Understanding the Global Hillslope Asymmetry in Semiarid Ecosystem

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November 24, 2022

Abstract

The effect of non-uniform solar radiation over opposing hillslopes leads to aspect-controlled vegetation patterns in semi-arid ecosystems. It creates a differentiation in soil properties and vegetation characteristics. In mid- to high-latitudes where available soil moisture is a limiting factor for vegetation growth, slopes with polewardfacing aspect tend to develop denser vegetation cover that provides more erosion protection than on the equatorward-facing hillslopes. The variation in erosion rates across opposing hillslopes causes the topographic asymmetry of hillslopes over long timescales. The magnitude of this asymmetry is measured by the hillslope asymmetry index (HAI), a metric given as the ratio of the median slope angles of opposite hillslopes. In this study, we present a novel approach to investigate the relationships of HAI with climatological, geomorphic, and ecologic variables at a global scale. Here, we analyzed these relationships using DEM data to compute HAI for 80 different catchments across the world, in which aspect-controlled vegetation has been reported in the literature. We used the CHILD landscape evolution model (LEM), which uses the continuity equation for water, sediment, and biomass, in order to investigate the control of climatological, geomorphic, and ecologic variables on the development of hillslope asymmetry. Preliminary results show that latitude and mean topographic gradient are the two dominant factors affecting hillslope asymmetry due to their vital role in controlling vegetation density through the modulation of incoming solar radiation. These results improve our understanding on how different climatic variables and geographic properties affect the magnitude of hillslope asymmetry and their implications on landform evolution modelling.

AGU 100 FALL MEETING San Francisco, CA | 9–13 December 2019

EP41D-2377

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1. Background and Motivation

- Due to **solar insolation**, **semiarid** landscapes experience differentiation in vegetation type and density on opposing hillslopes.
- Xeric and sparse vegetation on **equatorward** slopes while mesic and denser canopy exists at **poleward** slopes.
- The equatorward slopes are more prone to erosion due to **less vegetation** cover which causes the asymmetry of hillslopes over long timescales. It is measured by the **Hillslope Asymmetry Index** (HAI), (*Poulos et al., 2012*).
- However, there lies several limitations in *Poulos et al., 2012* such as existing tectonic controls, lack of the aspect-controlled vegetation differences, and no field sites in semiarid regions.
- The motivation behind this work is to investigate the relationship of HAI with geographic, ecologic, and climatological variables at a global scale by using observed and modeling studies.

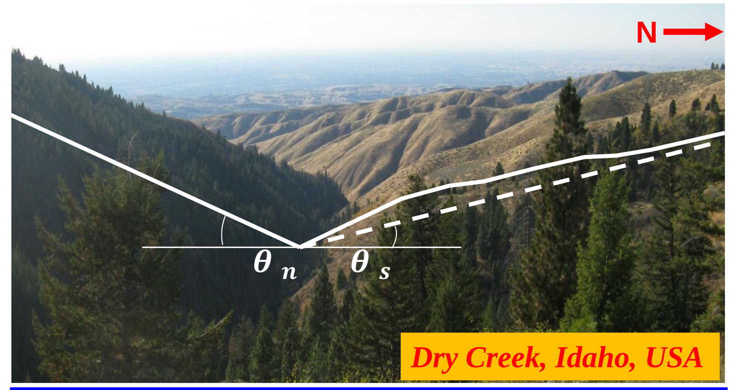


Figure 1. Dry Creek Foothills showing different vegetation pattern on north-facing and south-facing slopes (*Pierce and Poulos, 2013*)

