**Supporting Information.** Rana, S. K., K. Gross, and T. D. Price. Drivers of elevational richness peaks, evaluated for trees in the east Himalaya. *Ecology.* 2018.

## Appendix S1

**Figures S1–S13**



**Tables S1–S5**

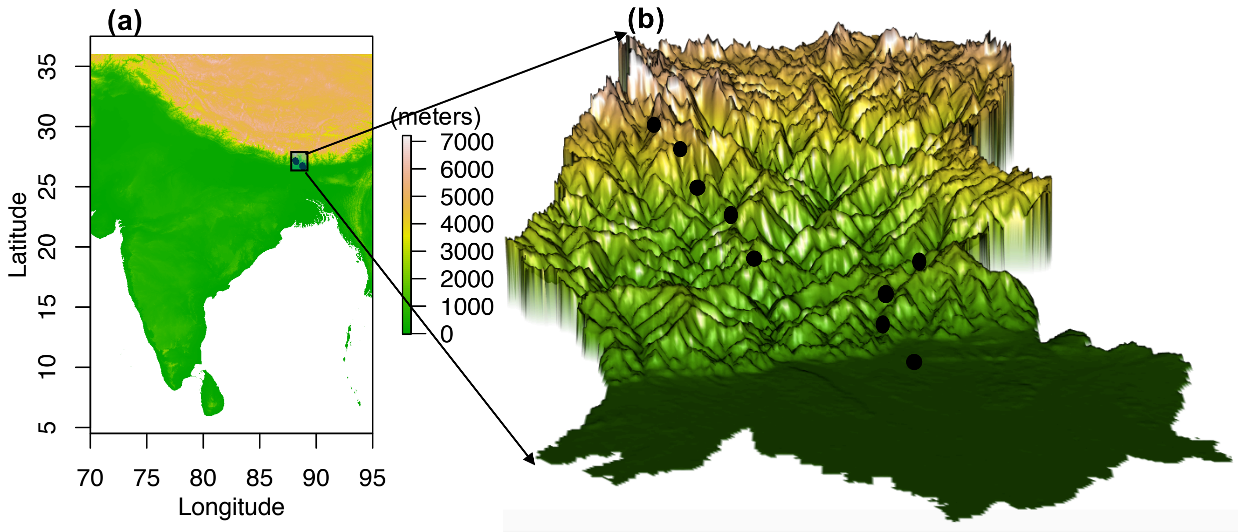



Fig. S1 Map of the study area showing (a) a digital elevation model of India with the location of sampling sites and (b) an enlarged 3D plot of study area spanning 9 sampling elevation zones in the eastern Himalaya (from Jarvis et al. 2008; www.cgiar-csi.org). The figure covers the whole of Sikkim and the two northern districts of West Bengal for which the information on elevational distribution of trees is presented in this paper.

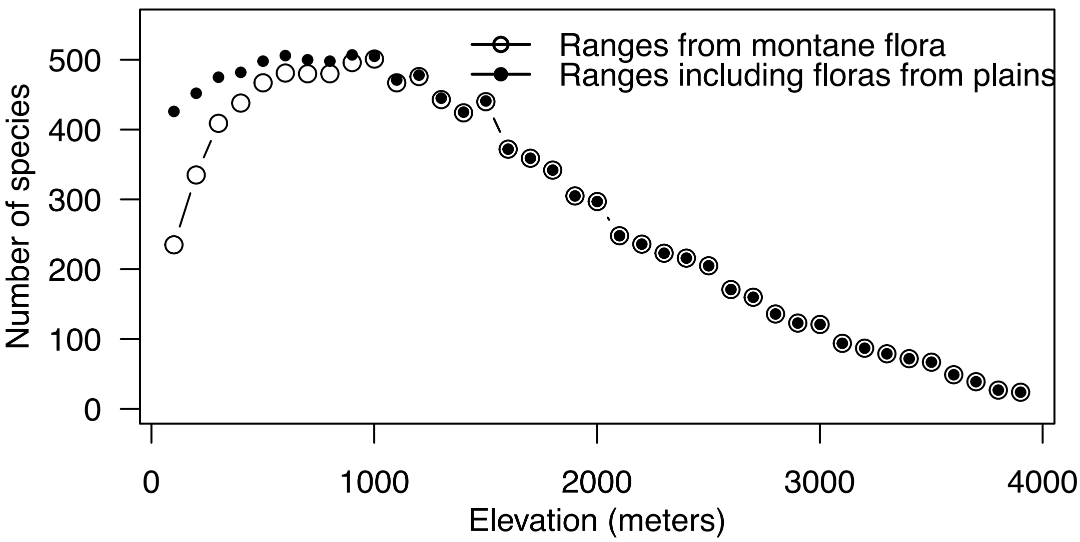



Fig. S2 Comparison of tree species richness along the elevational gradient in eastern Himalaya obtained by interpolation of elevational ranges from local mountain floras and reassigned ranges to species ascending from plains but missing in local floras. The curve shows a significant increase of species number in the foothills after reassigning elevational ranges.

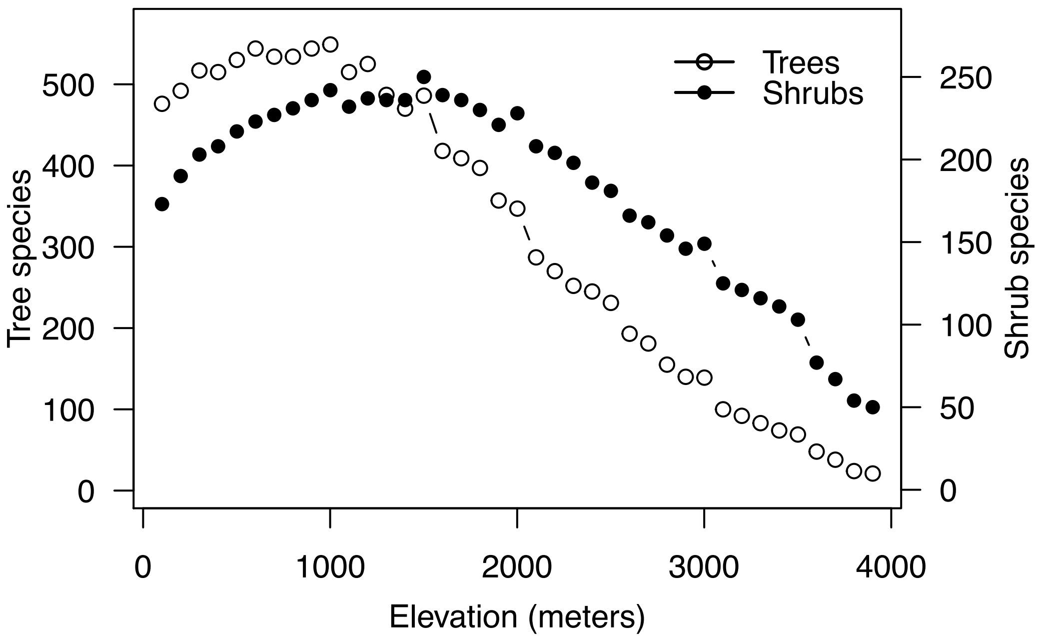



Fig. S3 Comparison of elevational species richness of trees and shrubs in eastern Himalaya based on range interpolation from the secondary literature.

