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Forest Composition and Structure Under Various Disturbance Regimes in the Alaknanda River Basin, Western Himalaya

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This study explored the resilience of mountain forests in a protected area in Alaknanda River basin, Western Himalaya, to various disturbance scenarios. The resource dependency of village communities in the Kedarnath Wildlife Sanctuary Landscape was studied through a questionnaire survey in 10 villages situated along an elevational gradient. Vegetation sampling was done in government-owned sanctuary forests and community-owned forests, both visited by villagers. Forest community composition, regeneration status, and tree population structure were studied to understand the impact of disturbance on forests and their resistance to anthropogenic alterations. Results indicated a reduction in both fuelwood and fodder consumption with decreasing elevation, with villages at higher elevations and located inside the sanctuary depending more on forest resources. Forests showed evidence of disturbance in the form of lower basal cover, mean canopy cover, regeneration, and disturbance-influenced distribution of shrubs. However, despite the signs of secondary succession, Quercus leucotrichophora *forest has retained the original tree species composition. Vegetation recovery on 3 landslide sites at varying successional stages was also studied. The old successional site had higher species richness than early successional sites. The only tree species with adult individuals recorded in early successional sites was* Alnus nepalensis*, an early successional nitrogen-fixing species. The community composition of the old successional site, at Bandwara, included young individuals of* Q. leucotrichophora*, the climax species of forests in that elevational range. The current forest structure of both disturbed forest and vegetation recovery on the old succession site indicate the resilient dynamism of native Himalayan forests. Considering the role of mountain forests in achieving sustainable development, it is imperative to study the dynamics of changes in forest community and structure in response to increasing human pressure and climate change impacts.*

Keywords: *Anthropogenic disturbance; elevation; Kedarnath Wildlife Sanctuary; resource dependency; regeneration; resilience; vegetation recovery; Sustainable Development Goals; Agenda 2030.*

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Introduction

Mountain forests around the world constitute an important natural capital stock, providing a plethora of ecosystem services to local and downstream communities and a source of livelihood for a large human population (MEA 2005; TEEB 2010). They play a multifaceted role in achieving the Sustainable Development Goals, particularly in developing economies like India, where they form the foundation of the local economy for a large part of the population. For mountain communities, forest resources are crucial to poverty alleviation, economic growth, and food security. In a region like the Himalaya, where very few livelihood options are available, mountain forests form an essential life-support system for local people (Khan et al 2014; Bhandari et al 2016). The region is prone to hydro-geomorphic disasters including landslides and floods, causing forest degradation and fragmentation, which are exacerbated by anthropogenic disturbances such as resource extraction (Ali et al 2005; Pandit et al 2007; Petley 2010; Ruiz-Villanueva et al 2017).

Both natural and anthropogenic disturbances are integral drivers of forest dynamics that alter species composition and diversity, which in turn determine ecosystem productivity and the flow of ecosystem services (Tilman et al 1997; Bagchi and Ritchie 2010; Bagchi et al 2012). Fragmented and degraded forests with altered forest structure, composition, and ecosystem processes are more vulnerable to climate change (Noss 2001), thus putting pressure on resource managers to focus on maintaining ecological resilience against various stressors. In the current scenario of uncertainty, altered disturbance regimes, and their implications for forest health and the flow of ecosystem services to humans, the role of Himalayan forests in achieving Sustainable Development Goals in the region might come under threat. It is important to understand the multiple successional sequences following disturbances in order to better understand forests' resilience to these events.

This study was conducted in the Alaknanda River basin in the western Himalaya to explore (1) the dependency of villagers on forest resources at different elevations, (2) the species composition and community characteristics of forests under different disturbance regimes, and (3) vegetation recovery and successional sequences at landslide sites of different ages (from 10 to more than 50 years). The Alaknanda Basin is characterized by rich biological and cultural diversity. It is representative of the Himalayan mountain system in terms of natural geological instability, intricately linked ecological and social systems, lack of economic opportunities leading to heavy dependence on natural resources, and anthropogenic disturbances in forests. Any unwanted structural and compositional changes to the region's forests will impact both biodiversity conservation and local livelihood security and thus the attainment of the Sustainable Development Goals in the region.

Study area

The Alaknanda River, a major tributary of the Ganga River, originates from the Satopanth and Bhagirath Kharak glaciers in the Rudraprayag district of the state of Uttarakhand, India. The river basin lies at 29°58′ to 31°04′N latitude and 78°34′ to 80°17′E longitude and drains an area of approximately 11,000 km^2. Like the rest of the Himalaya, because of a mix of hard and soft lithology and tectonic setup, the Alaknanda River basin is prone to slope failure and landslides (Joshi and Goel 1988; Negi and Joshi 2014). A single June 2013 event caused new landslides at 3472 locations covering 30.4 km^2 and a loss of around 46 ha of forest and 125 ha of grassland across Uttarakhand state, a large proportion of which occurred in the Alaknanda basin (Martha et al 2015).

An intensive study was carried out in Kalimath, Madhyamaheshwar, and Mandal Valleys in the Kedarnath Wildlife Sanctuary Landscape in the Alaknanda River basin (Figure 1). It included sampling within the sanctuary and proposed ecosensitive zone as per the guidelines of the Ministry of Environment, Forests, and Climate change of the Government of India. The sanctuary is part of the Himalayan biogeographic zone and the West Himalaya biotic province (Rodgers and Panwar 1988). A total of 173 villages are located in the protected area landscape, 12 of those inside the sanctuary. The inhabitants of these villages depend heavily on forests in the sanctuary for day-to-day sustenance; this has led to habitat degradation, worsened by frequent flash floods and landslides.

