max}} - E \text{le}_{\text{min}} \]  

A positive relationship between the mean basin slope and the basin total relief is accepted (Ahernert 1970). Relief is a measure of ‘missing mass’ (Whipple & Tucker 1999) within a landscape and as such it can only be increased by removal/erosion of mass out of the system. A positive relationship between the mean basin slope, basin total relief, and the mean basin erosion is a concept that has also been explored by previous authors (Ouimet et al. 2009; DiBiase et al. 2010; Montgomery & Brandon 2002). The third metric that was calculated is the basin hypsometric curve, which provides a proxy for the mass distribution within a basin. (Strahler 1962). In order to simplify, a representative hypsometric curve for each focus area was created by calculating the mean height distribution of all basins in one area. In general, the hypsometry of a basin characterizes the mass distribution in relationship to the area within a basin and can be used as a proxy for the erosional history. Low hypsometric curves indicate that a high percentage of mass has been transported out of the system.

In addition to the well-known basin metrics, we try to explore the sensitivity of the steepness index \( k_s \) to changes in the erosional system. The steepness index is used as a way to characterize the fluvial relief of a drainage area (DiBiase et al. 2010; Wobus et al. 2006). An empirical description of the behavior of a fluvial channel is Flint’s Law (Flint 1974):

\[ S = k_s A^{-\theta} \]  

This equation includes the channel steepness index \( k_s \) as a scaling factor between the local channel slope \( S \) [m/m], the upstream drainage area \( A \) [m\(^2\)] and the river concavity \( \theta \). A problem of this method is that the steepness index \( k_s \) is dependent on the channel concavity \( \theta \) which
makes it difficult to evaluate the $k_s$ value at a basin scale because spatial changes in $\theta$ could be interpreted as changes in $k_s$. This problem is solved by inferring a fixed reference concavity $\theta_{\text{ref}}$ (Wobus et al. 2006) which is used for all calculations of $k_s$ in the focus areas and therefore creating a normalized steepness index $k_{sn}$ which is comparable between different locations (DiBiase et al. 2010):

$$S = k_{sn}A^{-\theta_{\text{ref}}} \quad (3)$$

Reference concavities typically fall in the range of 0.35 – 0.65 (Snyder et al. 2000). For our study we use a reference concavity value of 0.45 which falls in the same range as reference concavities used in other studies in our focus area and elsewhere (Wobus et al. 2006; Hoke et al. 2007). A graded river channel is believed to follow a stream power model (Perron & Royden 2013; Whipple & Tucker 1999):

$$E = K * A^m * S^n \quad (4)$$

In this equation, $E$ equals the erosion rate [mm/yr], $K$ is the coefficient of erosion [m$^{0.1}$/yr], $A$ is upstream drainage area, $S$ is channel bed slope and $m$ and $n$ being empirical derived constants. The river concavity used in Eq. 2, can be described as $\theta = m/n$. Assuming topographic steady state, which means that the total uplift rate $U$ [mm/yr] equals the total erosion rate $E$, means that there is no change of mean basin elevation and the system can be described by:

$$\frac{dz}{dt} = U - E = 0 \quad (5a)$$

$$U - KA^mS^n = 0 \quad (5b)$$

By combining the stream-power law (4) and Flint’s Law (2) and inferring a topographic steady-
state (dz/dt = 0; mean elevation of the basins does not change) we can derive an expression for $k_{sn}$ [m$^{0.9}$] which links it directly to erosion rate $E$ and the erosional coefficient, $K$ (DiBiase et al. 2010):

$$k_{sn} = \left(\frac{E}{K}\right)^{\frac{1}{n}}$$  \hspace{1cm} (5)

Using the normalized steepness index as an indicator for the erosional stage of a basin was evaluated by various other authors (DiBiase et al. 2010; Ouimet et al. 2009) who found a strong positive relationship between basin wide $k_{sn}$ values and basin wide erosion rate.