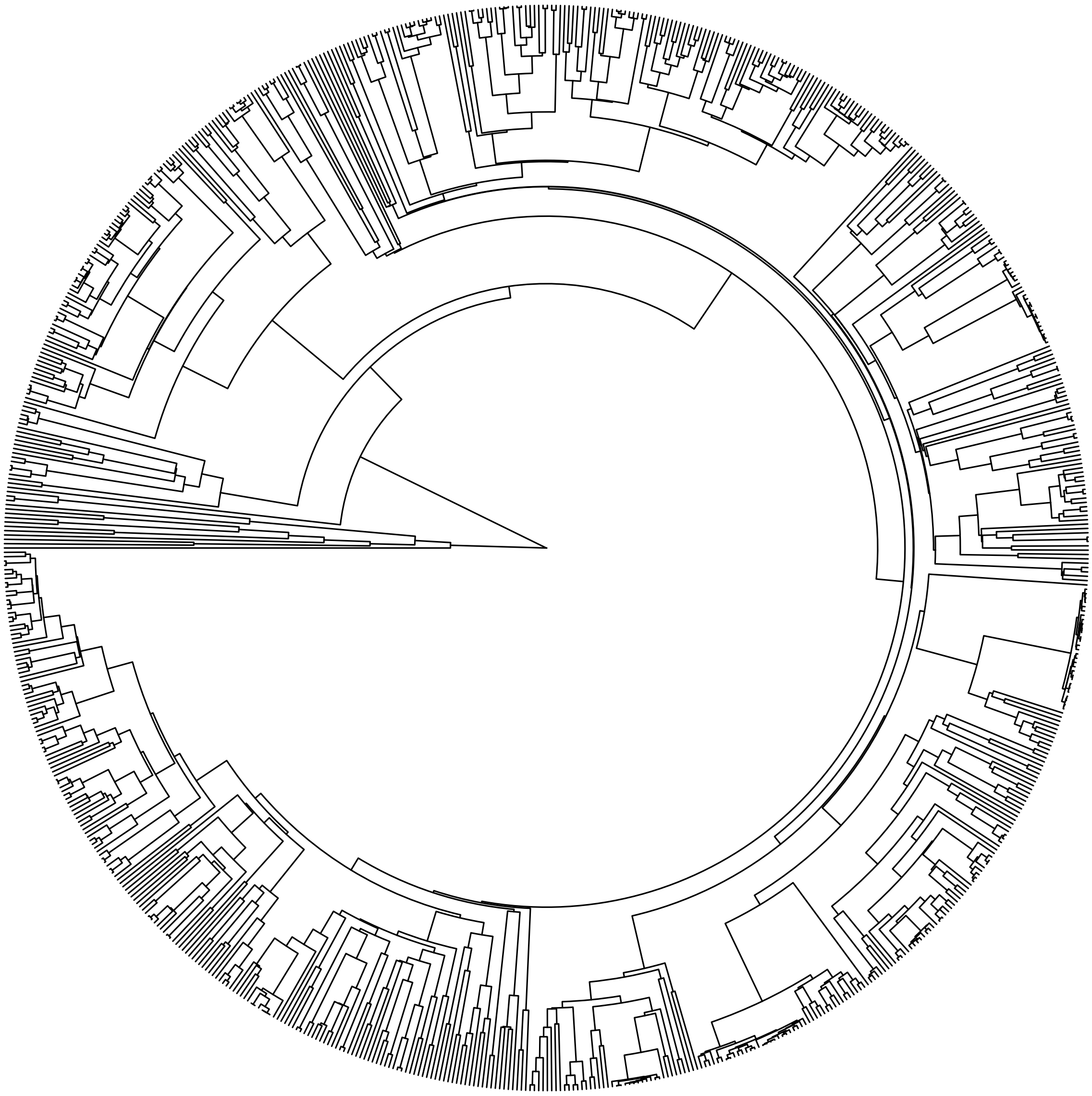
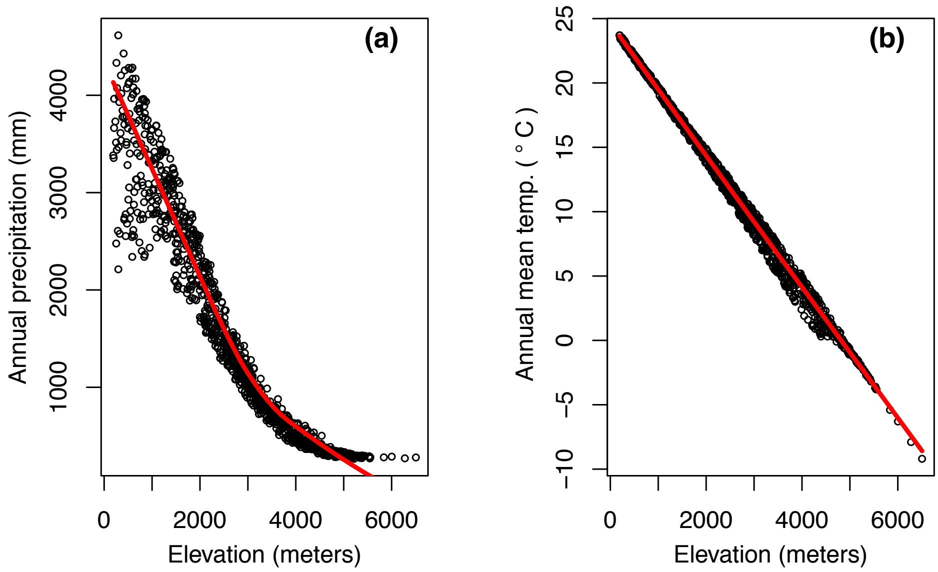
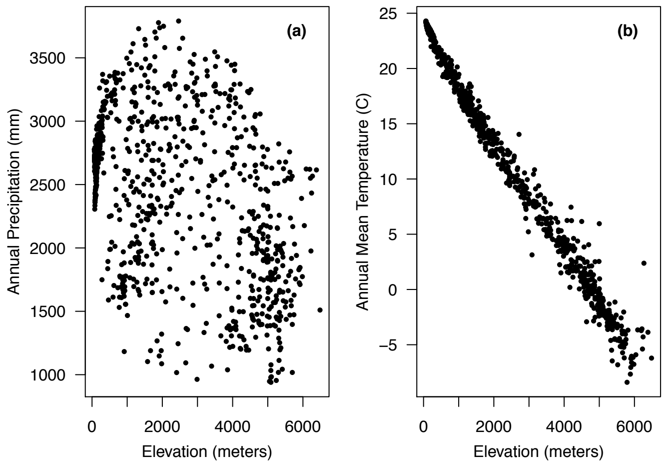
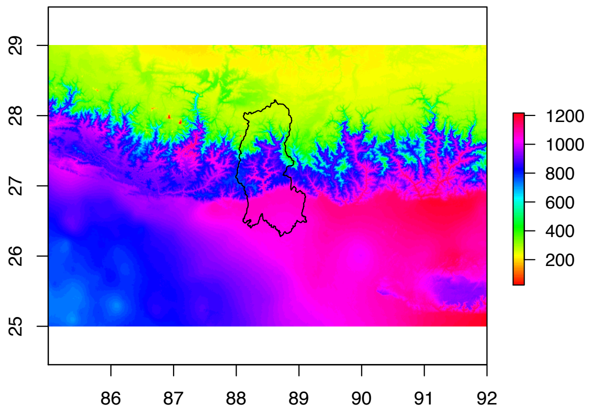