Resource use was studied in 10 villages in Kalimath and Madhyamaheshwar Valleys (Figure 1; Table 1), which differ in their proximity to Kedarnath Wildlife Sanctuary, forest management regimes, and elevation (Table 2). Vegetation disturbance and consequent changes in forest structure and composition were studied in forests visited by local communities for resource extraction. Vegetation recovery after extreme disturbance was studied in 3 landslide sites within the sanctuary landscape: 2 early successional sites, Jaggi-Bagwan (hereafter Jaggi) and Jugansu (about 15 years old), and 1 older successional site, Bandwara in Mandal Valley (>50 years old). The first landslide incident on Jaggi slope occurred some 70 years ago on a smaller scale and stabilized with time. However, with every extreme rainfall event the landslide area increased, particularly longitudinally. Thus, only more recent, stabilized landslide areas were accessible for sampling, as older parts moved towards the river and were mostly buried in new debris.

Methods

Field sampling

The data on local communities' dependency on forest resources and the socioecological variables affecting a household's dependency were collected in 3 stages. The first stage involved collection of secondary information from government agencies on demographic and socioeconomic indicators, and a reconnaissance survey to obtain information about village elevation, dependency on forest resources, and proximity to sanctuary forest, as well as major forest types. A total of 38 villages grouped into 23 *gram sabha* were identified in the study area. (A *gram sabha* is the village assembly of all the adults that forms the foundation for the Indian electoral system in rural areas.)

In the second stage, the collected data were subjected to principal component analysis and hierarchical cluster analysis (Badola et al 2012), using SPSS 16.0, to identify homogeneous groups of villages. A total of 33 variables were used to run principal component analysis, out of which 23 variables that caused the highest variance in the dataset were chosen for hierarchical cluster analysis. Representative villages ($n = 10$) were selected from each of 4 clusters that resulted from the cluster analysis and divided into 3 groups, based on the elevation of the forest that villagers accessed. Villages were categorized as high elevation if villagers frequently accessed forest at >2000 m above sea level (masl), medium elevation for forest at 1500–2000 masl, and low elevation for forest at 1000–1500 masl.

In the third stage, 260 households (20% of the total households) were interviewed from selected villages. A stratified random sampling was done wherein households were selected based on socioeconomic and ecological variables such as type of house, geographical location

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FIGURE 1 Location of study villages and landslide (succession) sites in Kedarnath Wildlife Sanctuary Landscape. (Map by Upma Manral)

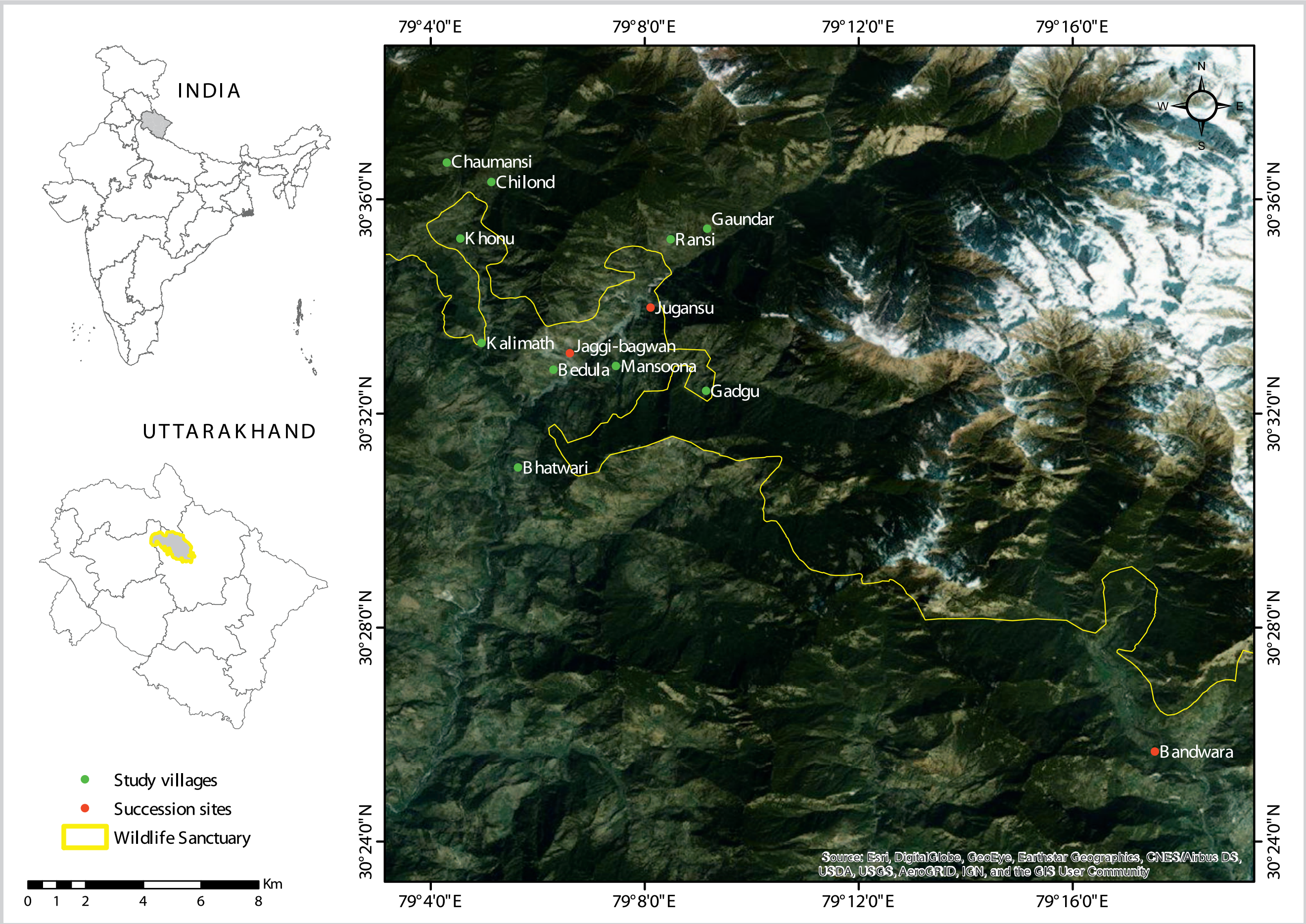

TABLE 1 Average annual resource dependency and household income across elevation gradient in the study area.

