Regeneration Patterns of Tree Species Along an Elevational Gradient in the Garhwal Himalaya

Authors: Sharma, Chandra Mohan, Mishra, Ashish Kumar, Tiwari, Om Prakash, Krishan, Ram, and Rana, Yashwant Singh

Source: Mountain Research and Development, 38(3) : 211-219

Published By: International Mountain Society

URL: https://doi.org/10.1659/MRD-JOURNAL-D-15-00076.1

Mountain Research and Development (MRD)
An international, peer-reviewed open access journal
published by the International Mountain Society (IMS)
www.mrd-journal.org

MountainResearch
Systems knowledge

Regeneration Patterns of Tree Species Along an Elevational Gradient in the Garhwal Himalaya

Chandra Mohan Sharma[1], Ashish Kumar Mishra[1,2], Om Prakash Tiwari[1], Ram Krishan[1], and Yashwant Singh Rana[1]*
** Corresponding author: ashishmishramlg@gmail.com*
[1] Department of Botany, Hemwati Nandan Bahuguna Garhwal University, Srinagar Garhwal, Uttarakhand-246174, India
[2] Department of Environmental Science, Babasahab Bhimrao Ambedkar University, Lucknow, Uttar Pradesh 227025, India

This study assessed the regeneration status of tree species at different elevations in Himalayan forests. For this purpose, we assessed the densities of seedlings, saplings, and adult trees of various forest-forming species to understand their population structure and regeneration patterns. Five elevational ranges—<2000, 2000–2500, 2500–3000, 3000–3500, and >3500 m above sea level—were selected in various ranges in the Bhagirathi River catchment area in the Garhwal Himalaya. The highest species richness was recorded at the lowest elevational range, and the lowest species richness was recorded at the highest elevational range. Species diversity, measured using the Simpson and Shannon–Wiener diversity indices, was highest at the lowest elevations and lowest at the highest elevations. Abies spectabilis, Cedrus deodara, Rhododendron arboreum, Pinus roxburghii, *and* Quercus oblongata *were dominant and widely adapted with appropriate regeneration potential at various elevations, whereas* Aesculus indica, Juglans regia, *and* Sorbus cuspidata *showed less ability to regenerate, indicating a threat to their survival in the near future. Tree species of subalpine forests* Abies pindrow, A. spectabilis, Acer acuminatum, Betula utilis, *and* R. arboreum *were observed to expand their upper limits into alpine meadows. Weak regeneration by some dominant tree species, and expansion by a few less-dominant or even rare species, indicate likely future compositional changes in Himalayan forests.*

Keywords: *Elevation; forests; regeneration patterns; Bhagirathi River; India.*

Peer-reviewed: *March 2018* ***Accepted:*** *June 2018*

Introduction

It is important to understand how evolution and the ecological potential of life forms help them to adapt to climate change (Woodward and Kelly 2008), because Himalayan forests are heavily influenced by climate change (Polanski et al 2014; Chakraborty et al 2018). In Himalayan forests, the regeneration potential of different species directly depends on climate, topography, and soil conditions and their geographical distribution (Sharma, Mishra, et al 2016a; Mishra et al 2017). Therefore, forest structure and regeneration are key to the understanding of forest ecological processes and dynamics (Elouard et al 1997).

Forest structure and composition in the Himalayan region are mainly driven by elevation and climate (Vetaas 2000; Sharma, Mishra, et al 2016b; Sharma et al 2017, 2018), and future changes in climate are projected to cause changes in vegetation distribution (Gao et al 2017). As elevation changes, geographical and climatic conditions change sharply (Bandopadhyay 2016). This generates diverse vegetation structures and high species diversity (Chawla et al 2008). Many environmental factors (eg temperature, precipitation, atmospheric pressure, solar radiation, and wind velocity) change systematically with elevation. Therefore, elevational gradients are powerful natural experiments for testing the ecological and evolutionary responses of forests to environmental changes (Cui et al 2005; Körner 2007). Although changes in species composition, distribution, diversity, and community structure along elevational gradients have been well documented (Guo et al 2013; Sharma et al 2017, 2018), regeneration dynamics have been insufficiently quantified to date, although such data are crucial to assess the role of climate change and species shift in high-mountain forests (Sharma et al 2014).

The existence of a community depends largely on its regeneration potential under varied environmental conditions: climate, soil characteristics, disturbance regimes, and seed bank composition. The regeneration of a species is affected by both natural (Behera et al 2012; Mishra, Behera, et al 2013) and anthropogenic (Chaturvedi et al 2017) factors. The causes of failure to

http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00076.1

regenerate include lack of viable seed production, insect and animal predation, unfavorable microclimatic conditions, overgrazing, habitat changes, and biological invasions. Successful regeneration guarantees long-term sustainability of a forest (Malik and Bhatt 2016). Regeneration is critical in a forest because it determines future species composition and stocking. When the regeneration of any species is confined to a particular range of habitat conditions, the extent of those conditions is a major determinant of that species' geographical distribution (Grubb 1977). The lack of adequate forest regeneration is an issue recognized by both foresters and ecologists (Ceccon et al 2004; Mishra and Singh 2017), and there is a need for forest restoration and conservation (Vieira and Scariot 2006; Wale et al 2012). Rehabilitation and ecosystem recovery also depend on regeneration capacity (Pandey and Shukla 2001), which plays a direct and vital role in forest growth and management.

The presence of a sufficient number of seedlings, saplings, and trees in a forest indicates successful regeneration (Dutta and Devi 2013). The density of species regeneration is expected to vary spatially because of forest structure and physiographic conditions (Ward et al 2006; Mishra, Bajpai, et al 2013). The understanding of processes affecting the patterns of regeneration of forest-forming species is of crucial importance to ecologists and forest managers (Slik et al 2003). It enables them to undertake proper forest management planning, which in turn helps make it possible to utilize a given forest ecosystem wisely and sustainably. Therefore, for successful management and conservation of natural forests, reliable data on regeneration trends are required (Eillul and Obua 2005). Regeneration patterns in Indian Western Himalayan forests have not been thoroughly studied, and a better understanding of this topic may be helpful in assessing many other parameters of forest ecosystems.