Fig. S4 Phylogeny for east Himalayan tree species obtained by using “S.PhyloMaker” function by Qian and Jin (2016) with resolved polytomies using the polytomy resolver function of Kuhn et al. (2011).


(a)
Annual precipitation (mm)
1000
2000
3000
4000
0
2000
4000
6000
Elevation (meters)
(b)
Annual mean temp. ( ° C )
−10
−5
0
5
10
15
20
25
0
2000
4000
6000
Elevation (meters)


(a)
Annual Precipitation (mm)
1000
1500
2000
2500
3000
3500
0
2000
4000
6000
Elevation (meters)
(b)
Annual Mean Temperature (C)
−5
0
5
10
15
20
25
0
2000
4000
6000
Elevation (meters)


25
26
27
28
29
86
87
88
89
90
91
92
1200
1000
800
600
400
200

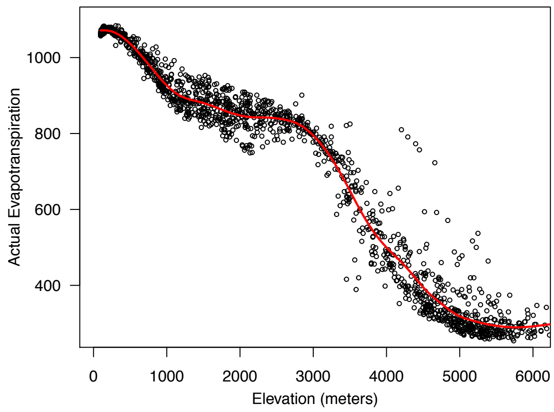

Actual Evapotranspiration
400
600
800
1000
0
1000
2000
3000
4000
5000
6000
Elevation (meters)

Fig. S5. *Above:* pattern of climatic variables along the elevation gradient in the east Himalaya, where 1000 random points spanning the shaded area in Fig. S1a were extracted from digital elevational map (Jarvis et al. 2008) available at http://www.cgiar-csi.org/data. Annual precipitation and annual mean temperature were extracted for these points using sp (Pebesma and Bivand 2005; Bivand et al. 2013) and raster (Hijmans 2016) package in R from the raster available at www.worldclim.org (Hijmans et al. 2005). Red lines are lowess fits. *Middle, Left* Precipitation from Karger et al. (2017) based on 1000 randomly extracted points. This modelled dataset shows a similarly negative correlation (r = -0.45) and no 500m peak to the worldclim data (cf. datasets indicated in the main text), although there is more variation than in the worldclim data. Temperature matches elevation (*Middle* right). *Below* Precipitation map from worldclim (*left*) and AET vs. elevation recast from Fig 1.