### 2.3. Study area selection

**Table 1** Overview over different study areas

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Vegetation</th>
<th>Precipitation mm/y</th>
<th>Number of Basins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azucar</td>
<td>Mostly granitic</td>
<td>Very sparse</td>
<td>100</td>
</tr>
<tr>
<td>Santa Gracia</td>
<td>Mostly granitic</td>
<td>Shrubs/cacti</td>
<td>300</td>
</tr>
<tr>
<td>La Campana</td>
<td>Mostly granitic</td>
<td>Green forrest</td>
<td>1100</td>
</tr>
<tr>
<td>Robleria</td>
<td>Mostly granitic</td>
<td>Green forrest</td>
<td>1900</td>
</tr>
<tr>
<td>Nahuelbuta</td>
<td>Mostly granitic</td>
<td>Rainforest</td>
<td>3000</td>
</tr>
</tbody>
</table>

For our analysis, we picked different areas in the Chilean Coastal Cordillera and its northern extension. The Coastal Cordillera is a discontinuous morphological feature, which extends from 33°S to 46°S (Moreno & Gibbons 2007). The Coastal Cordillera mainly consist of mesozoic volcano-sedimentary rocks which intruded by coeval plutonic belts. The studied areas are all part of the Coastal Cordillera and were picked because they show the most similarities in terms of lithological setting and tectonic history, but strongly differ in the climate/vegetation zone they are situated in. The main change and hence the most probable driving force of topographic evolution in those basins is therefore the climatic setting and the vegetation which is
characteristic for a specific climatic condition. An overview of the properties of the studied areas is given in Table 1. The climate data which was used for this study are long term monthly means from the years 1981 – 2010, compiled by Cort Willmot & Kenji Matsuura of the University of Delaware. The vegetation cover data comes from the USGS Land Cover Institute and is a MODIS (Moderate Resolution Imaging Spectroradiometer)-based 1km maximum green vegetation fraction dataset. The vegetation fraction dataset provides a good measure of the actual vegetation surface cover which directly influences the shear resistance of the top soil and therefore the resistance to erosion (Istanbulluoglu & Bras 2005).

The watersheds in the specific study areas show mostly equilibrium longitudinal river profiles, hence they can believed to be in steady-state. Only in steady-state basins it is possible to link the normalized steepness index $k_{sn}$ to basin-wide erosion rates. This was done by identifying basins which don’t have a spatially constraint jump in $k_{sn}$ values which was determined using $k_{sn}$ maps and slope/area plots of interesting basins. It was aimed for a minimum number of six drainage basins per study area and used more when it was possible. The exact picking of the areas was done by comparing a geological map of South America with the MODIS vegetation
dataset and the precipitation dataset. Basins which comply with the boundary conditions were picked and then tested by quick slope/area – analysis for major knickpoints which would disturb the system. This was done to exclude basins from the study that do not comply with the necessary conditions.

3. Results

3.1. River profile analysis

Fig. 2 showing the longitudinal river profiles of streams in study drainage basins. Y-Axis shows elevation above sea level, X-Axis shows distance from mouth. River mouth is defined as the geographical point where the river leaves the observed drainage basins. Different behavior is observable: Azucar rivers show mostly linear river profiles with constant gradient, Santa Gracia, La Campana and Robleria rivers show adjusted profiles with decreasing gradient. Nahuelbuta rivers show partly minor knickpoints or adjusted profiles.

The first part of the study incorporated the analysis of the stream profiles of each river in the observed drainage basins. Fig. 2 shows the longitudinal profiles in respect to their absolute
elevation above sea level. It shows that the river profiles differ much in respect to their shape. Two apparent end-members can be observed: The rivers in Azucar show a nearly linear profile with an almost constant gradient, whereas the rivers in Robleria have a very steep upper part which flattens out at an upward concave knickpoints describing a sudden change in channel slope. Knickpoints can reflect different geological conditions or may be used to give information about changes in erosional processes. Nahuelbuta river profiles show a few minor knickpoints within their profiles which don’t seem to follow any apparent spatial distribution.