In the Western Himalayan region, the effects of both elevation and climate change on forest composition are evident, but they need to be measured in more detail (Sharma, Mishra, et al 2016a, 2016b; Sharma, Tiwari, et al 2016). An assessment of species regeneration along the elevational gradient is critical in order to explore compositional changes and species migration in Himalayan forests. The regeneration potential of tree species in ridgetop forests with uniform environmental conditions can effectively predict the influence of climate change on Himalayan forests. Therefore, the objectives of this study were to analyze (1) the regeneration of various forest-forming tree species along elevational gradients and (2) the influence of elevation on forest structure and the regeneration potential of different tree species in the catchment area of the Bhagirathi River in the Garhwal Himalaya.

Methodology

Study area

This study was conducted in the catchment area of the Bhagirathi River, one of the headstreams of the Ganges, in India's Garhwal Himalaya, an area that contains tropical to subalpine forests. The study took place between latitudes 30°04′25.4″–30°49′56.2″N and longitudes 078°37′35.9″–078°47′35.00″E, in 2 districts, Uttarkashi and Tehri, in Uttarakhand State. It covered different forest types in 5 elevation ranges—<2000, 2000–2500, 2500–3000, 3000–3500, and >3500 m above sea level (masl) in the mountain ranges of Narendranagar-Hindolakhal (800–2050 masl), Mussoorie-Dhanolti (1900–2900 masl), Chaurangikhal-Harunta (2400–3300 masl), and Dayara-Gidara (2500–3750 masl). The study area is shown in Figure 1, and the forest types and their dominant species are shown in Table 1.

The study area has a subtropical to temperate monsoon climate with a mean annual rainfall of 2000 mm and 3 main seasons: a cool and relatively dry winter (October to February), a warm and dry summer (March to June), and a warm and wet period (July to September) called the monsoon or rainy season. Frost is common during the winter; at higher elevations, heavy snow may persist into April and May in shady locations.

Sampling methods

Ten sample plots of 0.1 ha each (31.62 × 31.62 m) were randomly laid out on ridgetops in each elevational range to analyze tree composition and regeneration. Within each 0.1-ha plot, eight 5 × 5-m quadrats for saplings (10 × 8 = 80) and four 1 × 1-m quadrats in each 5 × 5 m quadrat for tree seedlings (10 × 8 × 4 = 320) were analyzed (as per Phillips 1959). The size and number of quadrats were standardized using the species area curve method (Mishra 1968).

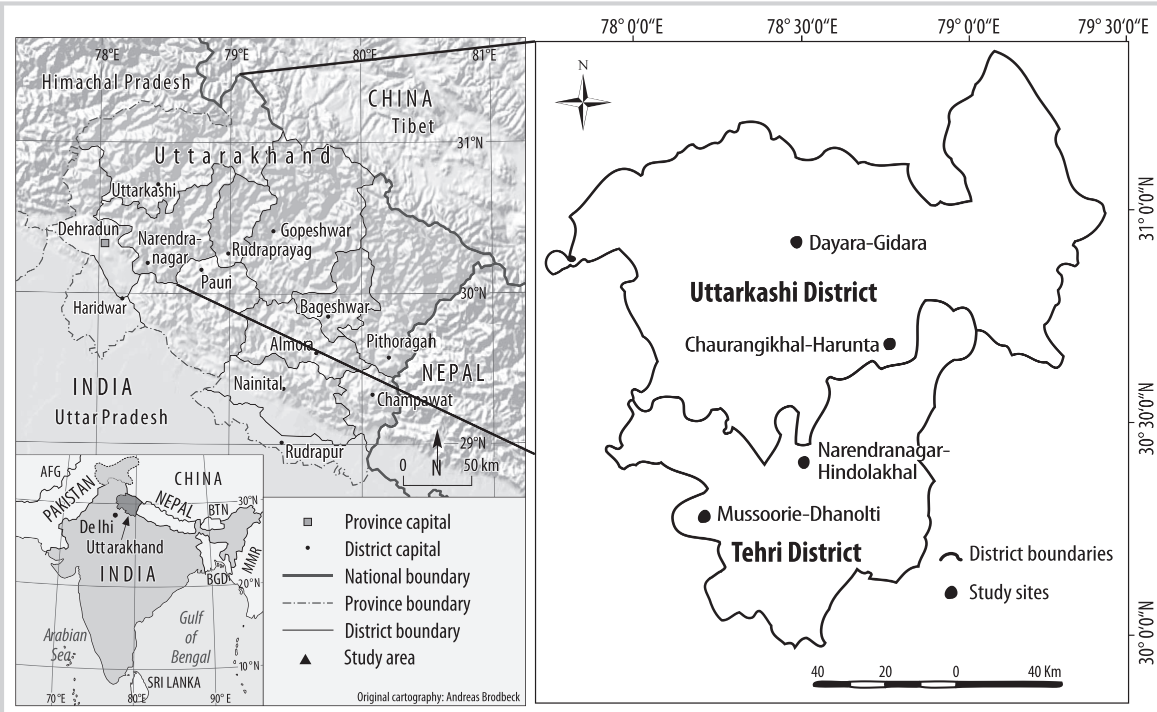
Samples were categorized as seedlings (height <20 cm), saplings (diameter at breast height <10 cm and height >20 cm), or mature trees (diameter at breast height >10 cm) as per Deb and Sundriyal (2008). Voucher specimens of tree species were collected and identified with the help of authenticated floras (Gaur 1999; Pusalkar and Singh 2012) and the herbarium of Hemwati Nandan Bahuguna Garhwal University in Srinagar Garhwal.

Data analysis

The structure and composition of forests was determined following Misra (1968) and Mueller-Dombois and Ellenberg (1974). Tree species diversity (species richness & evenness) was assessed using the Shannon–Wiener index, calculated as $-\Sigma\ (ni/N)\ \ln\ (ni/N)$, where ni is the importance value index (IVI) of a single species and N is the sum of the IVI values of all species (Shannon and Weaver 1949). Species dominance was assessed using the Simpson index,

http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00076.1

FIGURE 1 Map of the study area. (Map of the study area by Ashish K. Mishra; map of India by Andreas Brodbeck, courtesy of MRD)



calculated as $\Sigma\ (ni/N)^2$ (Simpson 1949). The IVI of each species was calculated by adding the relative values of their frequency, density, and basal area.