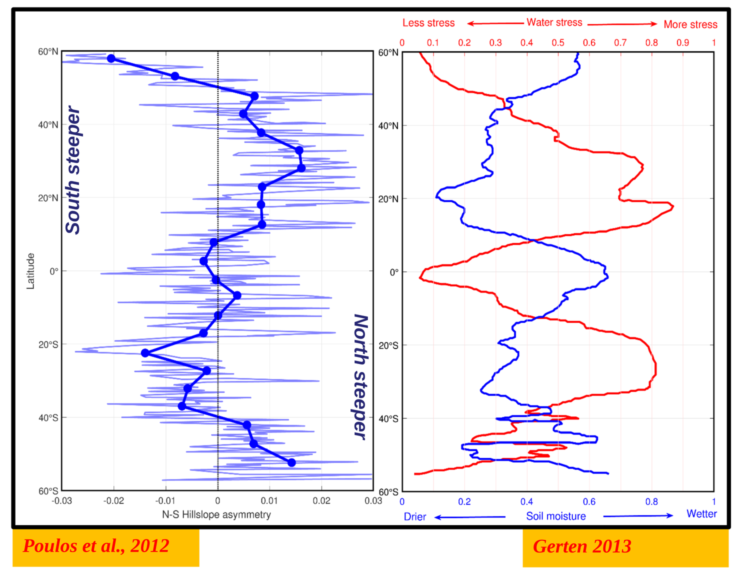


Figure 2. Latitudinal pattern of HAI, soil moisture and water limitation

2. Data and Methods

- The entire study was conducted on two basis: observed catchments based on the previous literature and modeling study using a Landscape Evolution Model.
- For the real world scenarios, a total of 75 different catchments across 28 sites worldwide were selected for this study based on careful review of previous studies reporting the existence of pronounced aspect-induced differences on vegetation at opposing hillslopes (*Kumari et al., 2018; 2019*).
- The HAI is calculated by using 30-m resolution digital elevation models (DEMs) obtained from the United States Geological Survey (USGS) for all the 75 catchments.

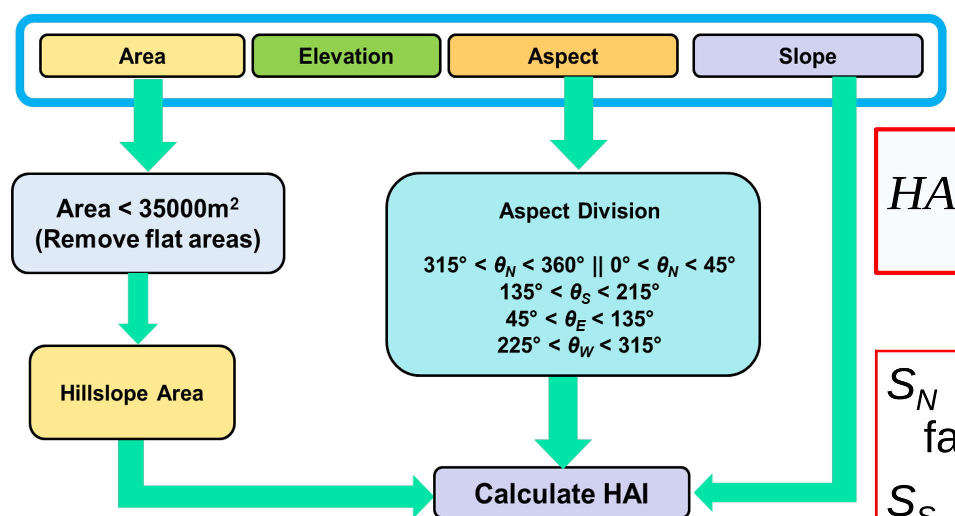


Figure 3. HAI estimation flow chart for observed and modeling study

$$HAI_{N-S} = \log_{10}\frac{med(S_N)}{med(S_S)}$$

S_N is slope (°) in North facing slopes (NFS)

S_S is slope (°) in South facing slopes (SFS)