### 3.2. Relationship between mean basin slope, basin total relief and mean basin $k_{sn}$

Catchment-mean $k_{sn}$ values and the catchment-mean slope correlate in our study areas with a Pearson linear correlation factor of 0.72 whereas the correlation between catchment-mean $k_{sn}$ and basin total relief is 0.64 (see Table 2). This suggests that in our study areas the different topographic indices are linked to each other with different sensitivities. This has also been demonstrated in the findings of other working groups which link the mean basin slope to mean basin channel steepness and basin wide erosion (Ouimet et al. 2009).

**Table 2 Correlation coefficient matrix for different topographic metrics.**

<table>
<thead>
<tr>
<th></th>
<th>Mean Basin $k_{sn}$</th>
<th>Mean Basin Slope</th>
<th>Basin Total Relief</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Basin $k_{sn}$</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Basin Slope</td>
<td>0.72</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Basin Total Relief</td>
<td>0.64</td>
<td>0.65</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Fig. 3 shows that the correlation between mean basin slope and mean basin $k_{sn}$ seems to be linear. It shows that the area with the highest precipitation (Nahuelbuta) and the area with the
lowest precipitation (Azucar) both have a general lower slope for the same $k_{sn}$ value as the areas with an intermediate climate.

The area with the overall highest $k_{sn}$ values is Robleria, the area with the second highest precipitation values. There are two basins with a very low basin wide $k_{sn}$ value of < 20. They belong to the Nahuelbuta and Robleria area, which are the basins with the highest precipitation values. The data shows an asymmetrical spread, with a higher variance in the $k_{sn}$ data and lesser variance in the slope data.

![Fig. 3 Relationship of mean basin slope values and mean basin $k_{sn}$ values. Solid line represents best 1st order fit with $r^2$ of 0.55. Datapoints suggest linear relationship of Slope/$k_{sn}$ until a threshold slope of 30° which resemble the findings of (Ouimet et al. 2009).](image)
3.3. Relationship between vegetation and precipitation in the study areas

This study tries to quantify the first order impact that vegetation has on the erosional system. Therefore, it is important to know how the precipitation of each area, which is an easily quantifiable metric, links to the green vegetation surface fraction. Fig. 4 shows the relationship between the mean annual precipitation of each area and the green vegetation surface fraction. The data suggests a linear increase in vegetation surface cover up to precipitation values of 1200 mm/y. After this value the linear increase stops and there is no significant increase in surface cover anymore. At this point the landscapes already reached a vegetation cover of 80% at only 37% of the maximum measured precipitation in our areas, so the maximum rainfall is

*Fig. 4* Graph showing the relationship between mean annual precipitation and vegetation surface cover. Each basin is represented by individual circles. Red dotted line represents a spline fit through the data and red crosses represents the median Vegetation Surface Cover for each area.
not needed to sustain a heavily vegetated landscape. This specific behavior is only valid in our specific climatic setting, namely the Coastal Cordillera of the Andes. For other areas, it is a valid assumption that other factors, which would contribute to sustainable vegetation covers, for example moisture, solar radiation, temperature, would yield a different relationship.

3.4. Relationship between landscape morphometrics and precipitation

For this part of the analysis, we tried to evaluate how the different erosional metrics change with increasing mean annual precipitation in the study areas. For this purpose the mean basin slope, basin total relief and basin mean $k_{sn}$ for each drainage basin was plotted with its corresponding precipitation value (Fig. 5). In the driest of our study areas, Azucar, mean slope, total relief and mean $k_{sn}$, show overall low values (Slope = 5° - 15°, Relief = 200m - 900m, $K_{sn} = 40 - 80$). With higher precipitation, the morphometrics also increase, with the most significant change happening between the two driest areas (Azucar: 100 mm/y, Santa Gracia 300mm/y). Between Santa Gracia and the Reserva Robleria (1900 mm/y), the medians of all three morphometrics increase and reach their maximum at Robleria.