The regeneration status of tree species was determined based on the population sizes of seedlings, saplings, and adults, according to Khan et al (1987), Shankar (2001), and Khumbongmayum et al (2006). Regeneration was categorized as follows:

- *good* if seedlings > saplings > adults;
- *fair* if seedlings > saplings ≤ adults;
- *poor* if there were saplings but no seedlings (irrespective of the relative numbers of saplings and adults);
- *none* if only adults were present, with no seedlings or saplings;
- *new* if only saplings and/or seedlings were present, with no adults.

TABLE 1 Dominant tree species at different elevations.

Elevation (masl)	Studied mountain ranges	Dominant forest type	Dominant tree species
<2000	Chaurangikhal Hindolakhal Mussoorie	Tropical moist forest Moist temperate forest	*A. latifolia* *P. roxburghii* *R. arboreum*
2000–2500	Dayara-Gidara Chaurangikhal Mussoorie	Moist temperate forest Subalpine forest	*P. wallichiana* *Q. oblongata* *R. arboreum*
2500–3000	Dayara-Gidara Chaurangikhal Mussoorie	Moist temperate forest Subalpine forest	*A. pindrow* *Q. semecarpifolia* *R. arboreum*
3000–3500	Dayara-Gidara Chaurangikhal	Moist temperate forest Subalpine forest	*A. spectabilis* *P. wallichiana* *Q. semecarpifolia*
>3500	Dayara-Gidara	Subalpine forest	*A. spectabilis* *B. utilis* *Q. semecarpifolia*

http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00076.1

Linear regression analysis was performed using SPSS version 20 (SPSS, Chicago, IL, USA) to assess the relation between forest structure and regeneration potential against the elevational gradients. Graphical representations of species richness, density, and the regeneration status of dominant species were done using SigmaPlot version 12.

Results

The dominant tree species in the seedling, sapling, and tree categories in each elevation range in the study area are presented in Table 1 and Figure 2. A total of 75 tree species were recorded: 69 in the tree/adult stage, 55 in the sapling stage, and 42 in the seedling stage. Forest composition by growth stage and elevation is summarized in Figure 3. The highest species richness was found in the forests below 2000 masl elevation, followed by 2500–3000, 2000–2500, and 3000–3500 masl; the lowest species richness was recorded above 3500 m (Figure 3). This showed that species richness was inversely proportional to elevation. Species density for all 3 growth stages increased with increasing elevation (Figure 3).

The lowest Simpson index value was recorded at the lowest elevations and the highest at the highest elevations. Tree species grew increasingly homogenous with increasing elevation (Figure 4). However, the highest Shannon–Wiener index value was found at the lower elevations. Therefore, the highest species diversity of tree species was recorded at the lowest elevations; diversity gradually decreased with increasing elevation. Trees and saplings had almost similar patterns in the Simpson and Shannon–Wiener indexes, whereas seedlings showed different trends (Figure 4). Across all elevations, the regeneration of widely adapted species such as *Abies pindrow*, *A. spectabilis*, *Anogeissus latifolia*, *Cedrus deodara*, *Pinus roxburghii*, *P. wallichiana*, *Quercus oblongata*, *Q. semecarpifolia*, and *Rhododendron arboreum* was good. On the other hand, *Acer caesium*, *Aesculus indica*, *Juglans regia*, *Populus ciliata*, *Sorbus cuspidata*, and *Taxus wallichiana* showed poor or no regeneration (*Supplemental material*, Table S1: http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00076.S1).

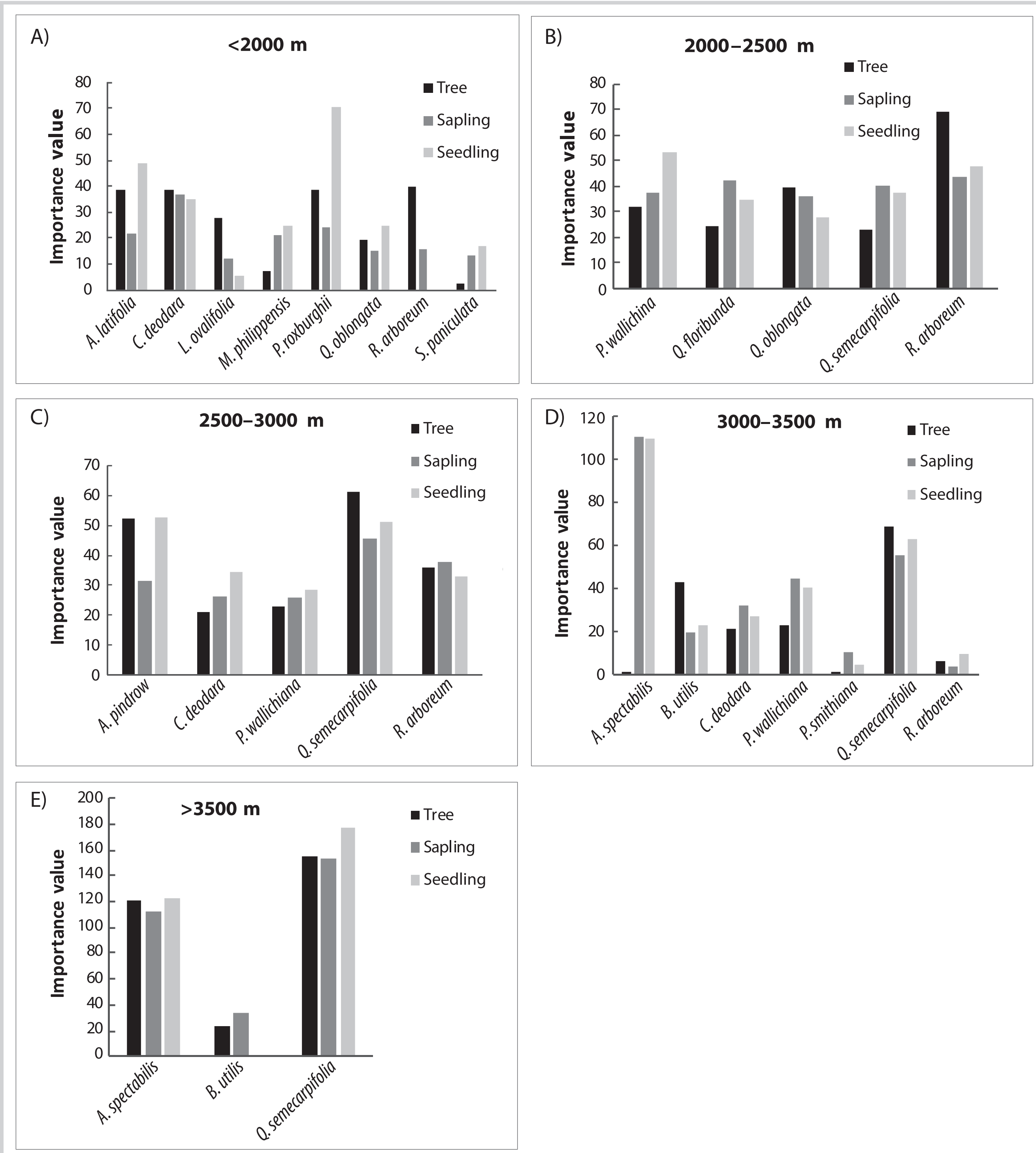
Figure 5 summarizes regeneration patterns at different elevations. The highest number of well-regenerating species was recorded at the lowest elevations (<2000 masl), followed by 2500–3000, 2000–2500, and 3000–3500 masl; the number was lowest above 3500 masl (Figure 5). The most nonregenerating species were found below 2000 masl, followed by 2500–3000 masl, 2000–2500 masl, and 3000–3500 masl; the fewest were found at 3000–3500 masl. "New" species (only seedlings and/or saplings found, with no mature trees) were most numerous below 2000 m, followed by 2500–3000 and 3000–3500 m. There were no new species at 2000–2500 m or above 3500 m. Linear regression analysis between the components of forest structure and regeneration against the elevational gradients is tabulated in Table 2.