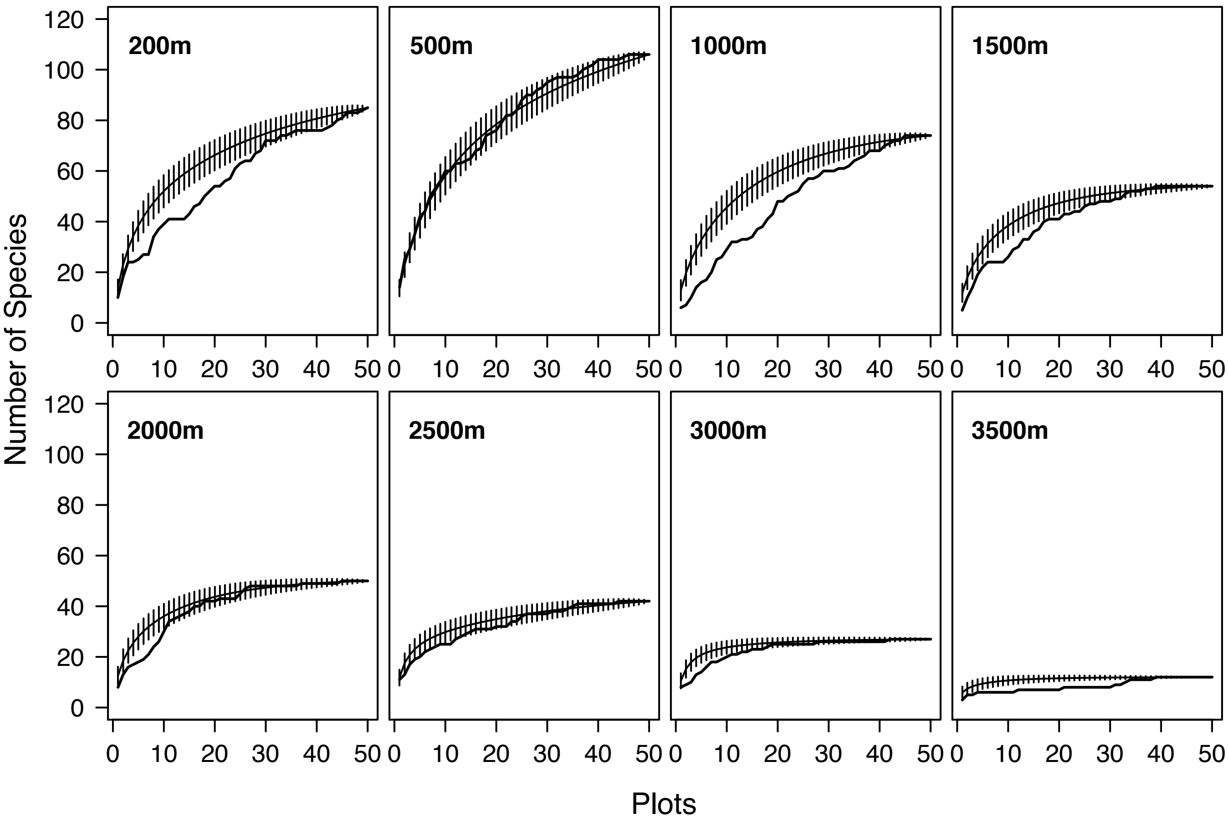



Fig. S6 Tree species collector's curves (dark lines) and rarefaction curves (lines with vertical bars) based on sampling and resampling of 50 plots of 0.1 ha area across eight elevation zones in the eastern Himalaya. The elevation zone at 500m has the steepest rarefaction curve beyond 40 plots implying it is the least well sampled, despite having the most species recorded.

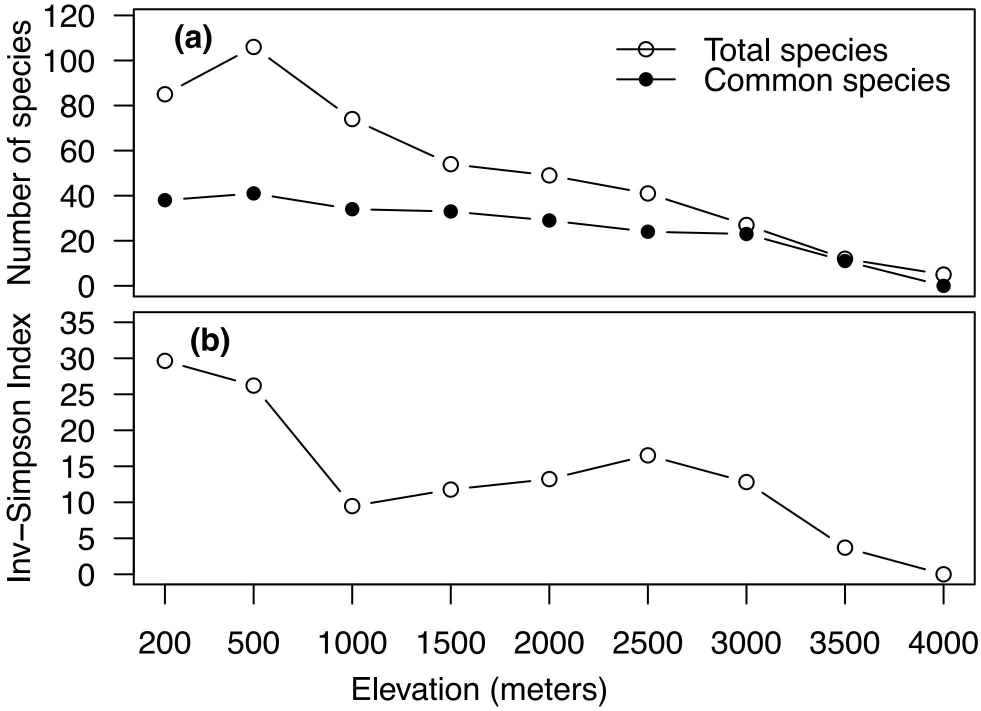



Fig. S7 Abundance patterns. (a) Total number of species shows maximum species richness at 500 m whereas species with more than 4 individuals present in 5 ha show a gradual decline with increasing elevation. (b) As a measure of species diversity we calculated the Inverse-Simpson index ($\lambda = 1/\sum Pi^2$) where P*i* represents the proportion of individuals found in *i*th species, and hence for the same richness is maximized when all species have the same abundance. Both richness and diversity show a steep decline above 500 m, although diversity again increases around 2000 m. At 1000 m and 1500 m diversity is particularly low, which reflects the presence of a few dominants. Indeed, at 1000 m three tree species comprise >40% of all individuals and at 1500 m three tree species comprise >50% of all individuals (Table S4).

More species are at 500 m than at 1000 m in the field samples, and more at 1000 m than 500 m in the literature survey (Fig. 2). One possible explanation for the discrepancy is that exceptionally rare species are unrecorded in field samples, while continuing to appear in the literature surveys up to 1000 m. These results emphasize the importance of field studies that estimate abundance, and the subsequent calculation of diversity indices, to which rare species contribute relatively little. While species richness may indeed plateau between 500 and 1000 m, species diversity shows a strong peak at 500 m.