The variance of the datasets also increases from Azucar to Robleria, which shows the largest errorbars around the medians of each dataset. From Robleria to Nahuelbuta (3000 mm/y) the data values, as well as the variance, shows a decline until it reaches values, similar as the values in the low-precipitation area Azucar.
Fig. 5 Graph showing the qualitative relationship between mean annual precipitation and mean basin slope (A), basin total relief (B) and mean basin k_{sn} (C). It is apparent that there seems to be no quantifiable relationship between the values but the pattern is similar for both metrics. The values increase fast with increasing precipitation with a peak at approximately 2000mm/y and then decrease again until, at the maximum precipitation, they reach values that are similar to the values of Azucar focus area.
3.5. **Relationship between erosional metrics and surface vegetation density**

The next step in the morphometric analysis was to evaluate if data that links topographic metrics to climatic metrics, also shows the same behavior to surface vegetation datasets. Our data shows that the relationship between vegetation density and morphometrics follows a similar pattern, but with significant changes in behavior of the individual metrics. The mean $k_{13}$ value, the total relief and the mean slope all follow a form of general trend which in a first approximation can be qualitatively described as a parabola function with the highest values for all three morphometrics at approximately 90% mean basin vegetation cover (Fig. 5) which resembles a mean annual precipitation of 2000mm (Fig. 4).

The data shows three different sections: Up to 30% vegetation cover, all three morphometrics show a significant increase. Between 30% to 80% vegetation cover no significant increase is apparent, but it has to be noted that there is a lack of enough datapoints in this field to make robust conclusions. The third area from 80% to 100% vegetation cover is characterized through an increasing spread in the datapoints. To get a qualitative visualization of the relationship, a 2nd - order polynomial interpolation of the data shows a declining trend, starting at around 80% vegetation cover and ends with values that are approximately similar to the values in the first section (up to 30% vegetation cover). Although all observed metrics show the same trend, they differ mainly in in the variance of the dataset, which increases in areas of higher vegetation cover.
Fig. 6 Graph showing the change of mean basin slope (A), basin total relief (B) and mean basin $k_{sn}$ (C) with mean basin vegetation cover. It can be seen that all of the data reflects the same overall trend with a peak at values of medium to high vegetation cover and a decrease at values of minimum/maximum vegetation cover. Red line shows 2nd – order polynomial interpolation between all datapoints, black lines show boundaries, which contain 50% of the data.
3.6. Monte-Carlo least square fits

Fig. 7 shows results of Monte-Carlo-Least-Square fittings with 10000 iterations for the mean vegetation cover dataset compared to mean slope, relief and $k_{sn}$ - morphometrics with a quadratic equation ($y = p1 \cdot x^2 + p2 \cdot x + p3$). It shows that the best correlation is achieved by the slope dataset ($r^2 = 0.71$) while the relief ($r^2 = 0.53$) and $K_{sn}$ ($r^2 = 0.45$) show an intermediate or bad correlation. The most variance between the possible functions is showing between vegetation cover values of 30% and 70%, where only a few datapoints of Santa Gracia and La Campana are available to use for fitting. In the case of the $k_{sn}$ fits there were also a minor set of solutions with a positive quadratic coefficient $p1$ whereas for the slope and the relief dataset all solutions have a negative $p1$ value and therefore resemble a downward concave parabola as the most likely solution.