Discussion

In the Bhagirathi River catchment area in the Garhwal Himalaya, *A. pindrow*, *A. spectabilis*, *Alnus nepalensis*, *A. latifolia*, *C. deodara*, *Cupressus torulosa*, *P. roxburghii*, *Q. semecarpifolia*, and *Q. oblongata* were the most dominant and widely distributed species for all 3 growth stages at all elevations. Tree species exhibited different patterns of distribution along elevational gradients. Total species richness was greater at lower, warmer elevations than at higher, cooler elevations. The higher mountain forests were represented by only a few tree species—*A. pindrow, A. spectabilis*, *Betula utilis*, *Q. semecarpifolia*, and *R. arboreum*—that can thrive under harsh climatic and environmental conditions. In general, a consistent decline in species richness was observed with increasing elevation; moreover, Simpson index and species richness were significantly negatively proportional to elevation (Figures 3 and 4). The occurrence of higher diversity and species richness at lower elevations might thus be explained by the communities' susceptibility to invasion, with ample gaps in the sparse vegetation due to anthropogenic disturbances (Choler et al 2001). At higher elevations, a single species or a few species dominated (as was revealed by the Simpson index). Other mountain studies (Burns 1995; Austin et al 1996) have also reported highest species richness at lower elevations. The variation in quantitative parameters like species richness and tree species composition at different elevations was also due to physiographic, climatic, and edaphic factors (Rosbakh et al 2014). Distributional ranges of several species varied with elevation (as was also reported by Kharkwal et al 2005). Pauses and Austin (2001) suggested that over any large region, the distribution of species richness is likely to be governed by 2 or more environmental factors and not by a single factor.

There was a gradual increase in the densities of trees and saplings (36.4–60 individuals 100 m^{-2}), and trees (5.5–6.2 individuals 100 m^{-2}) with an increase in elevation. Density of seedlings (427–940 individuals 100 m^{-2}) was lowest at <2000 masl and highest at upper elevations, decreasing at middle elevations (2500–3000 masl). Species density values conformed to the findings of Parthasarathy and Karthikeyan (1997) for the Western Ghats and Samant and Joshi (2003) for the temperate forests of Himalaya. The differences in relative proportions of seedlings, saplings, and trees at different elevations may be due to variations in biotic pressure and forest composition as well as abiotic factors. The reason for good regeneration at higher elevations can be attributed to the lower biotic pressure prevalent there. Sapling density values did not vary considerably across elevations; similar findings have been reported by other authors (Singhal and Soni 1989;

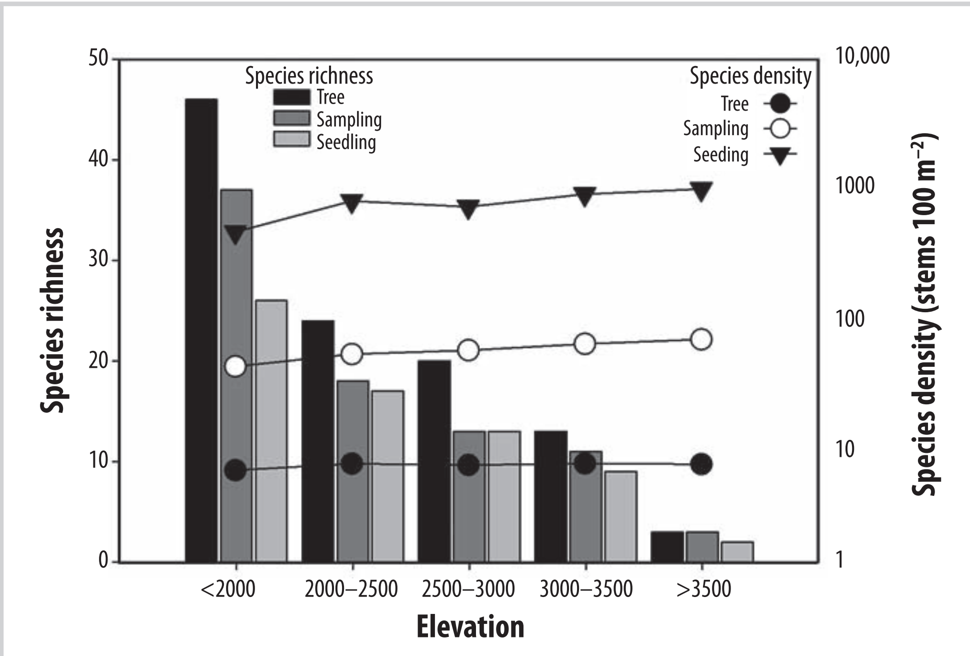
FIGURE 2 Population structures of dominant species at different elevations.



