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Topographical influence on recent deforestation and degradation in the Sikkim Himalaya in India; Implications for conservation of East Himalayan broadleaf forest

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A R T I C L E I N F O

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A B S T R A C T

Context: Land-cover change in tropical mountains is a significant concern for the loss of biodiversity and ecosystem function. In the eastern Himalaya, knowledge on the factors driving these changes is currently inadequate to development conservation and management plans.

Objectives: We computed land-cover change over a 23-year period for the Sikkim Himalaya in India for the elevation range 800–2800 m using Landsat satellite data and an extensive set of ground measurements of vegetation types and other landuse. We then tested how these land-cover changes may be influenced by topography, mediated through decisions on landuse.

Methods: We carried out supervised classification using 'Random Forests', and ensemble-based classification algorithm that is robust and accurate. We then used linear discriminant analyses to test which of seven common topographical variables can be used to discriminate the different land-cover types.

Results: The primary forest in the 800–2200 m elevation range was warm broadleaf forest, whereas the primary forest in the elevation 2200 m − 2800 m was Fagaceae dominated forest. Forest cover declined by over 30% in warm broadleaf forest, and primary forest declined by 16% overall, with concomitant increases in secondary forest and agriculture. Elevation was the strongest discriminant of landuse, followed by slope and aspect, presumably reflecting peoples' choice on landuse based on topography.

Conclusions: Tropical montane forests continue to decline in the Sikkim Himalaya, particularly at lower elevations. Topographical factors determine landuse decisions by local communities.

1. Introduction

Tropical forests continue to decline worldwide, mainly due to agricultural expansion, timber exploitation, and industrial development. More than 40 million hectares of primary forest have been transformed globally since year 2000, and much of this loss has occurred in the tropics (Hansen et al., 2013; Keenan et al., 2015). An equal or greater area of forest was also degraded by excessive resource extraction, grazing by livestock, and fire (Laurance, Sayer, & Cassman, 2014). In fact, the current global forest cover estimates show that modified vegetation and naturally-regenerated secondary forest together account for a greater fraction (57%) of total forest cover than primary forest (36%) (Laurance et al., 2014). While continental regions have seen significant forest regrowth, which calls for a deeper perspective on forest transitions (Mather, 1992, 2007), tropical deforestation and degradation continue to occur, and contribute to land-cover change (Turner, Lambin, & Reenberg, 2007) and carbon dioxide emissions to the atmosphere. The ensuing climatic changes exacerbate other problems associated with land-cover change (DeFries et al., 2002) and together constitute the largest threat to global biodiversity and ecosystem functioning, particularly in species-rich regions such as global biodiversity hotspots.

Within tropical latitudes, land-cover change has been greater in lowland areas, where the topography is more favorable for agriculture, plantations, and settlement (Achard et al., 2007; Hansen et al., 2013). However, tropical mountain regions are also being transformed in similar ways (Ataroff & Rada, 2000; Cayuela, Benayas, & Echeverría, 2006). Due to hard physical boundaries and complex and variable

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climatic conditions, tropical montane species may be more vulnerable than lowland species to environmental changes (Sheldon, Yang, & Tewksbury, 2011). In mountainous terrain, environmental variables change rapidly and result in complex effects on the microclimate. Species are therefore segregated and maintained along steep gradients with narrow ranges implying greater species loss due to habitat destruction and degradation (Bawa & Seidler, 2015). The first step towards understanding the impact of these transformations on biodiversity is to obtain accurate assessments of land-cover changes in tropical mountain regions.

Here we study the influence of topography on recent land-cover change that occurred during 1990–2013 in the Teesta River basin of the Sikkim Himalaya in India. This landscape is part of the Eastern Himalaya Biodiversity Hotspot (Mittermeier et al., 2005) and harbors species-rich tropical forest at middle elevations. There are relatively few reports on land-cover change in the Indian Himalaya, and even those focus on the Western and Central regions (Rao & Pant, 2001), while the Eastern Himalaya remains largely unexplored (Lele & Joshi, 2008). It appears that the middle hills of the Himalaya have been subjected to deforestation for decades (Ramakrishnan & Kushwaha, 2001), which is a matter of concern given that diversity often peaks at intermediate elevations (Sandel & Svenning, 2013), The lowest elevations (< 800 m above mean sea level (a.m.s.l.)) have long since been cleared for settlements and forestry plantations, while conifer-dominated forests continue to be present at high altitudes. Our goal in analyzing land-cover change here is to evaluate how topographical factors may have influenced practices or processes that led to the destruction and degradation of primary broadleaf forest. We hypothesize that topography influences the spatial distribution of changes in land-cover through its influence on decisions concerning land use. Our analysis constitutes the first step towards estimating any environmental consequences that may have occurred due to changes in land-cover.