Villages (village elevation, m)	Average annual household consumption (kg)		Average annual household income (US$)	Key occupations
	Fuelwood	Fodder		
High elevation **Chaumansi (2060–2130)** **Chilond (1800–1910)** **Ransi (1600–2269)**	6166	10,420	3413 ± 3292.7	Agriculture and animal husbandry Business (shops, lodge, restaurants along treks)
Medium elevation **Gadgu (1636–1850)** **Gaundar (1665–1907)** **Khonu (1480–1720)**	5235	9946	2506 ± 2271	Agriculture and animal husbandry Day labor
Low elevation **Kalimath (1300–1400)** **Mansoona (1250–1400)** **Bedula (1191–1551)** **Bhatwari (1050–1280)**	3629	7746	4189 ± 4055	Day labor Business Armed forces

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TABLE 2 Sampling intensity in the forests surrounding the study villages across elevation and disturbance gradient.

Villages (forest elevation)	Village (forest elevation, m)	Relation to Kedarnath Wildlife Sanctuary	Plot distribution across disturbance classes (%)		
			High	Moderate	Low
High	Chaumansi (2158–2334)	Inside	33.33	50.00	16.67
	Chilond (1658–2360)		50.00	25.00	25.00
	Ransi[a)] (1493–2695)		72.10	18.60	9.30
Medium	Gadgu (1495–2090)		71.43	21.43	7.14
	Gaundar (1604–1861)		37.50	25.00	37.50
	Khonu[a)] (1787–1910)	At the boundary	0.00	80.00	20.00
Low	Kalimath[a)] (1207–1736)		30.00	60.00	10.00
	Mansoona[b)] (1321–1564)	>2 km away	27.30	45.40	27.30
	Bedula[b)] (1139–1483)		16.67	66.66	16.67
	Bhatwari[b)] (1192–1267)		0.00	66.67	33.33

[a)] Sampling was done in both sanctuary and community-owned forests.
[b)] Sampling was done only in community-owned forests; in the rest sampling was done in sanctuary forests.

within the village, and location with respect to roads, forest, and sanctuary. The survey was conducted from March to October 2014. The interviewer used a semistructured questionnaire with both open- and closed-ended questions to derive both qualitative and quantitative information (Badola et al 2012). Questions were asked about the household's use of forest products, preferred resource species, distance traveled for resource collection, land and livestock holdings, occupations, and income (Sapkota and Odén 2008; Hussain and Badola 2010). The data were transcribed, and each unit was assigned a tentative code (Creswell 2013).

It is imperative to understand the resilience of forests both to anthropogenic alterations and to complete denudation, in order to inform adaptive strategies under the current scenario of large-scale forest degradation in the Himalayan mountain system. To this end, we sampled vegetation in the forests harvested by villagers as well as in landslide sites of varying ages and degrees of vegetation recovery. Stratified random transects were laid along major resource-use trails in forests visited by villagers, during 2014 and 2015. At the landslide sites, transects were laid on the stabilized debris where succession had started, during 2012–2014. Circular plots—of 10-m radius for trees and, within those, of 5-m radius for shrubs, seedlings, and saplings—were laid every 200 m along the transects (Mueller-Dombois and Ellenberg 1974). Trees were distinguished from shrubs, seedlings, and saplings based on girth at breast height (defined as 1.37 m): individuals with a girth of ≥30 cm were classified as trees. For trees we recorded the species, number of individuals, girth at breast height, and canopy cover; for all others, we recorded the number of individuals. Disturbance was noted in terms of lopping and grazing intensity, canopy cover, number of stumps, and amount of cattle dung. A total of 124 plots were examined in forests under disturbance and 20 at landslide sites.

Data analysis

Pearson's correlation coefficients were calculated to ascertain the relationship between plant resource extraction and the various environmental and socioeconomic parameters given in Table 3.

The sampled vegetation plots were scored for the following:

a. Average lopping intensity of trees ($\leq 30\% = 1$, $30–60\% = 2$, $>60\% = 3$);
b. Lopping proportion (number of lopped trees in the plot/total number of trees in the plot);
c. Grazing intensity (no grazing = 0, old grazing signs or mildly grazed = 1, heavily grazed with fresh grazing signs and animal dung = 2);
d. Regeneration proportion (number of regenerating species in the plot/number of adult tree species in the plot; regenerating individuals were both seedlings and saplings of a species).

A disturbance score was assigned to each plot using the calculation $a + b + c - d$. Disturbance was ranked as high for scores of ≥ 3, moderate for 1–3, and low for <1.

Density, total basal area, and importance value index (sum of relative frequency, relative density, and relative basal area with a value between 0 and 300) for tree species and density for shrubs were calculated. The population structure of tree species was characterized based on the relation of density to girth (Dhar et al 1997). Individuals were grouped into seedlings (<10 cm), saplings (10–30

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TABLE 3 Pearson's correlation coefficient between resource use parameters and environmental variables. Values are listed for which correlation is significant at or below the 0.05 level.

Variables	Maximum elevation	Per capita income	Sheep and goats	Fuelwood	Fodder extraction	Fodder from forest	Liquefied petroleum gas
Number of cattle per household	0.809						
Number of sheep and goats per household	0.841						
Annual fuelwood consumption per household	0.787						
Annual fodder consumption per household		−0.657					
Fodder extracted from forest per household	0.681	−0.637	0.654		0.822		
Fodder from agroforestry system per household	−0.732		−0.787			−0.897	
Fodder purchased per household	−0.789						
Liquefied petroleum gas consumption per month per household	−0.779	0.633		−0.804			
Presence in the sanctuary	−0.796		0.668			0.654	−0.779

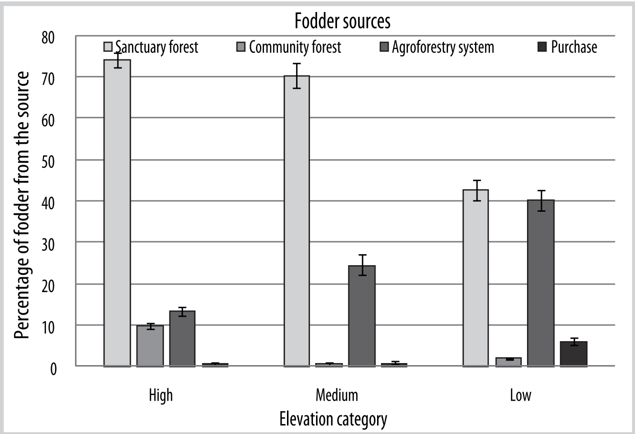
cm), and 4 classes of trees (30–60 cm, 60–90 cm, 90–120 cm, and >120 cm). To study regeneration status of trees within a plot, the number of regenerating species, density of seedlings and saplings, and pressure on these were calculated. A Dunn post hoc test was performed using SPSS 19.0 to see if distance of plot from human settlements, canopy cover, and regeneration status varied along the disturbance gradient.