Adhikari and Tiwari 1991; Ilorkar and Khatri 2003). For the Garhwal Himalaya, Pande (2001) reported densities of 792–1111 stems ha^{-1}, which are higher than our values. The Shannon–Wiener index showed significantly higher diversity (1.30) at lower elevations and lower diversity (0.39) at higher elevations (Figure 4), which was in accordance with the values reported for other temperate forests (Singh and Kaushal 2006; Sharma et al 2009, 2018).

http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00076.1

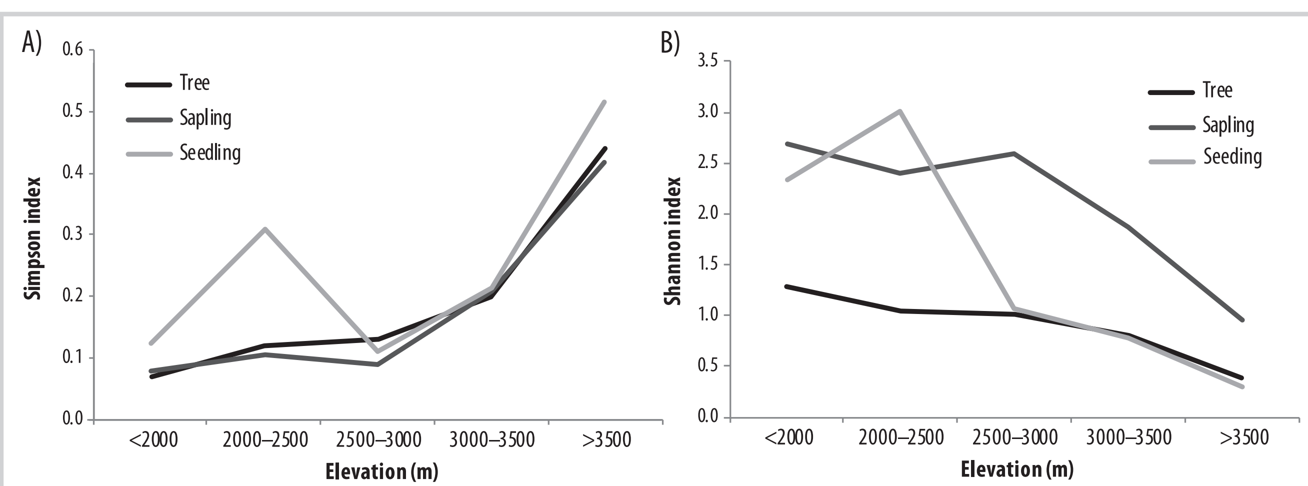
FIGURE 3 Species richness and density at different elevations.



The lowest Simpson index and highest Shannon–Wiener index values for saplings showed that forests at all elevations supported greater diversity and density of understory vegetation than of overstory and ground vegetation; sapling density was highest at 3000–3500 m. The Simpson and Shannon–Wiener indexes were significantly correlated with elevation (Table 2). In his long-term study of mountain birch forests, Durak (2012) recorded similar diversity trends for different growth stages in Himalayan forests.

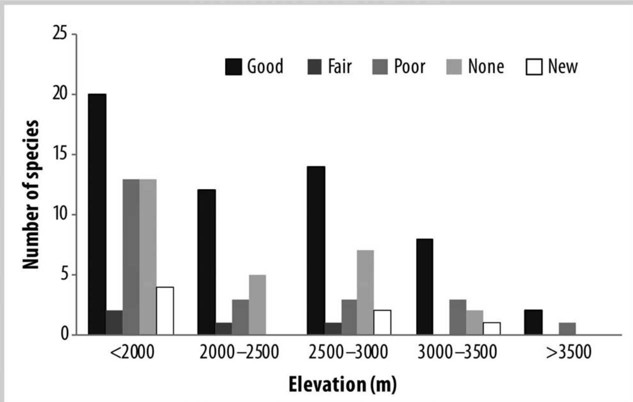
Limited regeneration and subsequently declining populations of some dominant native species such as *Acer acuminatum*, *B. utilis*, *Lyonia ovalifolia*, *Picea smithiana*, *Quercus floribunda*, *Q. semecarpifolia*, *R. arboreum*, *Prunus cornuta,* and *S. cuspidata* indicate that compositional changes may be expected in the near future. Poor regeneration was recorded for *A. indica*, *B. utilis*, *P. ciliata*, *Spondias pinnata*, *Falconeria insignis*, *Symplocos paniculata*, and *Ulmus wallichiana*. No regeneration was observed for *A. acuminatum*, *A. caesium*, *Albizia lebbeck*, *Albizia procera*, *J. regia*, *Terminalia tomentosa*, and *T. wallichiana*, which may be because of their greater economic value leading to overexploitation, a potential threat to their survival in the forests of the Garhwal Himalaya.

FIGURE 4 Species diversity by growth stage and elevation as measured by the Simpson and Shannon–Wiener indexes.



 http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00076.1

FIGURE 5 Species regeneration at different elevations—general trends.



