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Weak bedrock allows north-south elongation of channels in semi-arid landscapes

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ABSTRACT

Differences in the lengths of pole- and equator-facing slopes are observed in a variety of landscapes. These differences are generally attributed to relative variations in the intensity of mass-transport processes on slopes receiving different magnitudes of solar radiation. By measuring anomalies in the planform characteristics of drainage networks, we demonstrate that in the most asymmetric landscapes this asymmetry primarily arises from the equator-ward alignment of low-order valley networks. Valley network asymmetry is more severe in rocks expected to offer little resistance to erosion than in more resistant rocks when controlling for climate. This suggests that aspect-driven differences in surface processes that drive differences in landscape evolution are also sensitive to underlying rock type.

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1. Introduction

Micro-climatic differences that arise due to aspect-dependent insolation can influence geomorphic process and, in turn, landscape forms (Bass, 1929; Emery, 1947; Melton, 1960; Dohrenwend, 1978; Burnett et al., 2008; Istanbulluoglu et al., 2008; West et al., 2014; McGuire et al., 2014). This asymmetry is most commonly manifest in the Northern Hemisphere as north-facing slopes that are steeper than their south-facing counterparts (Poulos et al., 2012). Opposing aspects also commonly display differences in the degree of drainage dissection (Bass, 1929; Dohrenwend, 1978; Istanbulluoglu et al., 2008; McGuire et al., 2014), which likely measures the efficacy of hillslope transport relative to channel incision (Perron et al., 2009). This may reflect aspect-dependent variations in surface hydrology that directly control erosion or indirectly influence erosion via differences in vegetation (Bass, 1929; Emery, 1947; Melton, 1960; Dohrenwend, 1978; Istanbulluoglu et al., 2008; McGuire et al., 2014). Models that drive landscape evolution with processes whose intensity varies with aspect or solar insolation reproduce both local (McGuire et al., 2014) and continental measurements of topographic asymmetry (Yetemen et al., 2015a).

Early work in the central California Coast Ranges suggested that asymmetry in the cross-sectional shape of valleys was most pronounced in landscapes underlain by rock types expected to yield little resistance to incision (Dohrenwend, 1978). We test the idea that asymmetry is more pronounced in weak rocks by comparing the asymmetry in geographically proximal watersheds that expose rock types of different erodibility.

Within a catchment, satellite-based estimates of vegetation productivity approximate the response of biota to microclimates. We use these satellite-based metrics to define the range of climates where vegetation is less productive on south-facing slopes and therefore where microclimates may be influencing surface processes (Istanbulluoglu et al., 2008; Gutiérrez-Jurado et al., 2013). We identify four sites in this range of climates and compare topographic asymmetry in neighboring basins developed in contrasting rock types. Topographic profiles reveal that valley asymmetry is produced by steeper N-facing hillslopes as well as the concentration of low-order channels along the northern margin of E-W trending valleys. We compare the lengths and orientations of observed flow paths to determine whether or not they might plausibly represent a random sampling of these values. We demonstrate that asymmetric valleys host flow paths that are preferentially oriented toward the south at length scales likely associated with low-order valleys. Measurable topographic asymmetry is present to some degree in all four sites, but a strong preference for south-

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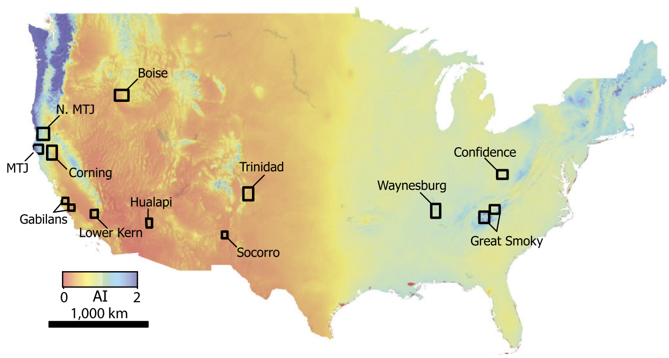

Fig. 1. Map of the ratio of precipitation to potential evapotranspiration, AI, from the CGIAR-CSI Global-Aridity database (Zomer et al., 2008) highlighting the regions used in this study. Lower values of AI correspond to more arid climates. In general, four or more drainage basins were selected from multiple geologic units within each site. Analyses were preformed on the intersection between basin outlines and geologic units; polygons for each site provided in supplemental material. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

directed tributaries is only seen in sites hosting weak rocks. These results support the idea that development of strongly asymmetric topography is sensitive to local rock type (Dohrenwend, 1978).