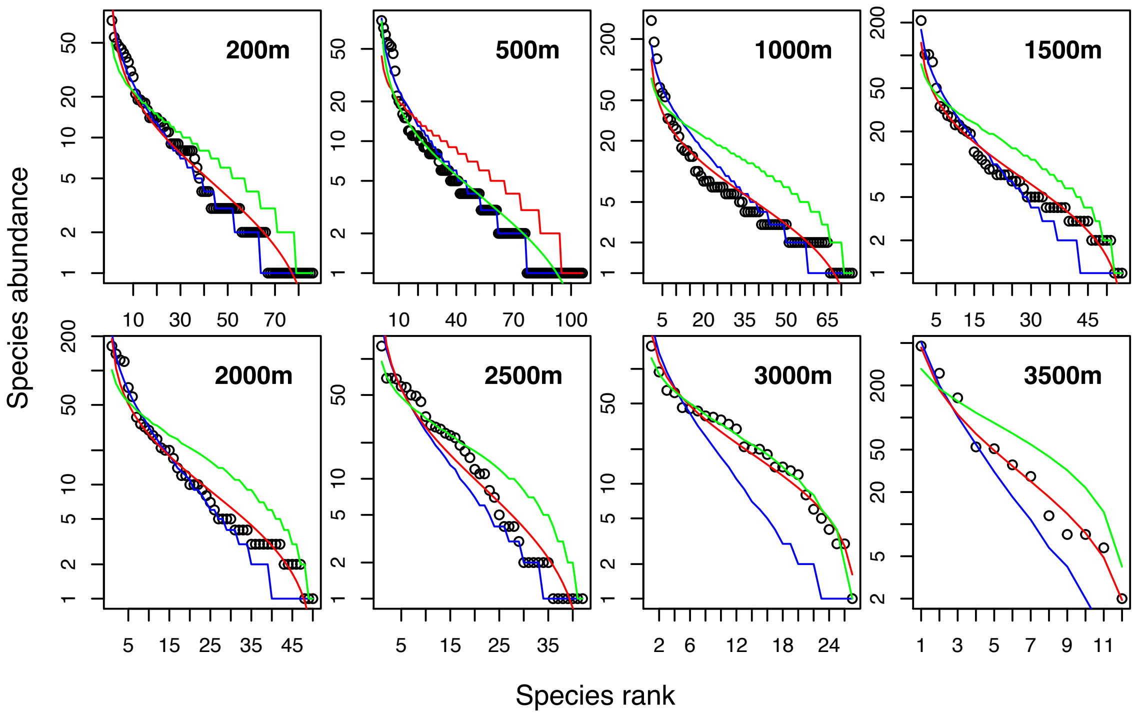



Fig. S8 Various models have been devised to describe species abundance distributions within a community (McGill et al. 2007). We compared log-normal, log-series and geometric distribution models of species abundance with the actual species abundance distribution using the sads package (Prado et al. 2015) in R. The log-series distribution tends to be more applicable when there are many rare species in the community (McGill et al. 2007, Silk et al. 2015). Observed (black), log series (blue), log normal (red), geometric series (green). The comparison of different models shows that species abundance fits to log-normal distribution except at 200 m and 500 m where the log series is the best fit (consistent with the presence of many rare species) and 3,000m where the geometric distribution model is a marginally better fit than the log normal (Table S5).

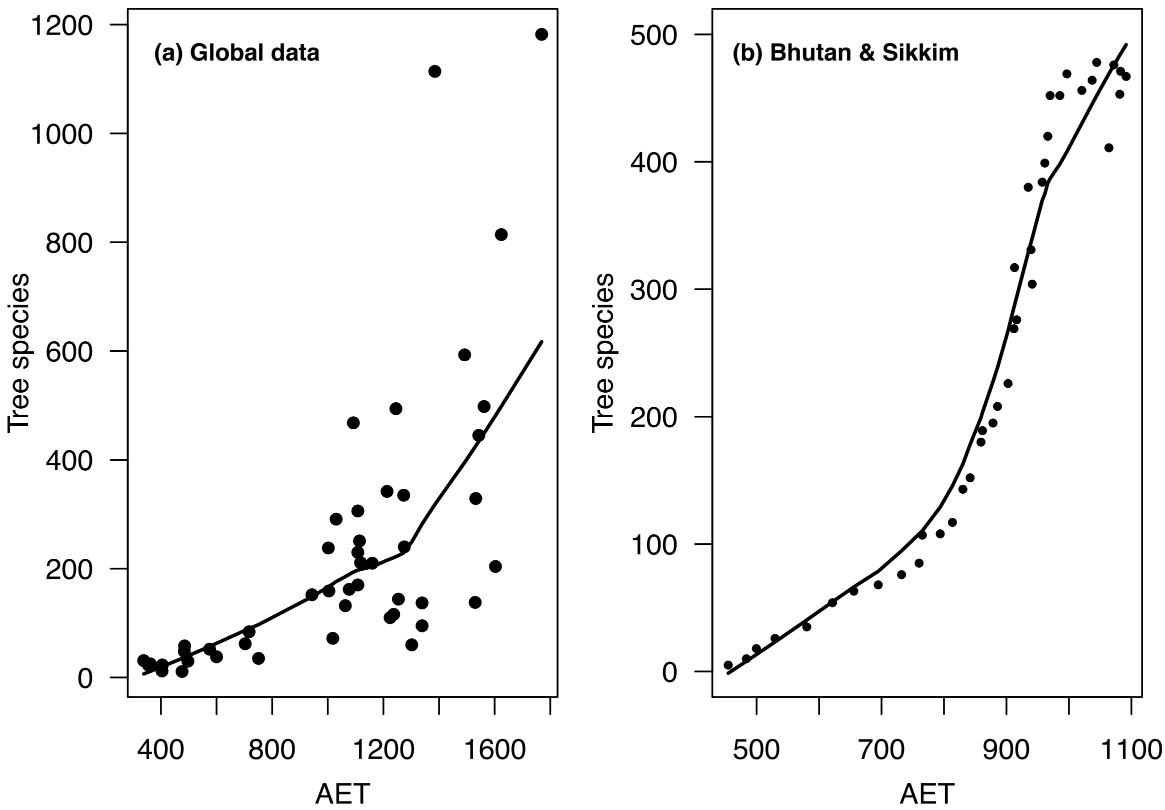



Fig. S9 Tree species richness against AET for (a) the global dataset discussed by Ricklefs and He (2016) and (b) Bhutan, Sikkim and northern Bengal. Both graphs suggest a monotonic increase in richness with AET (for (a) linear fit $P < 1*10^{-6}$, exponential fit $P < 1*10^{-13}$; For (b) linear fit $P < 1*10^{-16}$, exponential fit $P < 1*10^{-16}$). Note that the relationship in (b) at high AET levels may be confounded by the postulated geometric constrain that forms our explanation for the richness peak at 500-1000m.