Species including *Cocculus laurifolius*, *Ilex dipyrena*, *Neolitsea cuipala*, *P. cornuta,* and *Lindera pulcherrima* occurred as seedlings only, which indicates that they are recent invaders. The overall regeneration status was fairly high at higher elevations, maybe because these areas were less disturbed. *A. spectabilis* has shown wider ecological amplitude at high elevations (3000–3675 masl; Sharma et al 2017) with good regeneration ability and coexistence with other species (Table 1) and is therefore recommended as a prized tree species for higher elevations in the Garhwal Himalaya. Niche overlap, intra- and interspecific competition, availability of space (Chesson 2000), recruitment potential of seedlings and saplings (Chaturvedi et al 2012; Saikia and Khan 2013; Chaturvedi et al 2017), occurrence of fire (Murthy et al 2002), grazing, light (Behera et al 2012), canopy density, soil moisture, and soil nutrient status also affect species regeneration (Mishra, Bajpai, et al 2013).

P. wallichiana also showed good regeneration ability in all habitats except in *Q. semecarpifolia* forests at higher elevations. Out of 75 tree species recorded at all elevations in this study, 22 species were regenerating poorly and 23 species were not regenerating (Figure 5). A forest in which the seedling/tree ratio is higher than the sapling/tree ratio shows relatively low conversion of seedlings to saplings. The higher seedling and sapling densities and their ratios to mature tree densities indicate the forest composition of the future. The regeneration potential of a tree species hints at its future sustainability. Thus, the future composition of forests depends on the regeneration potential of existing tree species. Regression results clearly showed positive significant impact of elevation on basal cover values ($R^2 = 0.9597$) and Shannon–Wiener diversity indices ($R^2 = 0.9045$) and negative significant impact on Simpson indices.

The higher diversity and lower dominance on the ridgetops of lower elevations may be due to closeness to human settlements, which causes moderate disturbance and might have led to a variety of microclimates in this area. The higher elevations were represented by high dominance; lower diversity may be due to low temperature and harsh climatic conditions. Both positive regeneration ($R^2 = 0.8732$) and negative regeneration ($R^2 = 0.7451$) were significantly correlated with elevation. The study revealed fair to good regeneration of various tree species on the ridge tops at elevational ranges of $<$2000 masl, followed by 2500–3000, 2000–2500, and 3000–3500 masl, and lowest at $>$3500 masl. Negative regeneration was observed only in tree/adult growth stage at different elevations, with corresponding seedlings and saplings completely absent. Weak regeneration of some dominant tree species and significant contribution by a few less-dominant species clearly indicate future forest compositional changes in the Himalayan ranges.

Ridgetop forest plants may respond to climate change either by adapting their life cycles to the new conditions or by shifting upwards/downwards from their conventional distribution ranges to habitats that are more appropriate (Sharma et al 2014). Most high-mountain forests are sensitive to a variety of environmental changes. Regeneration results show that some tree species in the subalpine range—*A. pindrow, A. spectabilis, A. acuminatum, B. utilis, and R. arboreum*—are expanding into alpine meadows. Above the timberline, seedlings and saplings of these species were observed to expand their upper distribution limits of growth to alpine meadows (species

TABLE 2 Results of linear regression analysis of forest structure, regeneration potential, and elevation.

Parameter	R^2	Elevation regression formula
Species richness	0.8932	67.85850 − 0.01730
Tree density	0.5714	529.14000 + 0.02530
Basal cover	0.9597	23.10310 + 0.02010
Simpson index	0.7468	−0.19600 + 0.00019
Shannon–Wiener index	0.9045	1.90140 − 0.00040
Positive regeneration	0.8732	60.00310 − 0.12530
Negative regeneration	0.7451	68.12140 − 0.17090

http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00076.1

migration/shift). Therefore, forest structure and regeneration patterns at higher elevations in this region may change in the near future. Similarly, *P. roxburghii* and *C. deodara* were found to encroach on the habitats of mixed broadleaved forest at midelevation (2200–2500 masl) and higher elevations (> 3100 masl), respectively.

Conclusion

In the mountain ranges of the Garhwal Himalaya, mature forests were recorded at elevations of 2500–3500 masl and regenerating forests below 2000 masl (mainly because of anthropogenic pressures). Species with declining population size, infrequent regeneration, and narrow tolerance ranges—for example, *A. caesium*, *Betula alnoides*, *J. regia*, *Q. floribunda*, *S. paniculata*, *S. cuspidata*, *T. wallichiana,* and *U. wallichiana*—are at risk of extinction mainly because of habitat fragmentation (Malik and Bhatt 2016).

Forest management planning is becoming more challenging in the context of climate change; therefore, new decision support systems should be developed and applied to deal with uncertainty and risk in long-term forest management. Understanding the changes in structural and functional attributes of forests across a wide range of elevations will help us better predict the regeneration of trees, future forest composition, and forest productivity. Species with poor regeneration status should be recognized, so that proper measures can be adopted for their conservation, as they are susceptible to changing climatic conditions, which may result in their complete extermination. A systematic management plan is required for the conservation of Himalayan forests.

ACKNOWLEDGMENTS

The authors are thankful to Department of Science and Technology, Government of India, for providing financial assistance for this study (project no. SERB/SR/SO/PS/14/2010). The comments and recommendations of 2 anonymous reviewers and Associate Editor Anne Zimmermann are also greatly acknowledged.