3.7. Basin hypsometry

By calculating the basin hypsometry, it is possible to get another, well-known metric for the erosional state of a drainage basin. We calculated the hypsometric curve for all the individual drainage basins but for ease of interpretation of the data, we only show the mean hypsometric curves, which incorporated the data of all the basins for each focus area (Fig. 8). Through this analysis it is possible to create a hypsometric curve which does not resemble the elevation/area distribution of one basin, but shows the trend of the general distribution in our in our focus areas.
Fig. 7 Results of Monte Carlo Least-Square fits of Vegetation Cover with Slope/Relief/$K_{sn}$ datasets with 1000 iterations. Red dots represent datapoints, grey lines represent individual results of iterations, red line shows mean of 10000 iterations, blue line shows best fit through all datapoints. Equation for best fit is given in the figure (red: Monte-Carlo-Mean, blue: Overall best-fit). Slope-data shows best $r^2 (=0.72)$ value while $K_{sn}$ data shows weakest fit quality ($r^2 = 0.4472$). Most divergence of fits in a zone between 30% and 70% vegetation cover.
Fig. 8 shows that the curves with the highest hypsometric integral, which are an indicator for a basin that has not witnessed huge amounts of erosion, belong to the areas with the lowest/highest precipitation, Azucar and Nahuelbuta. The lowest hypsometric integrals however represent the areas with medium precipitation/vegetation. Our data suggests that the areas with the more extreme climatic conditions (wet or dry) also are the areas with the highest hypsometric integral whereas the areas with an intermediate condition are the ones with lower hypsometric values.

Fig. 8 Graphs shows the mean basin hypsometry curves. The individual curves represent the mean normalized elevations for each focus area in relationship to the normalized area for each basin. It can be seen that the areas with the lowest/highest precipitation/vegetation cover also have the highest hypsometry curves whereas the areas with medium precipitation/vegetation cover have the lowest hypsometry. Numbers represent corresponding hypsometric integral.
4. Discussion

4.1. Synthesis of Results

The correlation between mean basin $k_{sn}$ and mean basin slope, presented in Fig. 3 shows a positive relationship with a semi-robust correlation ($r^2 = 0.55$). This is not unexpected, if one assumes that the $k_{sn}$ values give a first order approximation about a river's capability to erode and therefore, to form the landscape. The mean slope value represents the reaction of the hillslope processes in a valley to external forcings. The positive correlation between slope/$k_{sn}$ values in all focus areas suggests that we are looking at landscapes in which the hillslope processes are linked to the erosional base level of the river and therefore the underlying erosional processes are coupled. By establishing this relationship, we can assume that the mean basin $k_{sn}$ value as well as the mean basin slope value can be used as a proxy for the erosional state of the analyzed basins. The fact that the total basin relief also shows a positive, but less strong, correlation with the $k_{sn}$ values indicates that the total relief also reacts to changes in erosional base level, but probably on a larger timescale than the smaller scaled fluvial and hillslope processes. This can be explained by the fact that the river processes, which reflect in the $k_{sn}$ data, are creating fluvial relief, which directly connects to the surrounding hillslopes and the hillslope relief. The combination of both fluvial and hillslope relief produces the basins total relief so those three indicators are proxies for processes on different length scales with different sensitivities.

In order to quantify and characterize the basin in terms of erosional setting we also tested how
the specific vegetation of each basin varies with the mean annual precipitation of each location. The data shown in Fig. 4 suggests that it is only partly a linear relationship. This means that it is important to quantify the changes in topographic metrics in respect to the changes in precipitation but also in respect to changes in vegetation density, to account for the non-linearity of those data.

By looking at the changes of mean basin slope, basin total relief and mean basin ksn value with changes in mean annual precipitation (Fig. 5) and mean vegetation surface cover (Fig. 6) we try to evaluate how the landscapes react to different external forcings. By looking at the results it is apparent, that there is an area of maximum slope/relief/ksn within the precipitation range at around 2000mm/y rainfall, as well as in the surface vegetation range at around 40% vegetation cover.

4.2. Topographic indices as proxy for the erosional state of a drainage area.

One of the goals in this study was to test the possibilities, which are given by using topographic indices, which can easily be obtained by remote sensing, as a proxy for the erosional state of a drainage area. This analysis demonstrates that a small, easy accessible set of indices, namely total relief, basin slope, hypsometry and channel steepness, are very well linked to each other and can be used to characterize a landscape. Assuming that the findings of various other studies (DiBiase & Whipple 2011; Ouimet et al. 2009) which link the basin-wide ksn values to basin-wide erosion rates (determined by 10Be-Analysis), also hold for the areas of this study, this will be a fast and inexpensive method for a first-order approach of getting tectonic information
out of DEM’s.