3. Global Hillslope Asymmetry: Insights from Observed Study

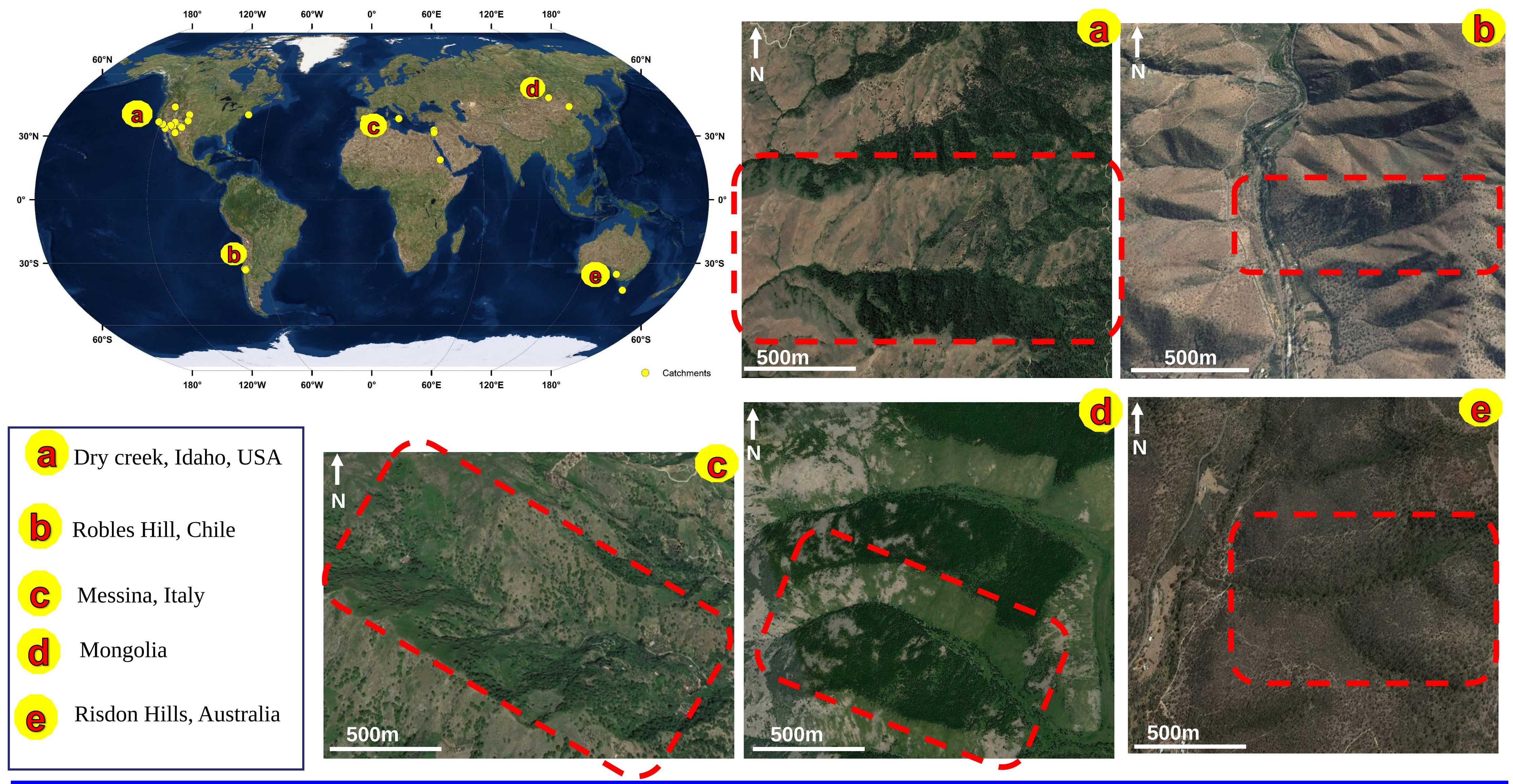


Figure 4. Location map for all the 75 catchments taken in this study in the Northern and the Southern Hemisphere