REFERENCES

Adhikari RS, Tiwari A. 1991. Microbial decomposition of oak leaf litter in temperate forest of Kumaun Himalayas. *Acta Botanica Indica* 19:195–200.
Austin MP, Pausas JG, Nicholls AO. 1996. Patterns of tree species richness in relation to environment in southeastern New South Wales, Australia. *Australia Journal of Ecology* 21:154–164.
Bandopadhyay S. 2016. Does elevation impact local level climate change? An analysis based on fifteen years of daily diurnal data and time series forecasts. *Pacific Science Review A: Natural Science and Engineering* 18(3):241–253
Behera SK, Mishra AK, Sahu N, Kumar A, Singh N, Kumar A, Bajpai O, Chaudhary LB, Khare PB, Tuli R. 2012. The study of microclimate in response to different plant community association in tropical moist deciduous forest from northern India. *Biodiversity and Conservation* 21:1159–1176.
Burns BR. 1995. Environmental correlates of species richness at Waipoua forest sanctuary, New Zealand. *New Zealand Journal of Ecology* 19:153–162.
Ceccon E, Sanchéz S, Campo-Alves J. 2004. Tree seedling dynamics in two abandoned tropical dry forests of different successional status in Yucatán, Mexico: A field experiment with N and P fertilization. *Plant Ecology* 170:12–26.
Chakraborty A, Saha S, Sachdeva K, Joshi PK. 2018.Vulnerability of forests in the Himalayan region to climate change impacts and anthropogenic disturbances: A systematic review. *Regional Environmental Change* 18(6):1783–1799. http://dx.doi.org/10.1007/s10113-018-1309-7.
Chaturvedi RK, Raghubanshi AS, Singh JS. 2012. Effect of grazing and harvesting on diversity, recruitment and carbon accumulation of juvenile trees in tropical dry forests. *Forest Ecology and Management* 284:152–162.
Chaturvedi RK, Raghubanshi AS, Tomlinson KW, Singh JS. 2017. Impacts of human disturbance in tropical dry forests increase with soil moisture stress. *Journal of Vegetation Science* 28:997–1007.
Chawla A, Rajkumar S, Singh KN, Lal B, Singh RD, Thukral AK. 2008. Plant species diversity along an altitudinal gradient of Bhabha Valley in western Himalaya. *Journal of Mountain Science* 5(2):157–177.
Chesson P. 2000. General theory of competitive coexistence in spatially-varying environments. *Theoretical Population Biology* 58:211–237.
Choler P, Michalet R, Callaway RM. 2001. Facilitation and competition on gradients in alpine plant communities. *Ecology* 8:3295–3308.
Cui HT, Liu HY, Dai JU. 2005. *Research on Mountain Ecology and Alpine Treeline*. Beijing, China: Science Press.
Deb P, Sundriyal RC. 2008. Tree regeneration and seedling survival patterns in old-growth lowland tropical rainforest in Namdapha National Park, north-east India. *Forest Ecology Management* 255:3995–4006.
Durak T. 2012. Changes in diversity of the mountain beech forest, herbs layer as a function of the forest management method. *Forest Ecology and Management* 276:154–164.
Dutta G, Devi A. 2013. Plant diversity, population structure, and regeneration status in disturbed tropical forests in Assam, northeast India. *Journal of Forestry Research* 24(4):715–720.
Eillul G, Obua J. 2005. Tree condition and natural regeneration in disturbed sites of Bwindi Impenetrable Forest National Park, southwestern Uganda. *Tropical Ecology* 46:99–111.
Elouard C, Houllier F, Pascal JP, Pelissier R, Ramesh BR. 1997. *Dynamics of the Dense Moist Evergreen Forests. Long-term Monitoring of an Experimental Station in Kodagu*. Karnataka, India: Institute français de Pondichéry.
Gao J, Jiao K, Wu S, Ma D, Zhao D, Yin Y, Dai E. 2017. Past and future effects of climate change on spatially heterogeneous vegetation activity in China. *Earth's Future* 5(7):679–692.
Gaur RD. 1999. *Flora of the District Garhwal, North-West Himalaya (with Ethnobotanical Notes)*. Srinagar Garhwal, India: Transmedia.
Grubb PJ. 1977. The maintenance of species-richness in plant communities: The importance of the regeneration niche. *Biological Review* 52:107–145.
Guo Q, Kelt DA, Sun Z, Liu H, Hu L, Ren H, Wen J. 2013. Global variation in elevational diversity patterns. *Scientific Reports* 3:3007. http://dx.doi.org/10.1038/srep03007.
Ilorkar VM, Khatri PK. 2003. Phytosociological study of Navegaon National Park (Maharashtra). *Indian Forester* 129:377–387.
Khan ML, Rai JPN, Tripathi RS. 1987. Population structure of some tree species in disturbed and protected sub-tropical forests of North East India. *Acta Oecologica* 8:247–255.
Kharkwal G, Mehrotra P, Rawat YS, Pangtey YPS. 2005. Phytodiversity and growth forms in relation to altitudinal gradient in the central Himalaya (Kumaun) region of India. *Current Science* 89(5):873–878.
Khumbongmayum ADD, Khan ML, Tripathi RS. 2006. Biodiversity conservation in sacred groves of Manipur north east India: Population structure and regeneration status of woody species. *Biodiversity and Conservation* 15:2439–2456.
Körner C. 2007. The use of altitude in ecological research. *Trends of Ecology & Evolution* 22:569–574.
Malik ZA, Bhatt B. 2016. Regeneration status of tree species and survival of their seedlings in Kedarnath Wildlife Sanctuary and its adjoining areas in Western Himalaya, India. *Tropical Ecology* 57(4):677–690.
Mishra AK, Bajpai O, Sahu N, Kumar A, Behera SK, Mishra RM, Chaudhary LB. 2013. Study of plant regeneration potential in tropical moist deciduous forest in northern India. *International Journal of Environment* 2(1):153–163.

