Supplement of Biogeosciences, 23, 4999–5018, 2026
https://doi.org/10.5194/bg-23-4999-2026-supplement

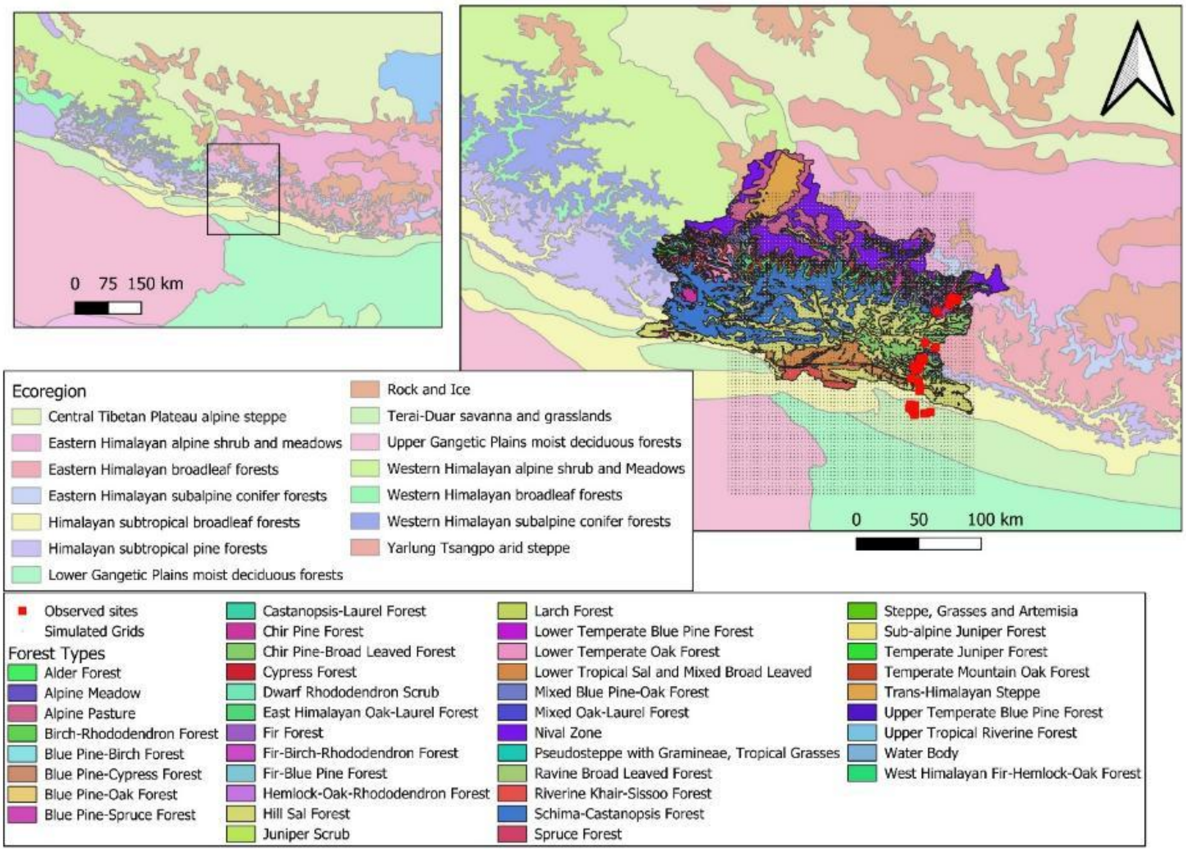
Biogeosciences
Open Access

Supplement of

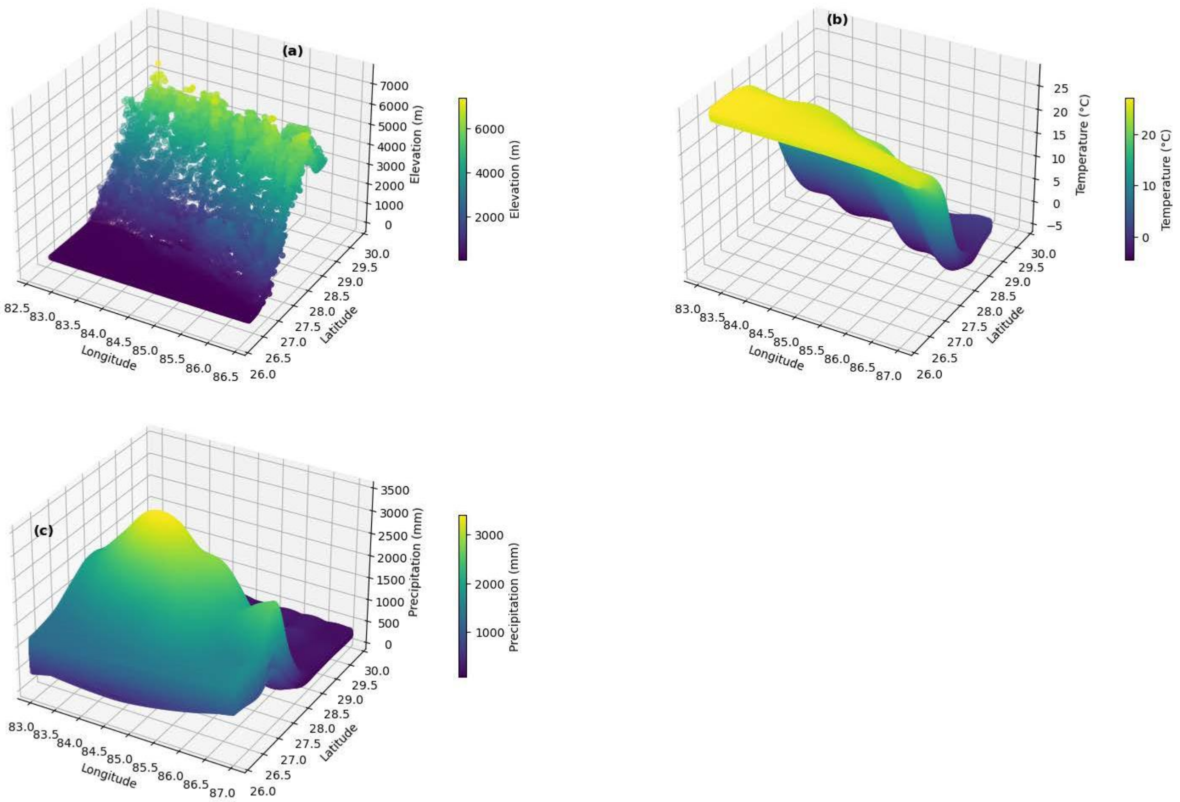
Vegetation patterns and competitive dynamics along elevation gradients: interactions between environmental factors and vegetation in the Central Himalayas

Prashant Paudel et al.

Correspondence to: Benjamin Smith (ben.smith@nateko.lu.se)



Supplementary Figure S1: Spatial distribution of forest area (by Land Resource Mapping Project, 1986) with ecoregion (from Olson et al., 2001) along the elevation gradient of the Himalayas.



Supplementary Figure S2: Patterns of environmental variables along the elevation gradient of the Himalayas. The graph indicates patterns along the studied (grid used for simulation) area of the Himalayan elevational gradient. With an increase in elevation, temperature (a) decreases, whereas precipitation (c) increases up to 2000m elevation and then decreases. (data source: elevation (Earth Resources Observation and Science (EROS) Center, 2000); Temperature and precipitation (CRU-JRA) (Araghi and Martinez, 2024).

Pokhrel and Sherpa (2020) reported that 165 tress species (National Forest Inventory, 2010-2014) are recorded in the study area in this gradient. Maharjan et al. (2020) stated that 31 species are most abundant in the gradient based on the frequency of observation and total carbon contribution. The 31 most dominant species were used for defining PFTs, which are representative of all traits and plant strategies recorded along the gradient. Phenological and morphological characteristics (Traits strategies) of dominant species representing all traits strategies were compiled from various sources. Both phonological and morphological characteristics of were used for clustering species. A hierarchical clustering process was used to group species into clusters based on similarity in plant dominant locality, plant traits, and strategies, with species progressively divided into functionally different groups. The process involves stratification by temperature zone followed by statistical clustering. Initially, species were grouped into climatic regions (Jackson, 1994; Thakur and Phulara, 2014). There were four temperature-defined groups: tropical, subtropical, temperate, and alpine. Subsequently, within these temperature strata, statistical hierarchical clustering, namely Ward's method (Murtagh & Legendre, 2014), was applied to trait data (e.g., SLA, wood density, leaf phenology, leaf longevity) to group species into functionally similar clusters. This analysis resulted in 13 distinct clusters with three PFTs represented in the coniferous group.