2. Methods

2.1. Measuring microclimates

Variation in the distribution and density of flora on slopes of opposing aspects is common in arid and sub-humid landscapes (e.g., Istanbulluoglu et al., 2008). We measure asymmetry in vegetation in 12 regions that span the range of climates observed in the contiguous United States (Fig. 1). Here climate is defined by the aridity index, AI (ratio of precipitation to potential evapotranspiration; Zomer et al., 2008). To study the influence of AI on microclimates we use the normalized difference vegetation index, $NDVI$, calculated from the intensity of the near infrared (NIR) and visible red (VIS) wavelengths:

$$NDVI = \frac{NIR - VIS}{NIR + VIS}. \quad (1)$$

In some regions $NDVI$ varies as a function of aspect, and past work recognized that these variations track the response of vegetation to microclimates (McGuire et al., 2014). We calculate the mean $NDVI$ on north- and south-facing slopes within drainage basins, $\overline{NDVI_n}$ and $\overline{NDVI_s}$, and quantify asymmetry in this quantity with a normalized difference:

$$NDVI_{asym} = \frac{\overline{NDVI_n} - \overline{NDVI_s}}{\overline{NDVI_n} + \overline{NDVI_s}}, \quad (2)$$

such that positive values indicate greater $NDVI$ on north-facing slopes (Fig. 2). We use the most recent pixel value in 32-day catalogs of $NDVI$ derived from Landsat 5, 7, and 8 (provided by Google Earth Engine (Gorelick et al., 2017)) to calculate $NDVI_{asym}$ every month from January 1st, 2000, to January 1st, 2016 (Fig. 2 A). By looking at both the sum of $NDVI_{asym}$ over the course of an average year, $\sum NDVI_{asym}$ (Fig. 2 B), and the day of the year and value where its magnitude is greatest, $max\left(NDVI_{asym}\right)$ (Fig. 2 C), we summarize the severity of differences in $NDVI$ with aspect.

2.2. Topographic analysis

We measure topographic asymmetry at four sites where modern AI is in the range observed to favor more productive vegetation on north-facing slopes. Sites were selected where local

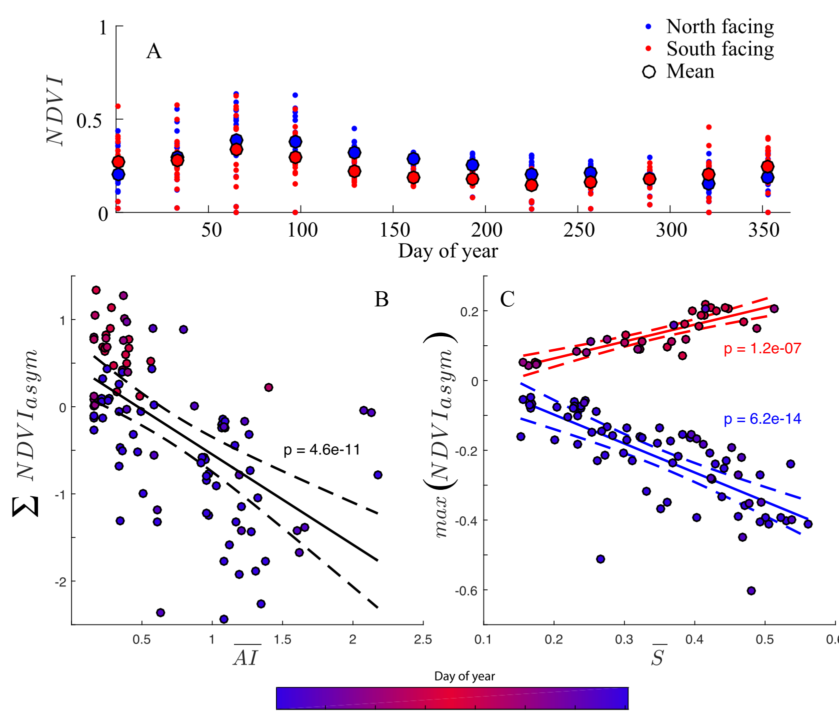

Fig. 2. Methodology and observations of asymmetry in $NDVI$ as a function of aspect. **A** Example data from the Gabilans site highlighting the approach used for calculating $NDVI_{asym}$ in a single GB polygon (see Fig. 3). Small dots represent the average $NDVI$ value on north-facing (blue) and south-facing (red) slopes measured in $NDVI$ catalogs collected at 32 day intervals over a 15 year period. Large circles represent the monthly averages over the 15 year period. **B** Correlation of $NDVI_{asym}$ with AI. Different colored dots represent the day of the year when $NDVI_{asym}$ has the greatest magnitude. **C** Variations in $NDVI_{asym}$ as a function of mean basin slope. Red line is a linear fit to 'dry' sites where north-facing slopes have greater average $NDVI$ than south-facing slopes. Blue line is a fit to 'wet' sites with the opposite sense of $NDVI_{asym}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)