Mishra AK, Behera SK, Singh K, Chaudhary LB, Mishra RM, Singh B. 2013. Influence of abiotic factors on community structure of understory vegetation in moist deciduous forests of north India. *Forest Science and Practice* 15(4):261–273.
Mishra AK, Behera SK, Singh K, Mishra R, Chaudhary L, Singh B. 2017. Characteristics of soil properties in response to different deciduous forest from northern India. *Climate Change and Environmental Sustainability* 5(1):66–74.
Mishra AK, Singh RP. 2017. Shift in plant species distribution and regeneration potential due to global warming and climate change in Himalayan region. *EnviroNews* 23(4). http://isebindia.com/17-20/17-10-2.html; accessed on 10 September 2018.
Misra R. 1968. *Ecology Workbook*. Calcutta, India: Oxford and IBH.
Mueller-Dombois D, Ellenberg H. 1974. *Aims and Methods of Vegetation Ecology*. New York, NY: Wiley.
Murthy IK, Murali KS, Hegde GT, Bhat PR, Ravindranath NH. 2002. A comparative analysis of regeneration in natural forest and joint forest management plantations in Uttara Kannada District, Western Ghats. *Current Science* 83:1358–1364.
Pande PK. 2001. Quantitative vegetation analysis as per aspect and altitude, and regeneration behaviour of tree species in Garhwal Himalayan forest. *Annals of Forest* 9:39–52.
Pandey SK, Shukla RP. 2001. Regeneration strategy and plant diversity in degraded Sal forests. *Current Science* 81:95–102.
Parthasarathy N, Karthikeyan R. 1997. Biodiversity and population density of woody species in a tropical evergreen forest in Courtallum Reserve Forest, Western Ghats, India. *Tropical Ecology* 38:297–306.
Pauses JG, Austin MK. 2001. Patterns of plant species richness in relation to different environments: An appraisal. *Journal of Vegetation Science* 12:153–166.
Phillips J. 1959. *Agriculture and Ecology in Africa*. London, United Kingdom: Faber and Faber.
Polanski S, Fallah B, Befort DJ, Prasad S, Cubasch U. 2014. Regional moisture change over India during the past millennium: A comparison of multi-proxy reconstructions and climate model simulations. *Global Planetary Change* 122:176–185.
Pusalkar PK, Singh DK. 2012. *Flora of Gangotri National Park, Western Himalaya, India*. Kolkata, India: Botanical Survey of India.
Rosbakh S, Romermann MB, Poschlod P. 2014. Elevation matters: Contrasting effects of climate change on the vegetation development at different elevations in the Bavarian. *Alpine Botany* 124:143–154.
Saikia P, Khan ML. 2013. Population structure and regeneration status of *Aquilaria malaccensis* Lam. in homegardens of Upper Assam, northeast India. *Tropical Ecology* 54:1–13.
Samant SS, Joshi HC. 2003. Floristic diversity, community patterns and changes of vegetation in Nanda Devi National Park. *In:* UAFD 2004. *Biodiversity Monitoring Expedition Nanda Devi*. A Report to the Ministry of Environment and Forests, Government of India, Uttaranchal State Forest Department. Dehradun, India: Bishen Singh Mahendra Pal Singh, pp 39–54.
Shankar U. 2001. A case of high tree diversity in a Sal (*Shorea robusta*)-dominated lowland forest of eastern Himalaya: Floristic composition, regeneration and conservation. *Current Science* 81(7):776–786.
Shannon CE, Weaver W. 1949. *The Mathematical Theory of Communication*. Urbana, IL: University of Illinois Press.
Sharma CM, Mishra AK, Krishan R, Tiwari OP, Rana YS. 2016a. Impact of climate on structure and composition of ridgetop forests in Garhwal Himalaya. *Taiwania* 61(2):61–69.
Sharma CM, Mishra AK, Krishan R, Tiwari OP, Rana YS. 2016b. Variation in vegetation composition, biomass production and carbon storage in ridgetop forests of high mountains of Garhwal Himalaya. *Journal of Sustainable Forestry* 35(2):119–132.
Sharma CM, Mishra AK, Prakash O, Dimri S, Baluni P. 2014. Assessment of forest structure and woody plant regeneration on ridge tops at Upper Bhagirathi Basin in Garhwal Himalaya. *Tropical Plant Research* 1:62–71.
Sharma CM, Mishra AK, Tiwari OP, Krishan R, Rana YS. 2017. Effect of altitudinal gradients on forest structure and composition on ridge tops in Garhwal Himalaya. *Energy Ecology and Environment* 2(6):404–417.
Sharma CM, Suyal S, Gairola S, Ghildiyal SK. 2009. Species richness and diversity along an altitudinal gradient in moist temperate forest of Garhwal Himalaya. *Journal of American Science* 5:119–128.
Sharma CM, Tiwari OP, Rana YS, Krishan R, Mishra AK. 2016. Plant diversity, tree regeneration, biomass production and carbon storage in different oak forests on ridge tops of Garhwal Himalaya. *Journal of Forest and Environmental Science* 32(4):329–343.
Sharma CM, Tiwari OP, Rana YS, Krishan R, Mishra AK. 2018. Elevational behaviour on dominance–diversity, regeneration, biomass and carbon storage in ridge forests of Garhwal Himalaya, India. *Forest Ecology and Management* 424:105–120.
Simpson EH. 1949. Measurement of diversity. *Nature* 163:688.
Singh Y, Kaushal A. 2006. Extraction of geomorphological features using radarsat data. *Journal of the Indian Society of Remote Sensing* 34:300–307.
Singhal RM, Soni S. 1989. Quantitative ecological analysis of some woody species of Mussoorie Himalayas (U.P.). *Indian Forester* 115:327–337.
Slik JWF, Kebler PJA, Van Welzen PC. 2003. *Macaranga* and *Mallotus* species (Euphorbiaceae) as indicators for disturbance in the mixed lowland dipterocarp forest of east Kalimantan (Indonesia). *Ecological Indicators* 2:311–324.
Vetaas OR. 2000. The effect of environmental factors on the regeneration of *Quercus semecarpifolia* Sm. in Central Himalaya, Nepal. *Plant Ecology* 146:137–144.
Vieira DLM, Scariot A. 2006. Principles of natural regeneration of tropical dry forests for restoration. *Restoration Ecology* 14:11–20.
Wale HA, Bekele T, Dalle G. 2012. Floristic diversity, regeneration status, and vegetation structure of woodlands in Metema Area, Amhara National Regional State, North western Ethiopia. *Journal of Forestry Research* 23(3):391–398.
Ward GA, Smith TJ, Whelan KRT, Doyle TW. 2006. Regional processes in mangrove ecosystems: spatial scaling relationships, biomass, and turnover rates following catastrophic disturbance. *Hydrobiologia* 569:517–527.
Woodward FI, Kelly CK. 2008. Responses of global plant diversity capacity to changes in carbon dioxide concentration and climate. *Ecology Letters* 11:1229–1237.

Supplemental material

TABLE S1 Species regeneration at different elevations—data for individual species.

Found at DOI: 10.1659/MRD-JOURNAL-D-15-00076.S1 (131 KB PDF).