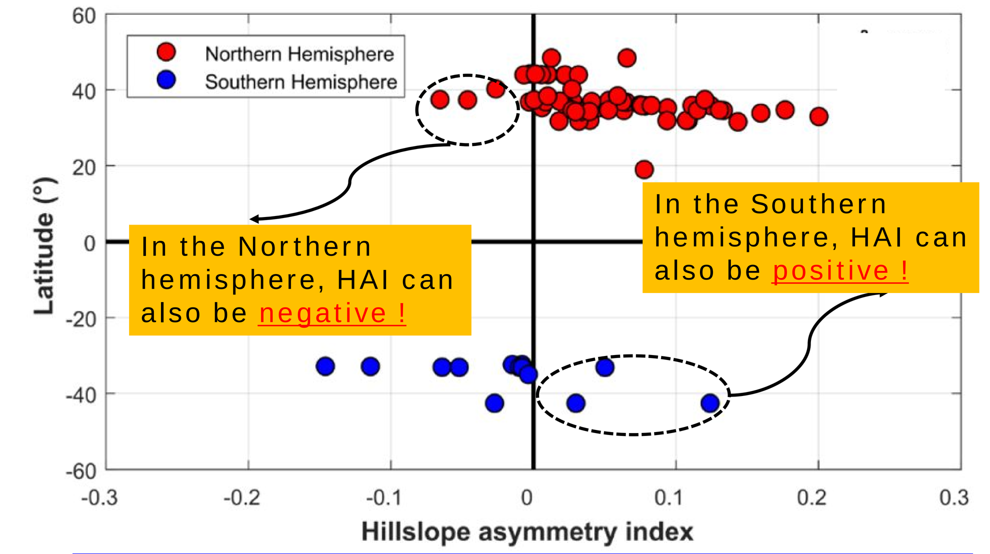


Figure 5. Latitudinal pattern of HAI observed in 75 catchments

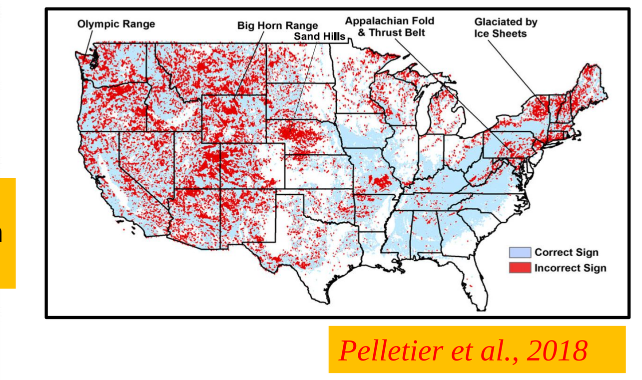


Figure 6. USA Map illustrating correct (+) and incorrect (-) signs of HAI

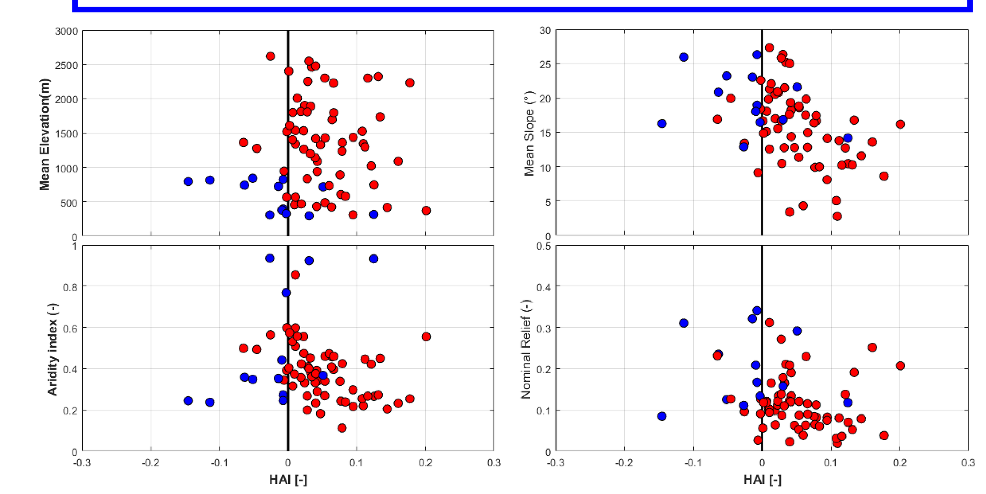


Figure 7. Observed analysis of factors affecting HAI in different catchments

- In the Northern (Southern) Hemisphere, ~70% of the sites have HAI positive (negative). It implies that NFS (SFS) is steeper than SFS (NFS). However, there are few sites which shows reverse pattern. Similar reverse pattern are observed in *Pelletier et al., 2018*.
- Other factors like elevation, slope, aridity, and relief does not show much clear correlation with HAI.