Results

Forest resource use

Average fuelwood and fodder consumption per year per household were higher in high-elevation villages, followed by mid- and low-elevation villages. Fodder was extracted from the forest or from agroforestry systems or was purchased from other families or villages (Figure 2). In low-elevation villages, almost 50% of the fodder came from agroforestry systems, which included agricultural byproducts and tree species, including *Celtis australis*, *Litsea* sp. and *Ficus* spp., which are planted along a farm's boundary or on noncultivated land. Members of these households visited forests in the Kedarnath Wildlife Sanctuary to collect dry grass for fodder only from September to November (10 to 15 days a month), because of their larger distance from the sanctuary. Fuelwood consumption per household per year positively correlated with elevation, and fodder extraction from forest positively correlated with elevation and presence of the village in the sanctuary. Fodder extracted from agroforestry systems or purchased from other families negatively correlated with elevation and presence in the sanctuary (Table 3; Figure 2). Low-elevation villages had the highest annual income per household, followed by high- and mid-elevation villages. A higher percentage of households in low-elevation villages were employed in the army, had permanent employment (in the government or the private sector), or ran a business (eg a shop or a food outlet in a market area), followed by high-elevation villages. More households in mid-elevation villages depended on wages from day labor, which is usually uncertain and poorly paying (Figure 3).

FIGURE 2 Percentage of fodder extracted from various sources across elevation categories. Error bars represent the standard error.



Forests under different disturbance and management regimes

Of the study plots, 52% fell in the high-disturbance, 32% in the moderate-disturbance, and 16% in the low-

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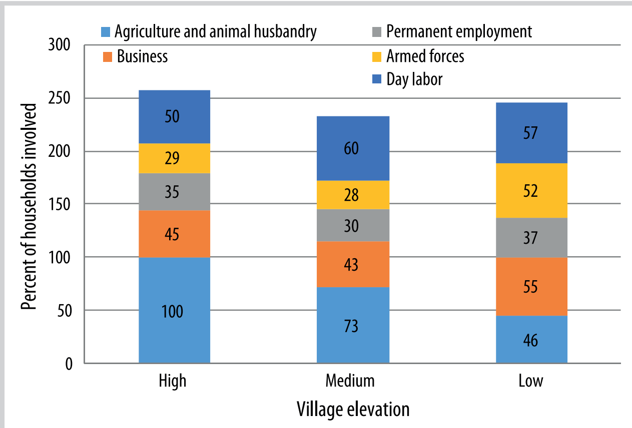
FIGURE 3 Major occupational categories in the study area.



disturbance category. Average plot distance from a settlement and mean canopy cover increased significantly from high- to low-disturbance areas (Tables 4, 5). Both high- and moderate-disturbance plots also had tree stumps; the proportion of lopped trees also varied significantly across disturbance classes (Table 4).

There were 2 forest management regimes in the study area: government-owned sanctuary forest and community-owned forest (Table 6). Sanctuary forest made up the highest proportion in all disturbance classes; 58% of sampled forest was part of the sanctuary. Villages located inside the sanctuary had a higher proportion of high-disturbance plots, whereas villages with community forests had few high-disturbance plots, indicating less disturbance and better protection (Table 2). Regeneration proportion improved in both management regimes as disturbance decreased. There was not much difference in lopping intensity or proportion under the 2 management regimes, but both decreased as disturbance in general decreased. Somewhat paradoxically, grazing in sanctuary plots decreased from high- to moderate-disturbance plots but then increased in low-disturbance plots. The low-disturbance plots with grazing were in higher-elevation forest closer to temperate grassy slopes, where residents of high-elevation villages take their livestock for 6 months of summer and monsoon and pastoralists stay with sheep and goats on their way to alpine pastures.

Adult individuals of 38 species of trees (of which 3 species were preferred as fodder, 5 as fuelwood, and 12 were used for both fodder and fuelwood) and 36 species of shrubs were recorded. The tree species richness (total number of species) along with the number of preferred fodder and fuelwood species were highest in high-disturbance plots, followed by moderate- and low-disturbance plots (Table 4; *Supplemental material*, Table S1: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00109.S1). The stand density (number per ha) was highest for moderate-disturbance plots, followed by low- and high-disturbance plots. The total basal area (m^2 per ha) for trees was highest for low-disturbance plots, followed by moderate- and high-disturbance plots (Table 4). *Rhododendron arboreum* was the dominant species (as measured by importance value) in both high- and moderate-disturbance sites, whereas in low-disturbance sites, *Pinus roxburghii* was the dominant species (*Supplemental material*, Table S1: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00109.S1). The second dominant species in all the disturbance classes was *Quercus*

TABLE 4 Characteristics of forests across various disturbance classes.

Characteristic	Disturbance class		
	High	Moderate	Low
Mean distance of plot from settlement (m)[a]	521.87 ± 364.15	652.5 ± 356.07	832.5 ± 524.97
Mean canopy cover (%)[a]	27.03 ± 17.92	37.32 ± 18.59	42.75 ± 23.87
Stumps (number per plot)[a]	0.5 ± 1.57	0.16 ± 0.73	0
Tree species richness	29	25	21
Stand density (number per ha)	418.00	451.70	431.03
Basal area (m^2 per ha)	21.45	23.86	24.80
Shrub species richness	32	24	20
Shrub density (number per ha)	1122.65	1196.43	1756.46
Regenerating tree species richness	35	32	33
Seedling and sapling density (number per ha)	890.96	1450.99	951.27
Regenerating species per plot[a]	3.01 ± 2.83	4.375 ± 3.01	4.2 ± 2.86

[a] Values represent mean ± standard deviation.