In this study, wood density values for all PFTs represent mean values averaged across multiple species rather than species-specific maxima or mature-wood measurements. These PFT averages were compiled from several sources (Maharjan et al., 2021; Thakur and Phulara, 2014; Amatya, Shrestha, and Cedamon, 2016), which include a wide range of growth forms, growth locations, and successional stages. As a result, the aggregated PFT-level values represent community-level means, which are consistent with the trait-averaging approach of the modelling framework. During simulation, wood density some PFTs was adjusted manually via iterative tuning to ensure consistency with model allometric relationships and other structural traits (e.g., height, leaf mass per area). These adjusted values preserve the typical structural characteristics of each PFT and wood density was within the range of observed values while allowing realistic growth, turnover, and competitive dynamics in the simulations.

Supplementary Table S1: Himalayan gradient Tree PFTs, their parameters, and parameter values used for simulations.

A. Alpine Group

Parameters and	Alpine Broadleaved Evergreen (BBE)	Alpine Needleleaved Evergreen (BNE)
Represented Species	*Rhododendron arboreum v1, Rhododendron barbatum, Rhododendron campanulatum, Rhododendron arboreum, Rhododendron arboreum var. cinnamomeum*	*Abies spectabilis, Juniperus recurva*
Leaf Phenology	Broadleaved	Needleleaved
Bioclimatic limit	Boreal tcmin_surv -21 tcmin_est -16 tcmax_est 3 twmin_est 5	Boreal tcmin_surv -31 tcmin_est -30 tcmax_est 3 twmin_est - 1000 ! no limited
Leaf Deciduousness	Evergreen	Evergreen
Shade tolerance	Intolerant	Tolerant
Drought tolerance	Sensitive	Sensitive
Wood density (kgC/m^3)	273	280
SLA (m^2/kgC)	13	9
Leaf Longevity (Years)	2	3
Leaf Turnover (fraction/year)	0.5	0.33
DBH-Height	h1 12 20 33.09 h2 0.67 0.53 0.48	h1 13.6 30.68 46.45 h2 0.59 0.55 0.51
DBH-crown radios	r1 8.42 5.90 3.94 r2 0.55 0.60 0.63	r1 6.67 4.75 3.60 r2 0.51 0.65 0.85
DBH-Crown Volume	v1 1400 850 425 * v2 1.05 1.16 1.36 *	v1 1210 700 550 v2 1.20 1.23 1.26

B. Temperate group

Parameters	Temperate broadleaved Shade-tolerant summer green (TeBSG)	Temperate Broadleaved evergreen (TeIBE)	Temperate broadleaved evergreen tree (TeBEt)	Temperate Needleleaved
Represented Species	*Lyonia ovlifolia, Betula utilis*	*Quercus lamellosa, Quercus lanata, Quercus semecarpifolia*	*Myrica esculenta Buch.,Eurya acum,inata DC.Pieris formosa*	*Pinus wallichiana, Tsuga dumosa*
Leaf phenology	Broadleaved	Broadleaved	Broadleaved	Needleleaved
Bioclimatic limit	Temperate tcmin_surv -1	Temperate tcmin_surv -10	Temperate tcmin_surv -10	Temperate tcmin_surv -10

Parameters	Temperate broadleaved Shade-tolerant summer green (TeBSG)	Temperate Broadleaved evergreen (TeIBE)	Temperate broadleaved evergreen tree (TeBEt)	Temperate Needleleaved
	tcmin_est 0 tcmax_est 18.8 twmin_est 5	tcmin_est 0 tcmax_est 18.8 twmin_est 5	tcmin_est 0 tcmax_est 18.8 twmin_est 10	tcmin_est -2 tcmax_est 10 twmin_est 5
Leaf Deciduousness	Summergreen	Evergreen	Evergreen	Evergreen
Shade tolerance	Intolerant	Intolerant	Tolerant	Intolerant
Drought tolerance	-	Resistant	-	-
Wood density (kgC/m³)	265	282	281	235
SLA (m²/kgC)	18	15	15	18
Leaf Longevity (Years)	0.5	2	2	3
Leaf Turnover (fraction/year)	1	0.5	0.5	0.33
DBH-Height	h1 16.42 26 40 h2 0.63 0.46 0.43	h1 22 29 41 h2 0.70 0.64 0.55	h1 10 24 35 ! h2 0.55 0.50 0.45 !	h1 30 35 55 ! h2 0.65 0.62 0.57 !
DBH-crown radios	r1 6.42 5.85 4.59 r2 0.45 0.56 0.61	r1 10.80 8.16 4.20 r2 0.54 0.58 0.65	r1 6.16 3.71 2.50 r2 0.53 0.63 0.69	r1 8.50 6.30 4.42 r2 0.53 0.63 0.75
DBH-Crown Volume	v1 1400 850 425 * v2 1.05 1.16 1.36 *	v1 1580 665 360 v2 1.20 1.25 1.34	v1 1400 850 425 * v2 1.05 1.16 1.36 *	v1 850 490 380 v2 1.13 1.25 1.51