2. Methods

2.1. Study area and land-cover

Our study area is the mid-elevation region of the Teesta River basin of the Sikkim Himalaya. Sikkim is located in the Eastern Himalaya biodiversity hotspot in India and extends within coordinates 27° 04′ 46″ to 28° 07′ 48″ N and 88° 00′ 58″ E and 88° 55′ 25″ E, covering an area of 7096 km^2 (Fig. 1). The region has high topographical relief, with elevation ranging from 300 m to well over 5000 m, and the landscape includes the world's third highest mountain Khangchendzonga peak at 8586 m above m.s.l. (Tambe, Arrawatia, & Sharma, 2011). The complex topography creates diverse bioclimatic zones ranging from near tropical, subtropical, and lower temperate to upper temperate, subalpine evergreen, alpine evergreen, alpine shrubs and meadows. The subtropical region in the landscape extends over 1000–2000m elevation and harbors warm broadleaf forest (Grierson & Long, 1991), also known as subtropical forest or East Himalayan subtropical wet hill forest (Champion & Seth, 2005). It is the most diverse and dynamic vegetation system in the landscape (Acharya, Chettri, & Vijayan, 2011a). The broadleaf forest found at higher altitudes (2000–2800 m) is dominated by Fagaceae species (Grierson & Long, 1991). These two formations are generally difficult to distinguish as they are structurally very similar and share many species, with the transition from one to another being gradual and continuous.

We studied a large mid-elevation range (800 m–2800 m a.m.s.l) in Sikkim, which has multiple types of land-cover, and identified the following broad types based on extensive field surveys:

i) **Primary forest**: We designated all the primary mixed species forests in a single class as primary forests (broadleaf forest).
ii) **Secondary forest**: We designated *secondary forests* as those forest areas that are regenerating patches of vegetation after clear felling for agriculture, or other types of modification of old-growth forests alter tree density and composition.
iii) **Alder forest**: This is a unique vegetation formation, consisting of single species plantations of *Alnus nepalensis*, D. Don (Family - Betulaceae), a pioneer species typically found in the 1500–2000 m elevation range.
iv) **Agriculture and fallow**: Agriculture is widespread at low and middle elevations and includes maize and paddy based farming. Substantial agricultural land is also maintained as fallows.
v) **Settlements**: Small townships and rural settlements, which occur scattered across the landscape.
vi) **Other**: Other identifiable aspects of land-cover include water bodies and bare ground.

2.2. Remotely-sensed data

We used Landsat TM/ETM + images and supervised land-cover classification to map forest cover and forest-cover change during the period 1990 to 2013 (Table 1). We selected images after thorough screening to ensure minimal influence of cloud cover and atmospheric haze. Despite the availability of numerous images, very few met our requirements for analyses, and we finally chose one each of pre- and post-monsoon images for years 1990, 2005 and 2013. We clipped the images to the 800–2800 m elevation range using the ASTER DEM Digital Elevation Model (DEM) and obtained a total study area of 2206 km^2. Since the study area has high topographic relief, some topographical aspects are not fully visible to the satellite sensors, which creates “shadow” regions in the images. ‘Hard shadow’ areas with completely dark pixels cannot provide any spectral information so we excluded them from further analyses (Tan et al., 2013).

2.3. Ground measurements and training data

We collected ground data through extensive field surveys and vegetation sampling during 2011–2013. We recovered ground truth information at 20 to 30 locations for each land-cover type using a GPS unit. Further details are available in the Supplementary Material.

2.4. Land-cover classification

We conducted supervised classification of land-cover using ‘Random Forests’ (RF), an ensemble based decision-tree classification algorithm. Here several regression trees are generated and a consensus tree is derived by averaging the predictions of the individual trees, which improves classification accuracy (Cutler et al., 2007). For mapping mountainous terrain, RF has been reported to outperform other approaches, and apart from increased classification accuracy, RF can measure variable importance, work with larger data sets, and is robust to outliers and over-fitting of data (Rodriguez-Galiano, Ghimire, Rogan, Chica-Olmo, & Rigol-Sanchez, 2012). We used 18 predictor variables including five Landsat Bands, four vegetation indices (Specific Leaf Area Vegetation Index, Normalized Difference Vegetation Index, Brightness Index, and Normalized Difference Moisture Index), and seven topographic variables (including elevation, slope, aspect, ruggedness, wetness, profile curvature, and plan curvature) to build the RF model (see Supplementary Material).

To detect and compute land-cover change over time (1990–2013), we obtained classified images from the predictions of the RF model and used the land change modeler module in IDRISI Selva (Eastman, 2012). To measure the importance of individual predictor variables, we excluded the given predictor from the analysis and then computed the mean decrease in classification accuracy compared to the when all predictors were used (Cutler et al., 2007).