4. Global Hillslope Asymmetry: Insights from Modeling study

- We used the **Channel-Hillslope Integrated Landscape Development model (CHILD)** landscape evolution model (LEM) coupled with a vegetation dynamics component.

Radiation balance: $R_n = (1-\alpha)R_{SW} + (\downarrow R_{LW} - \uparrow R_{LW})$

Water balance: $nZ_r\frac{ds}{dt} = I(s) - ET(s) - D(s)$

Elevation: $\frac{\partial z}{\partial t} = U - \nabla q_{sd} - \nabla q_{sf}(q_w, V)$

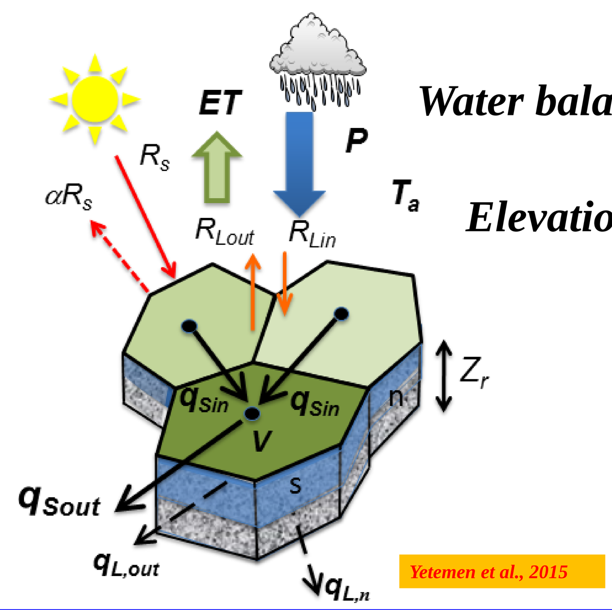


Figure 8. Illustration of the modeled variables in a Voronoi cell used in the CHILD