The obtained data suggests a linear relationship between slope, relief and $k_{sn}$ which gives information about the coupling of hillslope erosion to fluvial incision processes in our study areas: Rivers are, in non-glaciated landscapes, the main agent of erosion and therefore in the most direct contact with tectonic forcings upon a landscape. A river will carry a new tectonic information throughout the basin, where the hillslope system will react to the new forcings and adjust their slope. Over time this will create relief and shape the basins on a macro-scale. It is reasonable to assume that the shown relationship between topographic metrics and basin wide erosion holds in most landscapes as long as they share similar boundary conditions. Lithological parameters should be approximately the same to ensure that they don’t influence the channel steepness by changing shear-stress resistance or erosional patterns. Another necessary condition is that there should be no major faults in the drainage areas, because faults are known to change uplift patterns spatially and could produce knickpoints. Those knickpoints would affect the regional uplift pattern and probably disturb the system, so that the steady-state assumption would not be reasonable anymore. These boundary conditions already limit the suitable basin a way because they indirectly limit the size of the basins: it is very likely that basins above a certain size will contain different lithological units and faults.

4.3. Limits of the method: Fluvial vs. Hillslope dominated Landscapes

In the previous sections, we showed that the method of large-scale calculation of a river steepness index can produce reliable information about the tectonic regime of drainage basins.
However, there is danger in over interpreting such results when landscapes do not exhibit a power law relationship between slope and area. In Section 3.1, Fig. 2, showing the analyzed river profiles, it is clear to see that they have significant differences from each other. It is widely accepted that a river, which is in so called quasi-steady-state, shows a smooth, concave upward profile which resembles the different transport processes in the energetic regimes of the river. The channel slope S changes downstream because the drainage area A of the river expands and to uphold steady state conditions S must decrease to compensate this effect (Eq. 3). By looking at the driest of the focus areas, the Parque Nacional Pan de Azucar, which receives around 300mm/y precipitation, it is clear to see that the corresponding river profiles have a nearly linear shape. This means that the gradient of these profiles does not change over the distance the river travels downstream. This indicates a significant change in the underlying transport processes, which act in the specific basin.

At this low values of annual precipitation, it is probable that most of the rainfall will occur during intraseasonal, high-intensity events. Most of the erosional work on a drainage network is done, during those high-magnitude storm events (Chorley & Morgan 1962), because only then the critical amount of overland flow is reached. In addition, the low values of surface vegetation cover in Azucar will not provide the top soil layer with an increased slope stability (Dunne et al. 1991), which will contribute to channel formation during high overland flow. The linear river profiles however indicate a system that is not in full steady state conditions. The slope/area-plots also support this argument by showing that the slope is stationary over the drainage areas of most of Azucars rivers which would indicate a dominance of planar hillslopes over the whole area (Tucker & Whipple 2002). This is also indicated by the shape of the mean
hypsometry curve (Fig. 8): The curve which represents the area of Azucar shows nearly a decreasing downward concave curve, which indicates lots of material in the upper reaches of an area which was interpreted as a result of diffusive hillslope processes (Cohen et al. 2008).

The analysis of the mean $k_{sn}$ values, carried out in the drainage areas, depends on the assumption that the basins are in a state of fluvial quasi-steady state. A basin, which would be dominated mostly by hillslopes, would be hard to quantify solemnly based on their mean $k_{sn}$ value. This could lead to wrong results because the underlying equations assume a bedrock channel in equilibrium between erosion and uplift.