C. Subtropical Group

Parameters and	Sub-tropical Needleleaved (StrNE)	Sub-tropical broadleaved evergreen intermediate shade tolerant (STrIBE)	Sub-tropical broadleaved evergreen (STrBE)	Subtropical broadleaved Rain green (StrRG)
Represented Species	*Pinus roxburghii*	*Schima wallichii*	Ficus and other fodder species	*Alnus nepalensis*
Leaf phenology	Needle leaved	Boeadleaved	Broad leaved	broadleaved
Bioclimatic limit	Sub-tropical tcmin_surv 8.0 tcmin_est 8.0 tcmax_est 1000 ! no limit twmin_est -1000 ! no limit	Sub-tropical tcmin_surv 8.0 tcmin_est 8.0 tcmax_est 1000 ! no limit twmin_est -1000 ! no limit	Sub-tropical tcmin_surv 8.0 tcmin_est 8.0 tcmax_est 1000 ! no limit twmin_est -1000 ! no limit	Sub-tropical tcmin_surv 8.0 tcmin_est 8.0 tcmax_est 1000 ! no limit twmin_est -1000 ! no limit
Leaf Deciduousness	Evergreen	Evergreen	Evergreen	Raingreen
Shade tolerance	Intolerant	Intermediate tolerant	Tolerant	Intolerant
Drought tolerance	Resistant	-	-	sensitive
Wood density (kgC/m³)	210	265	145	200
SLA (m²/kgC)	10	20.85	17	25
Leaf Longevity (Years)	3	1	1	0.5
Leaf Turnover (fraction/year)	0.33	1	1	1
DBH-Height	h1 25 35 60 h2 0.71 0.64 0.60	h1 17 28 40 h2 0.66 0.63 0.58	h1 9.81 20.81 40 h2 0.72 0.63 0.61	h1 12.50 20 40.85 h2 0.75 0.56 0.53
DBH-crown radios	r1 9.00 6.50 4.41	r1 8.92 6.25 2.96	r1 12.26 6.41 2.96	r1 7.56 6.04 3.51

Parameters and	Sub-tropical Needleleaved (StrNE)	Sub-tropical broadleaved evergreen intermediate shade tolerant (STrIBE)	Sub-tropical broadleaved evergreen (STrBE)	Subtropical broadleaved Rain green (StrRG)
	r2 0.55 0.60 0.71	r2 0.64 0.67 0.71	r2 0.67 0.73 0.77	r2 0.54 0.59 0.69
DBH-Crown Volume	v1 860 495 380 v2 1.15 1.30 1.51	v1 1180 700 450 v2 1.08 1.0 1.20	v1 1400 850 425 * v2 1.05 1.16 1.36 *	v1 1400 850 425 * v2 1.05 1.16 1.36 *