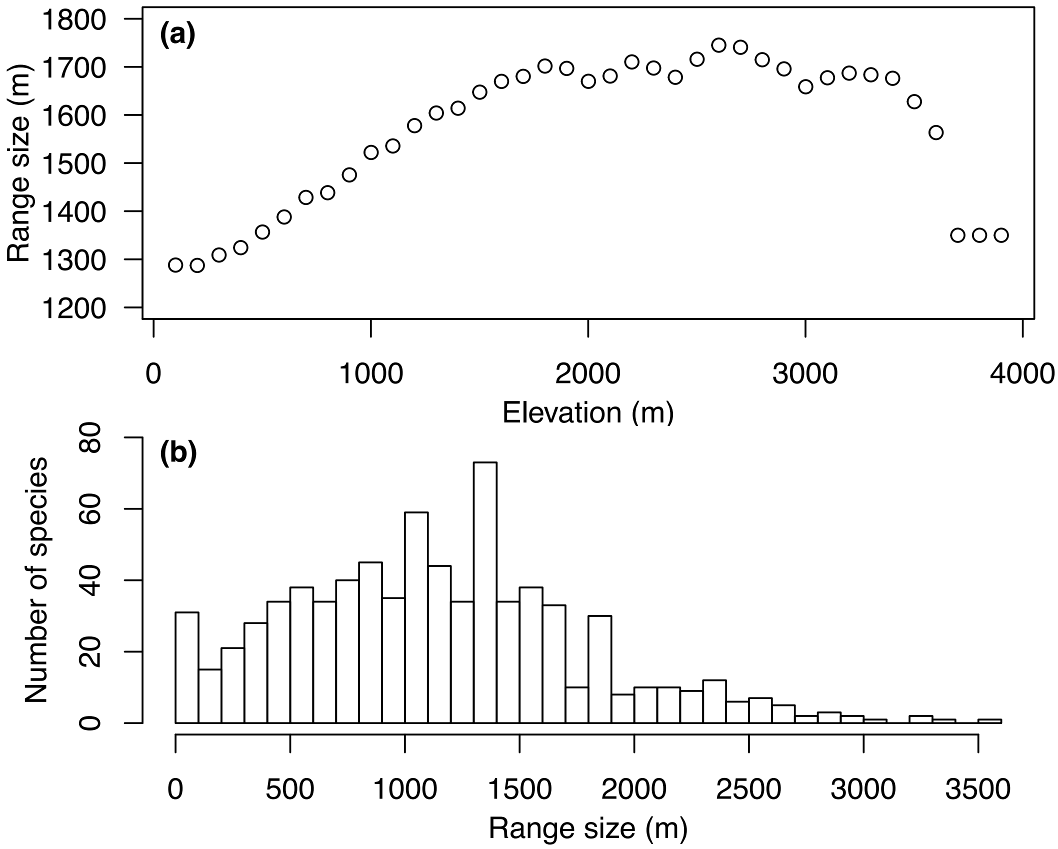



Fig. S10 (a) Average elevational range size of tree species along the elevational gradient of eastern Himalaya. Following Stevens (1992) ranges of all species overlapping every 100m elevation zone are averaged. (b) Distribution of range sizes.

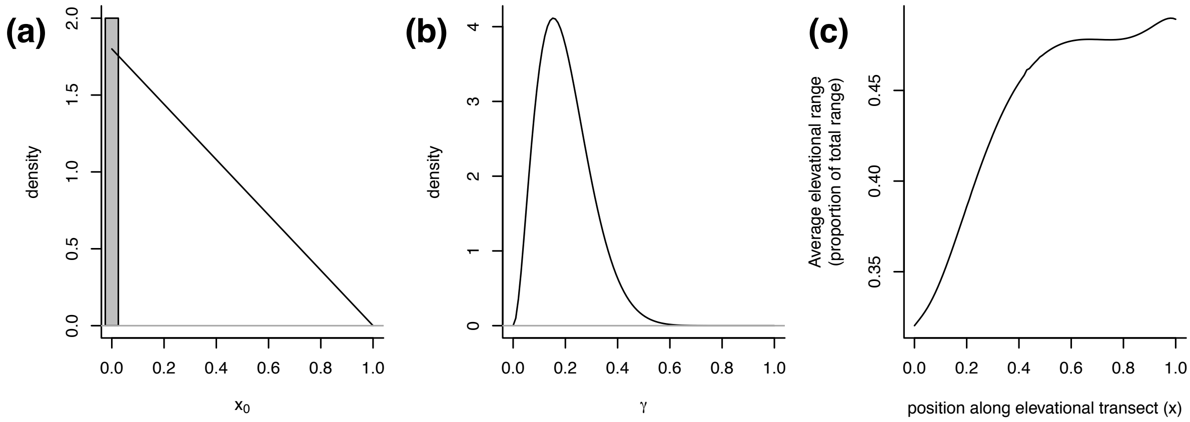



Fig. S11 Model inputs, and predicted relationship between average elevational range and elevation for these inputs. (a) Probability density of $x_0$, species optimal elevations. The additional probability mass at $x_0 = 0$ represents species with an optimal elevation on the neighbouring lowland plains. The probability density of $x_0$ is chosen to align with AET. (b) Probability density of $\gamma$, species elevational tolerances. A species range will extend up to a maximum of $\gamma$ away from its optimal elevation. (c) For these inputs, the model predicts an increasing relationship between the average elevational range (as a proportion of the total range of the elevational transect) and elevation. Plot fashioned after Stevens (1992) and can be compared with Figure S7, which shows the data.