TABLE 5 Differences in anthropogenic pressure and regeneration across disturbance classes (Dunn's post hoc test). Values are listed for which correlation is significant at or below the 0.05 level.[a)]

Variable	Disturbance classes compared		
	High and moderate	Moderate and low	High and low
Variables indicating anthropogenic pressure in the forests			
Distance of plot from settlement	0.208	0.924	**0.035**
Lopping and grazing pressure on seedlings and saplings	**0.001**	1.000	**0.001**
Canopy cover	**0.017**	1.000	**0.012**
Proportion of lopped trees	**0.001**	1.000	**0.001**
Variables indicating regeneration status of tree species in the forests			
Proportion of regenerating species	**0.014**	0.343	**0.000**
Number of regenerating species	**0.045**	1.000	0.218
Abundance of regenerating individuals	**0.013**	0.876	0.795

[a)] For values listed in cells in bold font, correlation is significant at or below 0.05 level.

leucotrichophora (banj oak), which is the most highly preferred species for both fodder and fuelwood. Its basal cover increased as disturbance decreased. Shrub species richness was highest for high-disturbance plots, followed by moderate- and low-disturbance plots. Total shrub density was highest for low-disturbance plots, where hill bamboo (ie *Arundinaria falcata* and *Thamnocalamus spathiflorus*) contributed more than 50% (*Supplemental material*, Table S2: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00109.S1).

Forty-one tree species were regenerating in the study area (*Supplemental material*, Table S3: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00109.S1), with the highest species richness recorded in high-disturbance plots (Table 4). The highest density of seedlings and saplings and average number of species per plot were recorded in moderate-disturbance plots. Banj oak had the highest density in both high- and low-disturbance sites. *Engelhardtia spicata*, a subordinate species in chir *Pinus roxburghii*, had the highest density in moderate-disturbance sites. The number of regenerating species and their abundance varied significantly between high- and moderate-disturbance sites, and the proportion of regenerating species and anthropogenic pressure on regenerating species varied significantly between high- and moderate-disturbance plots and between high- and low-disturbance plots (Table 5). Density of trees in higher girth classes was low in all 3 disturbance classes (Figure 4). High-disturbance plots had higher tree density in a lower girth class (30–60 cm), whereas both moderate- and low-disturbance plots had higher density in larger girth classes than the high-disturbance plots. Almost all the dominant species showed a similar trend, except for *Alnus nepalensis,* which was found predominantly in high-disturbance sites,

TABLE 6 Values of anthropogenic pressure and disturbance ranking variables in 2 management regimes across disturbance gradient (values in parentheses are percentages of plots under each regime).

	High disturbance		Moderate disturbance		Low disturbance	
	Sanctuary forest (63%)	Community-owned forest (37%)	Sanctuary forest (53%)	Community-owned forest (47%)	Sanctuary forest (55%)	Community-owned forest (45%)
Regeneration proportion	0.73	0.71	0.99	1.23	1.50	1.50
Lopping intensity	2.65	2.50	1.81	1.74	0.45	0.44
Lopped proportion	0.64	0.71	0.43	0.41	0.20	0.05
Grazing score	1.73	1.46	0.71	1.00	1.18	0.44
Canopy cover (%)[a)]	31 ± 19	19 ± 14	38 ± 21	36 ± 16	45 ± 24	40 ± 25
Plot distance from settlement (m)[a)]	607 ± 388	379 ± 273	783 ± 369	508 ± 286	1127 ± 417	472 ± 414

[a)] Values represent mean ± standard deviation.

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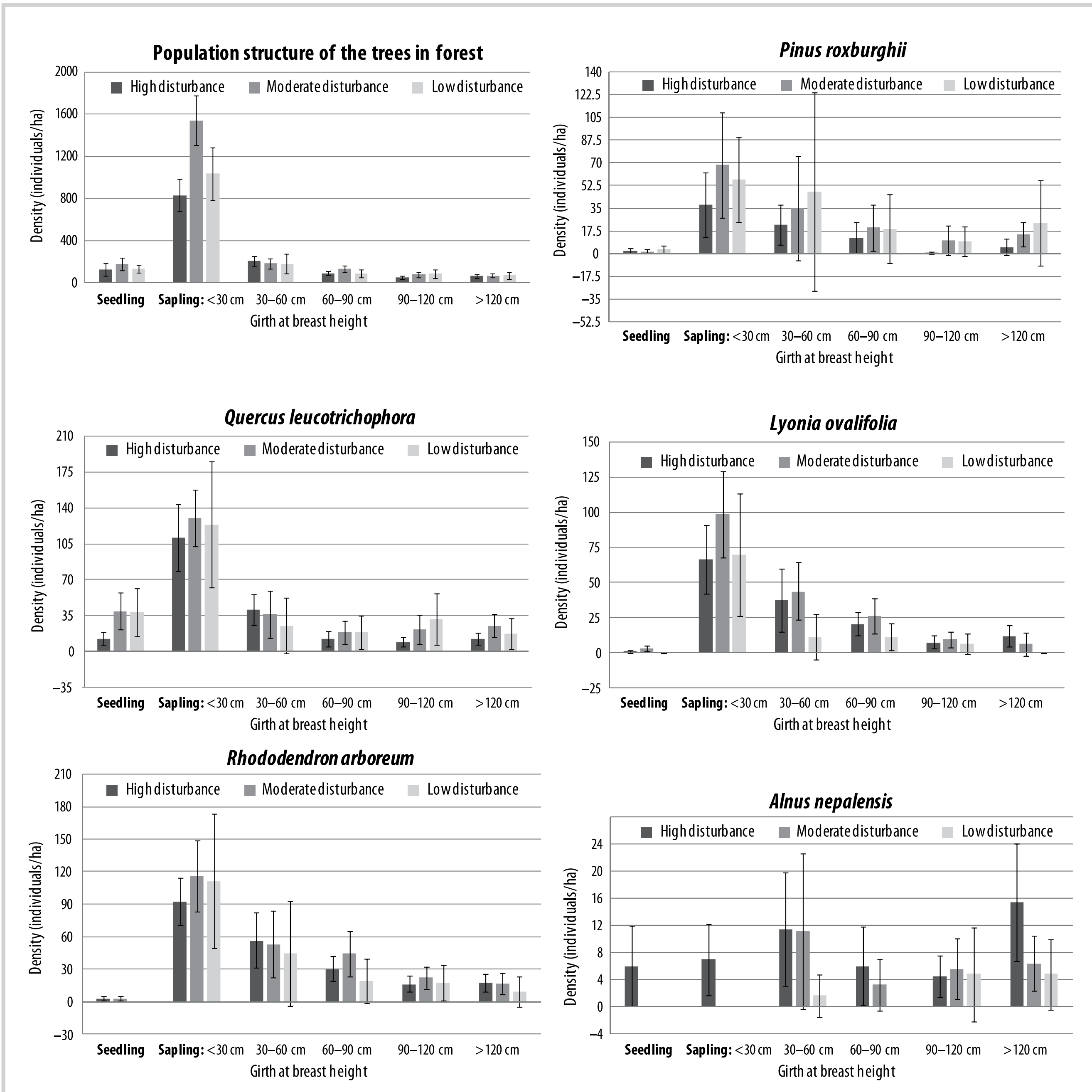
FIGURE 4 Population structure of the forest as a whole and of dominant tree species across disturbance regimes. Error bars represent the standard error.