As suggested in the results (Fig. 5, Fig. 6) the Azucar $k_{sn}$ dataset agree with the results from the slope/relief – analysis. This indicates that the fluvial system of the drainage areas is probably active enough to be in contact with the remaining topography, but the topographic signal is disturbed by hillslope processes, which form the landscape in the remaining time between high-precipitation events.

### 4.4. Vegetation-erosion-coupling

The main focus of the study was to assess the effects of the surface vegetation cover and the mean annual precipitation to the topographic metrics which are typically used to define a landscape. Based on the data plotted in Fig. 6, it is apparent that the mean basin slope, basin total relief as well as the mean basin $k_{sn}$ value respond to changes in surface vegetation cover. All three tested metrics show one broad peak between 40% and 80% vegetation cover, which spans a set between the areas Santa Gracia and La Campana. By considering the relationship of these three metrics as proxies for the general erosional setting in a drainage area (DiBiase
it is possible to identify an interval of vegetation cover which supports higher basin wide denudation.

The highest values for all three metrics are achieved in the areas of Santa Gracia, La Campana and Robleria whereas the values for the areas with the smallest/highest vegetation cover of Azucar and Nahuelbuta remain at the smaller end of scale. This suggests two counteracting effects which act on the landscapes: The increase of precipitation leads to an increase in surface vegetation fraction. This increases the surface stability of the corresponding soil (Horton 1945; Istanbulluoglu & Bras 2005). The increase in precipitation leads to higher values of overland flow which is known to increase the erosional forcing on the top-layer (Horton 1945). Therefore, the increase of rainfall on a landscape directly leads to a system of two contradicting processes acting on the morphology of a landscape.

The results of the Monte-Carlo analysis indicate that the mean basin slope is the morphometric with the highest correlation to basin vegetation cover, whereas the basin total relief shows an intermediate correlation and the mean basin $k_{sn}$ values a weak correlation. While the slope/$k_{sn}$ datasets show high correlation between each other, the Monte-Carlo results indicate that, based on our basin-data, predictions for the behavior of channels in different vegetation-settings will be not very robust. Predictions about slope angle will have a higher statistical robustness.

Fig. 9 shows the relationships between precipitation, vegetation and the analyzed topographic metrics. The precipitation and vegetation reach their maximum in the most southern focus area Parque Nacional de Nahuelbuta (39°S). It is apparent that all three topographic metrics
Fig. 10 The upper two figures show the mean annual precipitation and the vegetation surface cover in respect to their geographic location. It is evident that both parameters increase to the south with both maxima located at the most southern focus area Nahuelbuta. The third figure shows a schematic overview of the changes in our observed topographic values (green: $k_{sn}$, yellow: slope, red: total relief) which all show their maximum at the Robleria area.
reach their maxima at the focus area of the Reserve Nacional de Robleria, which is located to the north of Nahuelbuta (34°S) and witnesses approximately 1000mm/y less precipitation and shows a 10% smaller surface vegetation cover. Our data suggests a relationship as shown in Fig. 11, which indicates that at low values of precipitation there is a high value of erosional potential. This means that the landscape doesn’t show much protection against erosion but there is not enough rainfall to do a lot of mass transporting. This would resemble the focus areas of Azucar and Santa Gracia, which show an increase in basin wide slope/relief/ksn values.

In the transition zone, the vegetation has grown to a point where the slope stability is big enough to counteract the erosional forcing and therefore the erosional system will stagnate. This can be seen in the topographic metrics (Fig. 5, Fig. 6) as the flat peak between the areas of La Campana and Robleria. At high values of precipitation, we have a fully developed vegetation cover and therefore the erosional potential is at such low values because of high root density, high infiltration rates (Reubens et al. 2007; Wainwright et al. 2000) and because the overall surface roughness (Gyssels et al. 2005) have stabilized the ground to its maximum. This leads to a decline in basin wide erosion rates because, although the erosion forcing is at its maximum due to high amounts of overland flow, the erosional potential is so low that only in a few events of extraordinary rainfall conditions there will be erosion happening. This shows the declining trend in the morphometric data from the Robleria focus area to the Nahuelbuta focus area (Fig. 5, Fig. 6).
Apart from the first-order trend approximation, the data shows a distinct pattern in standard deviation (Fig. 12). The variance coefficient (Cv), which is a comparable metric for spread in datasets, increases from N to S and shows a maximum at the Robleria focus area, like the other topographic metrics. This suggests a relationship between data standard deviation and erosional efficiency. A higher standard deviation would result from higher differences between different basins in terms of topographic appearance, hence difference in topographic metrics. A higher erosion factor is directly linked to a higher sediment yield, which could produce valley infill and distort the calculation of the topographic metrics. Most river profiles (Fig. 2) show a