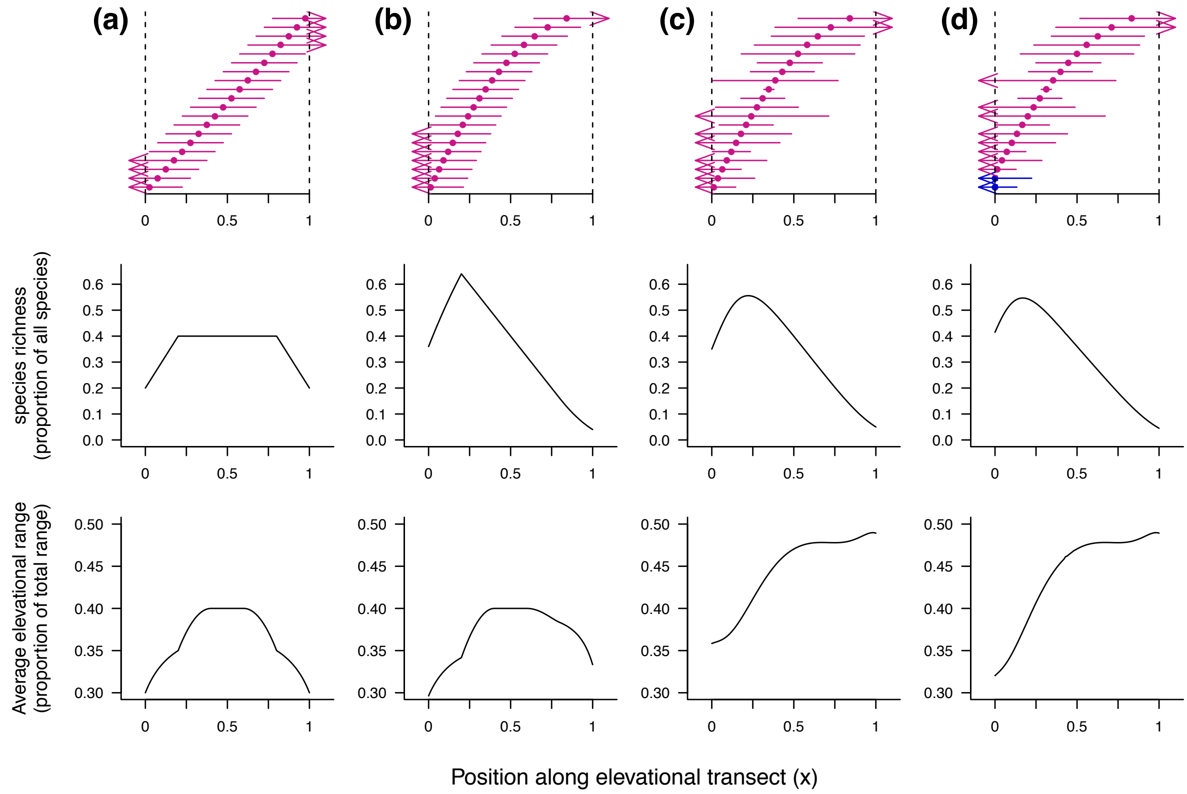



Fig. S12 A graphical explanation for the genesis of a low-elevation diversity peak. Each column of panels shows results for a single set of parameter inputs. Top row: A sample of species ranges. Middle row: Species richness (as a proportion of total species) vs. position on the elevational gradient. Bottom row: Average elevational range vs. position on the elevational gradient. Column (a): Species elevational optima are uniformly distributed across the gradient, and all species have the same environmental tolerance. Species richness and average elevational range decline symmetrically at either edge of the domain. Column (b): as in (a), except that species elevational optima are now more heavily weighted towards low elevations. A greater density of species optima at low elevations shifts the richness peak downwards. Column (c): as in (b), except that species elevational tolerances now vary independently of elevational optima. Variation in elevational tolerance smooths the richness peak, but does not change its location. Species with large elevational tolerances are over-represented throughout the domain, but predominate especially at the high-elevation edge, driving the average elevational range upwards. Column (d): As in (c), but now 10% of species environmental optima occur on the neighbouring lowland plains (ranges shown in blue in the top panel). Encroachment from lowland-plains species increases diversity at low elevations, shifting the diversity peak lower.

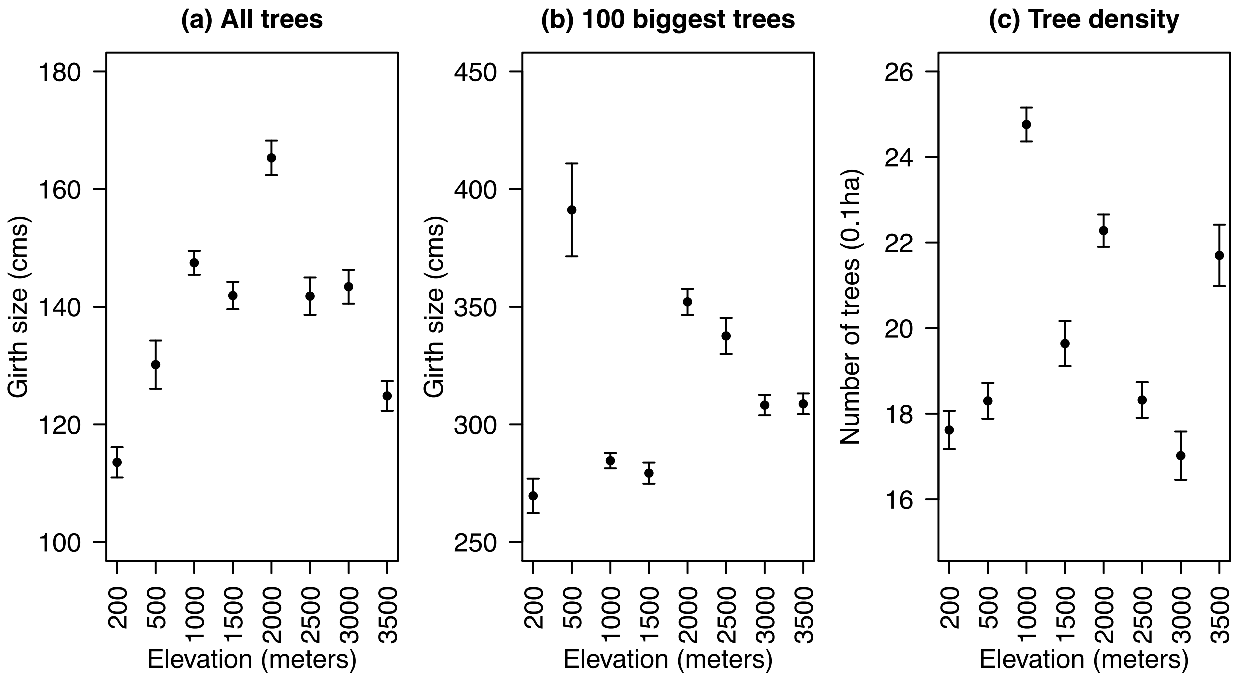



Fig. S13 Mean girth size and tree density along the elevational gradient in eastern Himalaya. Error bars are standard errors, based on 50 0.1 ha plots at each elevation as replicates. (a) Mean girth size of all trees. (b) Mean girth size of the 100 largest trees. (c) Mean tree density. The correlation between mean girth size at an elevation and density i.e. points in (a) and (c) is $r = 0.447$, $N = 8$, $P = 0.2$.

**Supplemental Tables**

Table S1 Summary of studies on plant species richness along elevational gradients in the Himalaya.

| **Life forms and gradient** | **Method** | **Location** | **Species diversity pattern** | **Authors** |
|---|---|---|---|---|
| Plants (100-6000m) | Range interpolation | Nepal | Unimodal peak at 1500-2500m | Grytnes and Vetaas 2002 |
| Plants (250-4250m) | Range interpolation | Nepal | Unimodal peak at 1000m | Carpenter 2005 |
| Plants (100-5000m) | Range interpolation | Nepal | Unimodal peak at 1500-2500m | Veetas and Grytnes, 2002 |
| Plants 1000-5800m | Range interpolation | Bhutan | Unimodal peak at 2000m | Kluge et al. 2017 |
| Plants 300-5300m | Range interpolation | Sikkim | Unimodal peak at 1800m | Manish et al. 2017 |
| Plants (100-5000m) | Range interpolation | Bhutan Jammu & Kashmir | Unimodal peak at 1500m Plateau at 300-2500m. | Rana et al. unpublished |
| Plants (100-1500m) | Field sampling | Nepal | Unimodal peak at 700m | Bhattarai and Vetaas 2003 |
| Trees (200-2200m) | Field sampling | Arunachal Pradesh | Unimodal peak at 600-1000m | Behera and Kushwaha 2007 |
| Trees (300-4700m) | Field sampling | Sikkim | Unimodal peak at 1500m | Acharya et al. 2011 |
| Trees (100-4300m) | Range interpolation | Nepal | Unimodal peak at 1000m | Bhattarai and Vetaas 2006 |
| Woody flora (100-5000) | Range interpolation<br>Field sampling (interpolated) | West Himalaya<br>Kedarnath Sanctuary | Unimodal peak at 1500-2000m<br>Unimodal peak at 2000m | Oommen and Shanker 2005 |
| Woody flora (500-4800m) | Range interpolation | Kashmir | Unimodal peak at 2000m | Khuroo et al. 2011 |

| | | | | |
|---|---|---|---|---|
| Orchids (100-5200m) | Range interpolation | Sikkim | Unimodal peak at 1500m | Acharya et al. 2011 |
| Ferns (100-4800m) | Range interpolation | Nepal | Unimodal peak at 2000m | Bhattarai et al. 2004 |
| Bryophytes<br>Ferns<br>(100-5500m) | Range interpolation | Nepal | Unimodal peak at 2700m<br>Unimodal peak at 2000m | Grau *et al*. 2007 |