where it had a bimodal distribution, with adult individuals in smallest and largest girth classes being more abundant.

Vegetation recovery in landslide sites

A total of 74 species of vascular plants were recorded at the landslide sites. Species richness increased with the age of the site; Bandwara had highest richness (60), followed by Jugansu (34) and Jaggi (31). Fifteen tree, 16 shrub, 30 herb, 6 grass, and 7 climber species were recorded. *A. nepalensis* was the only tree species with adult individuals present in Jugansu and Jaggi. The highest density of species was recorded at the Jugansu landslide site, followed by Jaggi and Bandwara (*Supplemental material*, Table S4: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00109.S1).

Of the species, 90% were perennial, showing established secondary succession in all sites. *Eupatorium* *adenophorum*, *Reinwardtia indica, Bidens pilosa, Achyranthes aspera,* and *Girardinia diversifolia* had profusely colonized the sites. *Apluda mutica, Saccharum rufipilum,* and *Themeda arundinacea* were common grasses. The Bandwara site had 11 regenerating tree species, whereas Jugansu and Jaggi had 3 and 4 species, respectively (*Supplemental material*, Table S4: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00109.S1). Among shrubs, *Sarcococca saligna* had the highest density, followed by *Randia tetrasperma* in Bandwara. Bandwara also had higher herb species richness and was the only site where climbers and hill bamboo were recorded (*Supplemental material*, Tables S5, S6: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00109.S1). Twenty-six plant species were also encountered outside the sampling plots; of these, 17 were common to all sites and 9 were recorded only from Bandwara (*Supplemental material*, Table S6: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00109.S1).

Discussion

Forest resource use

High-elevation villages and those inside the sanctuary were more dependent on forest resources, whereas low-elevation villages depended more on alternative fuels such as liquefied petroleum gas, and on agroforestry systems for their fodder requirements. Other studies have also found that fuelwood consumption increases with increasing elevation in Himalaya, particularly during prolonged winters, when a large amount of wood is used for space heating (Awasthi et al 2003; Dhanai et al 2015). As community forests are closed for most of the year, a large part of fuelwood and fodder demand was met from sanctuary forests. Though the forest is protected under the Wildlife (Protection) Act 1972, bona fide residents of the area have the right to graze their livestock, lop, and cut grass (Anonymous 2010). The easy accessibility has resulted in higher dependence of high-elevation villages on sanctuary forest. This supports the argument that excessive state control and management of common-property resources contributes to higher degradation of these systems (Ostrom 1990: 279; Jodha 2001). In community-owned forests, on the other hand, the primary objective of community-enforced regulations is management of resources, which effectively leads to forest conservation in many regions (Berkes 2009). Sanctuary forests thus had a higher percentage of high-disturbance sites than community-owned forests owned by villages like Mansoona and Bhatwari, which had lower disturbance despite their proximity to settlements. Similar observations were made by Baland et al (2010) and Måren et al (2013), who concluded that forests managed by local communities were less lopped and degraded than state-protected and state-managed forests. Other than management regime, dominant species also affect biotic pressure, as broad-leaved forests provide higher utility to local people than *Pinus* forests.

Rural economies across Himalaya depend to a large extent on forests, particularly for energy, with many traditional societies utilizing forest resources depending on socioeconomic, demographic, and environmental conditions (Samant and Dhar 1997; Adhikari et al 2004; Maskey et al 2006; Baland et al 2007; Angelsen et al 2014). This not only has serious environmental effects in the form of forest degradation and air pollution, but also has adverse health implications for women, who walk across treacherous terrain to gather resources and cook on polluting stoves. Various government and nongovernment programs provide local communities with renewable energy alternatives at subsidized rates. However, these often fail because of lack of trained staff and public education and the high costs of sustaining the programs (Mirza et al 2003; Aggarwal and Chandel 2010).