**Fig. 11** Showing a sketch of the proposed relationship between erosional forcings and erosional potential. Note that they both depend heavily on precipitation (erosional forcing) and vegetation cover (erosional resistivity). This aims not to be a quantifiable mathematical expression but more a qualitative representation of the effects of increasing precipitation/vegetation cover.
distinct upward concave knickpoints for the rivers in the Robleria focus area, which could indicate a change from bedrock river systems to riverbeds in a gentle sloped sediment basin produced by valley infill.

An option for future studies would be to prevent this distortion of the topographic signal by excluding the proposed, sediment infilled, areas from the topographic analysis. In this study, the overall trend of the data is still significant but it is proposed that in larger basins with a higher infill/bedrock – ratio the signal could be so much distorted that a correct interpretation would be prone to errors.

**Fig. 12** Variance Coefficient \((Cv = \sigma / \bar{Z})\) for the slope/relief/\(k_{sp}\) data. High values of \(Cv\) indicate a large standard deviation in the dataset. The \(Cv\)-data suggests an increase in standard deviation from Azucar (N) to Robleria (S) where it reaches its peak and then a sudden decrease at Nahuelbuta.
5. Conclusion

The straight north-south strike of the Andes and the Coastal Cordillera leads to a strong gradient in climatic conditions over an area with a very similar tectonic history. Satellite datasets were used to analyze changes in mean annual precipitation, vegetation surface cover and topographic slope/relief/k_{sn}, which lead to three main conclusions:

1. Average slope correlates with average k_{sn}, which agrees with previous studies and suggests slope and k_{sn} as proxies for basin wide erosion (DiBiase et al. 2010).

2. Basin mean annual precipitation and vegetation surface cover increase from North to South. Topographic metrics show lowest values at northern area Azucar and at southern area Nahuelbuta. Highest values occur in precipitation interval between 1000 mm/y and 2000 mm/y precipitation and with 80% vegetation cover, which indicate an interval of high erosive conditions.

3. The areas, which have the highest morphometric values, have around 80% mean vegetation cover whereas the area with the highest vegetation cover, Nahuelbuta, shows a decline in morphometric values. Vegetation in Nahuelbuta has stabilized the soil, which reached equilibrium surface stability and is therefore very resistant to erosional forcing. Monte Carlo least square fittings to a quadratic equation predict a relationship between erosional metrics and surface vegetation with a correlation ranging between r^2 = 0.71 for the topographic slope, r^2 = 0.53 for relief and r^2 = 0.45 for the k_{sn} dataset.
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all metrics have their maxima at Robleria.

**Fig. 10** Showing a sketch of the proposed relationship between erosional forcings and erosional potential. Note that they both depend heavily on precipitation (erosional forcing) and vegetation cover (erosional resistivity). This aims not to be a quantifiable mathematical expression but more a qualitative representation of the effects of increasing precipitation/vegetation cover.

**Fig. 11** Variance Coefficient ($Cv = \sigma / \bar{Z}$) for the slope/relief/$k_{sn}$ data. High values of $Cv$ indicate a large standard deviation in the dataset. The $Cv$-data suggests an increase in standard deviation from Azucar (N) to Robleria (S) where it reaches its peak and then a sudden decrease at Nahuelbuta.
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