Table S2 Elevational sites for field sampling of trees and observed species information in eastern Himalaya (see also Fig. 1).

| Elevation (meters) | Name of location | GPS location | Species sampled | Species in literature | Total Individuals | Average basal area ± sd ($m^2$/tree) |
|---|---|---|---|---|---|---|
| 200 | Chapramari WLS | N26.88734 E88.83657 | 85 (71*) | 378 | 894 (1208*) | 0.15 ± 0.25 (0.13 ± 0.22)* |
| 500 | Sakam NVNP | N27.00246 E88.75963 | 106 | 454 | 921 | 0.26 ± 0.81 |
| 1000 | Mauchuki NVNP | N27.01520 E88.78887 | 74 | 467 | 1235 | 0.21 ± 0.19 |
| 1500 | Yuksum KNP | N27.36482 E88.21449 | 54 | 402 | 982 | 0.20 ± 0.20 |
| 2000 | Bhotekharka NVNP | N27.06260 E88.76993 | 49 (38*) | 265 | 1114 (1648*) | 0.29 ± 0.32 (0.14 ± 0.24)* |
| 2500 | Bakhim KNP | N27.42680 E88.18485 | 41 | 191 | 916 | 0.23 ± 0.33 |
| 3000 | Tshoka KNP | N27.43449 E88.18157 | 27 | 116 | 851 | 0.22 ± 0.25 |
| 3500 | Fidong KNP | N27.44888 E88.17840 | 12 | 62 | 1085 | 0.18 ± 0.24 |
| 4000 | Dzongri KNP | N27.47429 E88.16088 | 5 | 40 | --- | |

GPS locations are of the first plot at each elevation. WLS: Wildlife Sanctuary, NVNP: Neora Valley National Park, KNP: Khangchendzonga National Park. *shows the number of individuals and species encountered in single 5 ha grid at these two elevations.

Table S3 Top five commonest tree species (top dominant) at different elevation zones in eastern Himalaya.

| Elevation (meters) | Commonest species in decreasing order of abundance |
|---|---|
| 200 | *Syzygium cumini* (8.17%)*, Terminalia bellirica* (6.15%)*, Schima wallichii* (5.59%)*, Shorea robusta* (5.26%)*, Aphanamixis polystachya* (5.1%). |
| 500 | *Syzygium claviflorum* (8.9%)*, Ailanthus integrifolia* (7.8%)*, Crateva unicularis* (6.9%)*, Magnolia pterocarpa* (6.1%), *Pterospermum acerifolium* (5.9%). |
| 1000 | *Schima wallichii* (24.6%), *Ostodes paniculata* (15.4%), *Terminalia myriocarpa* (10.4%), *Acer hookeri* (5.4%), *Duabanga grandiflora* (4.8%). |
| 1500 | *Schima wallichii* (21.3%), *Engelhardia spicata* (10.4%), *Alnus nepalensis* (10.4%), *Ficus racemosa* (8.9%), *Ostodes paniculata* (5.1%). |
| 2000 | *Litsea glutinosa* (14.7%)*, Machilus duthiei* (12.7%)*, Quercus lamellosa* (11.1%)*, Symplocos lucida* (10.8%)*, Acer campbellii* (6.4%). |
| 2500 | *Lithocarpus pachyphyllus* (14%)*, Litsea glutinosa* (7.5%)*, Symplocos lucida* (7.5%)*, Prunus nepalensis* (7.4%)*, Machilus duthiei* (6.4%). |
| 3000 | *Tsuga dumosa* (18.6%)*, Rhododendron arboream* (11.1%)*, Rhododendron wightii* (7.6%)*, Prunus nepalensis* (7.3%)*, Betula utilis* (5.4%). |
| 3500 | *Rhododendron hodgsonii* (43.1%)*, Abies densa* (24%)*, Betula utilis* (14.1%)*, Viburnum nervosum* (4.9%)*, Rhododendron arboream* (4.7%). |

Table S4 Pearson's correlations between various metrics of trees along the elevational gradient in eastern Himalaya (N = 8 elevations).

| | No of species | Diversity | No. of individuals |
|---|---|---|---|
| Diversity (Inv. Simpson) | 0.77* | | |
| Number of individuals | -0.06 | -0.58 | |
| Mean basal area | 0.10 | -0.04 | 0.15 |

*P < 0.05

Table S5 Akaike's information criterion values between the tree species abundance distribution models at different elevations in eastern Himalaya.

| Elevation and model | Delta AIC | DF |
|---|---|---|
| **200 m** | | |
| **Log series** | **0** | 1 |
| Log normal | 14.5 | 2 |
| Geometric series | 28.8 | 1 |
| **500 m** | | |
| **Log series** | **0** | 1 |
| Log normal | 17.0 | 2 |
| Geometric series | 54.6 | 1 |
| **1000 m** | | |
| Log series | 1.0 | 1 |
| **Log normal** | **0** | 2 |
| Geometric series | 65.7 | 1 |
| **1500 m** | | |
| Log series | 8.3 | 1 |
| **Log normal** | **0** | 2 |
| Geometric series | 24.4 | 1 |
| **2000 m** | | |
| Log series | 2.4 | 1 |
| **Log normal** | **0** | 2 |
| Geometric series | 21.0 | 1 |
| **2500 m** | | |
| **Log series** | **0** | 1 |
| Log normal | 8.8 | 2 |
| Geometric series | 12.6 | 1 |
| **3000 m** | | |
| Log series | 15.7 | 1 |
| Log normal | 4.0 | 2 |
| **Geometric series** | **0** | 1 |
| **3500 m** | | |
| Log series | 1.2 | 1 |
| **Log normal** | **0** | 2 |
| Geometric series | 3.7 | 1 |

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