Forests under different disturbance and management regimes

Though individual households and villages may extract only a small amount of biomass, the cumulative effect of chronic disturbance over a wide area has left little or no time for forest recovery. In the study area, high-disturbance sites had higher species richness of both trees and shrubs, which could be due to the larger area sampled or to the effect of disturbance, as disturbance increases diversity by mixing species of different successional stages (Kumar and Ram 2005). Tree stand and shrub densities, basal cover of trees, and mean canopy cover increased from high-disturbance to moderate- and low-disturbance forests and were well below those previously recorded for Himalayan oak forests (Singh and Singh 1992). This could be due to extraction of timber and continuous lopping resulting in reduced biomass accumulation. Continuous biotic pressure in the form of logging, lopping, grazing, and litter removal is known to change the species composition and structure of mountain forests globally (Savage 1991; Dzwonko and Gawronski 2002; Gimmi 2008; Bagchi et al 2012; Bebi et al 2017). In the study area, only 8 tree species had an importance value index of >10, which shows that less than one fourth of the recorded species were well represented in the area. Continuous biotic pressure on climax communities such as *Quercus* spp. has resulted in dominance of subordinate species (Singh and Singh 1992), as was noted in the study area for *R. arboreum,* which had a higher importance value in the forests.

In the study area, the forest showed an abundance of trees in smaller girth classes, indicating a young population. The seedling density was very low compared to saplings; this could be due to high competition for establishment in some stands with higher canopy cover, high grazing pressure, and the low frequency of successful and mast seed years in the recent past (Singh et al 2011).

The density of saplings was higher than that of trees in the 30–60-cm girth class, indicating their failure to convert to trees. The sapling density was higher in moderate-disturbance plots, indicating that moderate disturbance and low canopy cover might be benefiting regeneration (Thadani and Ashton 1995). Younger trees had higher density in high-disturbance sites, whereas older trees had higher density in moderate- and low-disturbance sites. Other studies have also found that continuous disturbance brings major structural changes in forests, leading to a preponderance of younger individuals (Savage 1991).

Q. leucotrichophora, a climax species in the region, was under great anthropogenic pressure and had lower density of both regenerating individuals and older trees in high-disturbance sites. The seedlings and saplings of the species showed signs of browsing and lopping. Lopping, along with leaf litter collection, create a double disturbance, as lopping reduces production of acorns and litter collection sweeps away the acorns and leads to desiccation of the remaining acorns and seedlings by exposure to the sun. Singh et al (2014) found that this incessant small-scale disturbance adversely impacts the functioning of banj oak forests in the central Himalaya, with significantly higher biomass stocks, soil carbon, and carbon sequestration rates observed in the least human-influenced forests. However, Singh et al (2016) found that regeneration patterns were adequate across the banj oak zone in Uttarakhand, though their results also indicated large-scale fragmentation of these forests. Previous studies have shown that despite lower regeneration rates, oak forests tend to survive disturbances reasonably intact (Singh et al 1985; Thadani and Ashton 1995). Canopy openings and protection of seedlings from grazing maintain the banj oak population in the area.

The low seedling density of most subordinate species might pose a threat to their populations in the future if current trends of regeneration prevail. Seedling establishment is sustained by favorable climatic conditions and protection from grazing and forest fires. However, current trends of disturbances, including human-induced forest fires in some of the forests in the region, would impact regeneration. *A. nepalensis* and *Carpinus viminea*, both pioneer species in Himalaya, had higher density in high-disturbance sites, indicating secondary succession due to both human-caused disturbance and landslides.

Though the tree communities tend to show good resistance to disturbance-caused changes, the same cannot be said about shrub communities. Microclimatic conditions on the forest floor caused by disturbance are suitable for certain species, whereas other species show sensitivity to disturbance by either a decrease in density or complete absence in disturbed sites (Prasad et al 2015). Disturbance-tolerant species that occur in open-canopy forests, such as *Berberis* spp., *Clematis buchananiana, Rosa moschata, Indigofera heterantha,* and *Himalrandia tetrasperma*, were found to have higher density in high-disturbance sites. Density of disturbance-sensitive species that prefer a closed canopy and good litter deposition, such as hill bamboos and *Daphne papyracea,* improved with receding disturbance and improved canopy cover. *Leptodermis lanceolata* prefers sites with steep slopes, usually devoid of disturbance, and its density improved with declining disturbance. A prominent weed species recorded in the area, *E. adenophorum*, was also associated with disturbance, as its average coverage decreased from 16.6% in high-disturbance plots to 5.75% in low-disturbance plots. Our results support previous studies carried out in the Himalaya that have shown that unregulated biomass extraction is widely associated with vegetation-related changes and declining forest cover and biodiversity (Dhar et al 1997; Pandit et al 2007; Tiwari 2008; Thakur et al 2011; Singh et al 2014, 2016; Prasad et al 2015; Bhatt and Bhatt 2016).

Vegetation recovery as a sign of resilience

Both Jugansu and Jaggi had a higher density of annuals, primarily *G. diversifolia,* an early colonizer. Other early colonizer herbs included *Rumex hastatus, Pouzolzia zeylanica, Urtica dioica, Cyathula tomentosa,* and *Boehmeria* spp.; these were also found in the old successional site. These species take advantage of canopy openings and colonize quickly around the borders of landslides, as reported by Joshi (1990). Figure 5 gives a comparison of the recently denuded Jugansu site and a recovered vegetation community, thus providing an idea of recovery on a landslide site. Jaggi had vegetation islands surrounded by debris, which might have slipped down with no significant damage to plant communities. Loss of soil and aboveground vegetation due to landslide slows vegetation recovery, whereas the presence of remnant forest patches promotes it (Chazdon 2003). Mass–seed-producing annuals start colonizing the site in first year, whereas early successional shrubs and trees that favor inorganic soils are recruited within 2–3 years of the disturbance (Singh and Singh 1992). Herb species richness tends to increase from 15 years to 45 years after a landslide and then stabilize (Reddy and Singh 1993), which was true for our study also. Shrubs like *Rubus* spp., *I. heterantha* (a nitrogen fixer), and *Debregeasia saeneb* had higher density in early successional sites, being early colonizers in bouldery sites and inorganic soils. *S. saligna,* which occurs in areas with rich humus, and *Berberis* sp., which prefers old disturbed sites and open canopy, were present only in the old successional site. That site had higher species richness of trees, mostly early colonizers including *Myrica esculenta,* with nitrogen-fixing root nodules, and *C. viminea,* which colonizes freshly formed soils in old landslides. The dominant tree species in all the sites was *A. nepalensis,* a fast-growing deciduous species that contributes to forest