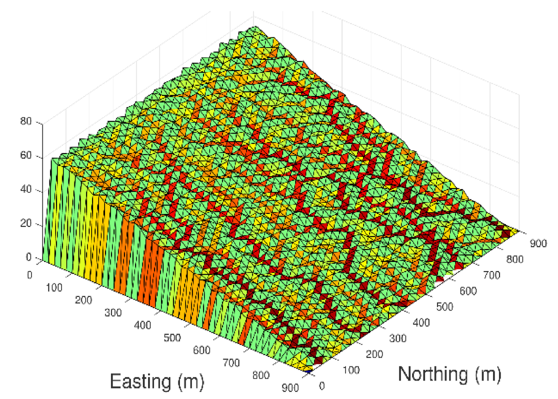
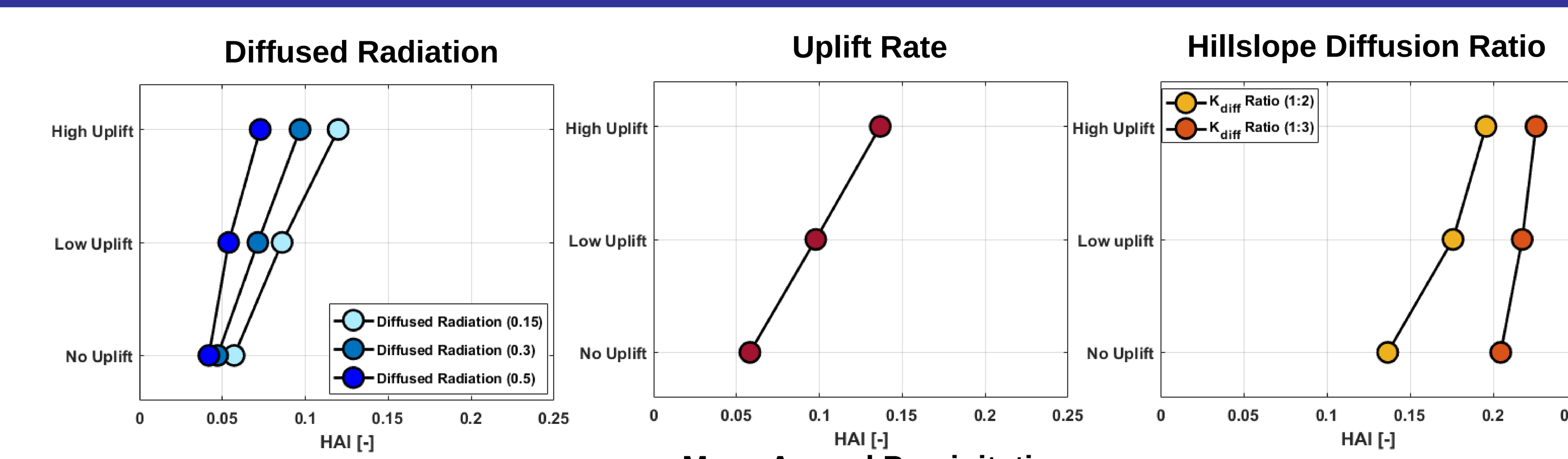
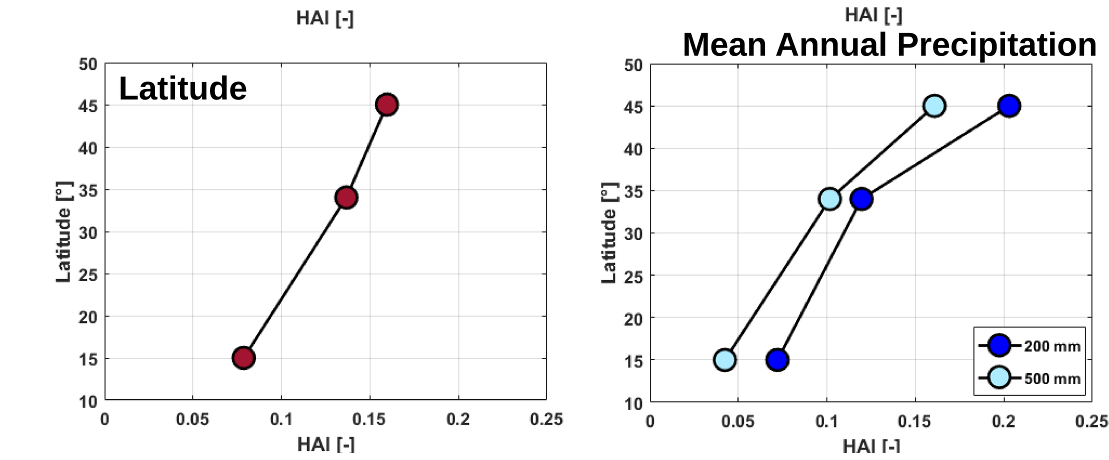


Figure 9. Synthetic domain used in the CHILD simulations

Dimensions	: 900 m by 900 m
Grid size	: 20 m
Initial Max Height	: 60 m
Simulation duration	: 700,000 years
Outlet	: one side open-boundary
Uplift	: No uplift, 0.05 mm/y, and 0.1 mm/y





- *Uplift rate* affects topographic steepness.
- The *Diffused radiation* is ratio of indirect solar radiation to total radiation.
- The *Hillslope diffusivity* (K_{diff}) ratio is the ratio of hillslope diffusion on NFS to SFS.

Figure 10. Modeling results for factors affecting HAI using CHILD LEM

5. Conclusion

- HAI increases towards the higher latitude due to enhanced variation in incoming solar radiation on opposing aspects; hence, there is a positive correlation between HAI and latitude, which is not much enhanced in the field site analysis because they lie mostly at same latitudes.
- The findings from the CHILD modeling study suggest that HAI increases with increase in uplift (function of elevation and slope), increase in K_{diff} ratio; while decreases with increase in precipitation and diffused radiation.

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