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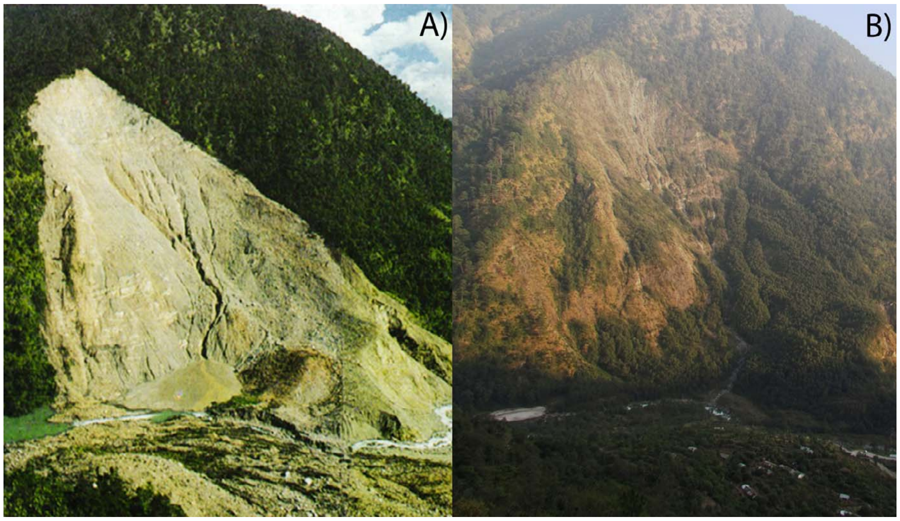
FIGURE 5 Vegetation recovery on Jugansu landslide: (A) August 1998; (B) November 2012. (Photo [A] reproduced with permission from Rautela and Thakur 1999; photo [B] by Dr Gajendra Singh)



biomass and improves soil conditions with greater return of nutrients through litter fall and nitrogen fixation in secondary forests (Sharma et al 1998). Banj oak that starts appearing at 15 years in its preferred zone with young trees established in a 40-year-old site (Singh and Singh 1992), was recorded in the old successional site only. *R. arboreum,* having windblown seeds, also had established young trees in the sunny aspects of the old successional site. *Toona ciliata*, a species that colonizes old debris and boulder areas along riverbanks and disturbed sites, had started appearing in early successional sites. These results indicate that, with time and in the absence of further disturbances, landslide sites are restored to their original state with a similar characteristic taxonomic composition (Chaudhary 1989; Joshi 1990; Reddy and Singh 1993).

Conclusion

Forest resources contribute substantially to the livelihood security of remote and isolated rural communities across the Himalayan region; their use is influenced by factors such as elevation, income, and access to free resources. The study area underwent a 13% population growth during 2001–2011, which is remarkably high compared to population growth in the Rudraprayag district as a whole during the same period. This increasing human population and unregulated resource extraction, along with frequent landslides in river catchments, have degraded vast stretches of forest, resulting in secondary succession conditions and augmenting the growth of early succession species. The low density of trees in higher girth classes and relatively low recruitment of seedlings indicate disturbances have affected the successional trend of the native community; however, abundant saplings and regenerating forests at the sites of old landslides and other disturbances indicate the resilient dynamism of Himalayan forests. The natural process of vegetation recovery on degraded sites is well known; however, in the current scenario of unpredictable disturbances and changes, it becomes imperative to aid restoration with a better understanding of vegetation recovery and changing nutrient dynamics. Most of the afforestation activities to reclaim degraded and denuded lands focus only on planting trees; however, it is imperative to understand the sequence of appearance of various herbaceous flora and to identify indicator species for eco-restoration and monitoring. This will accelerate the recovery of native habitats by providing favorable understory conditions. However, care should be taken to avoid overcrowding of the understory, which might affect the growth of tree saplings.

Any degradation of ecosystem functions and services will increase both the environmental and socioeconomic vulnerability of mountain communities. Thus, it is imperative to formulate long-term energy strategies and promote renewable-energy technologies. This may include funding the transformation of laboratory discoveries into commercial products such as photovoltaic lights, solar cookers and water heaters, and improved cook stoves; effective monitoring along with continuous upgrading to make them more efficient and economically accessible to a larger population; and tax breaks for local entrepreneurs. Local communities across Himalaya have been provided with solar lamps; however, it is necessary to upgrade these products. Another alternative could be to increase biomass production within human systems through scientific or organizational innovation, such as by planting fast-growing native grasses on common land, which might also reduce lopping and grazing within forests. It was evident in the study area that households with better access to biomass from agroforestry made fewer trips to forests for biomass collection. Efforts by implementing agencies can not only reduce pressure on conventional energy sources in sensitive and fragile mountain regions; they can also reduce indoor and outdoor atmospheric pollution and lessen the drudgery of rural people, particularly women, by providing cleaner kitchens and reducing the effort needed to access natural resources, thus enhancing their wellbeing.

The pursuit of the Sustainable Development Goals requires recognition of the role that mountain forests will play in achieving sustainable development. Understanding the current status of mountain forests and the dynamics of mountain socioecological systems can contribute to the establishment of policies and action programs to enhance the ecological sustainability of the water towers of the world.

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Supplemental material

TABLE S1 Tree species uses, density, total basal area (TBA), and importance value index (IVI) across different disturbance classes. F, fodder; F*, preferred fodder; FW, fuelwood; M, miscellaneous uses (including agricultural implements and support for climber crops); T, timber.
TABLE S2 Shrub species density (number/ha) across different disturbance classes.
TABLE S3 Density (number/ha) of seedlings and saplings across different disturbance classes.
TABLE S4 Tree species density, total basal area, and importance value index at 3 landslide sites.
TABLE S5 Shrub and herb species density (number/ha) at 3 landslide sites.
TABLE S6 Plant species that were recorded at landslide sites but were not observed during sampling.

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