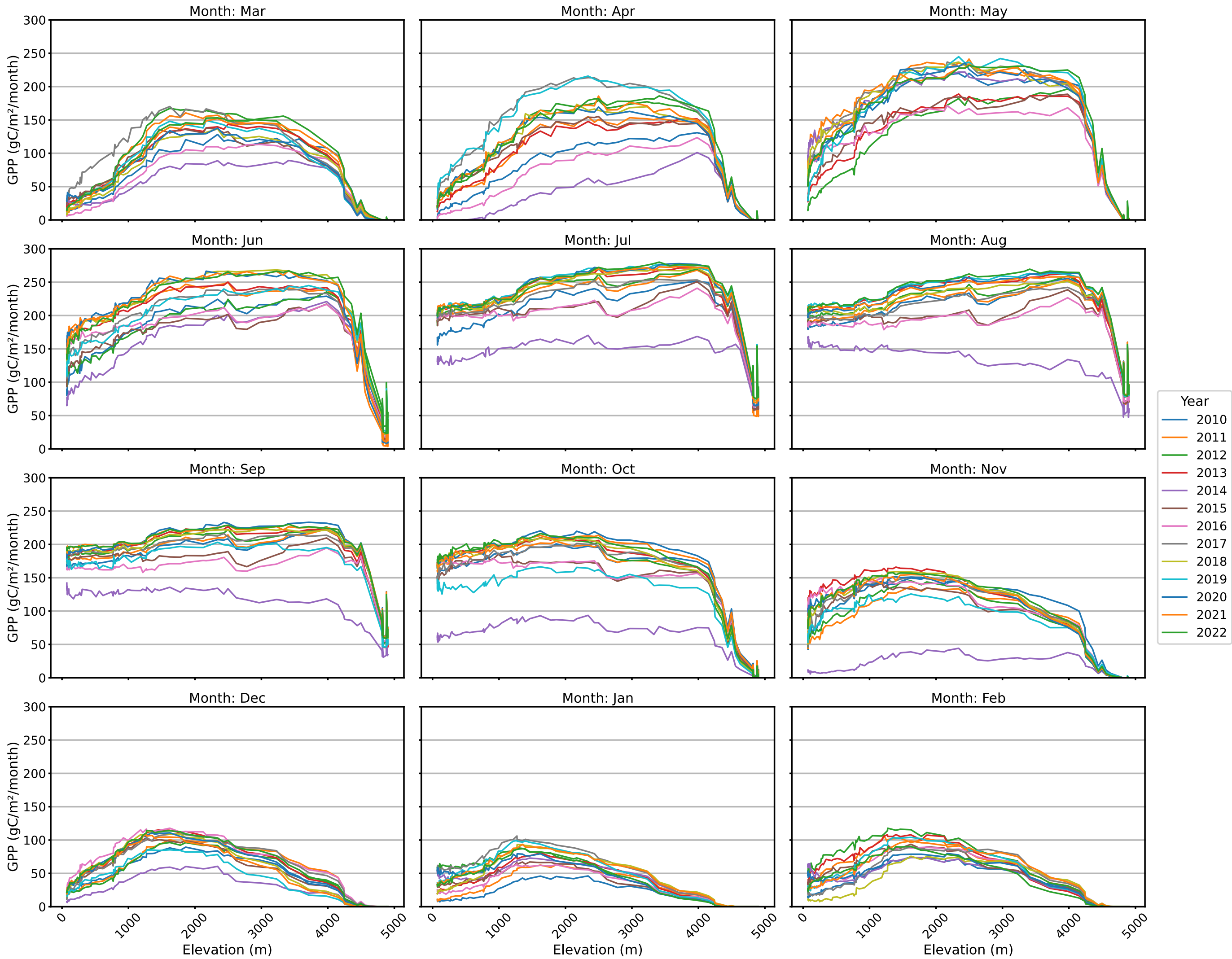
D. Tropical group

Parameters and	Tropical Broadleved Summer green (TrBRG)	Tropical Boradleaved Evergreen (TrBE)	Tropical Boradleaved Summer Green (TrBSG)
Represented Species	*Shorea robusta, Terminalia alata*	*M_philippensis, Syzygium cumini, Largerstomia_parviflora*	*Dalbergia latifoila, Aegle Marmelos; Bombax ceiba, Dalbergia Sisoo, Haldina cordifolia*
Leaf phenology	Broad leaved	Broad leaved	Broad leaved
Bioclimatic limit	Tropical tcmin_surv 13.5 tcmin_est 12.5 tcmax_est 1000 ! no limit twmin_est -1000 ! no limit	Tropical tcmin_surv 13.5 tcmin_est 12.5 tcmax_est 1000 ! no limit twmin_est -1000 ! no limit	Tropical tcmin_surv 13.5 tcmin_est 12.5 tcmax_est 1000 ! no limit twmin_est -1000 ! no limit
Leaf Deciduousness	Rain green	Evergeen	Summer green
Shade tolerance	Intolerant	Tolerant	Intolerant
Drought tolerance	Resistant	Resistant	Resistant
Wood density (kgC/m^3)	250	290	247
SLA (m^2/kgC)	18	22	21
Leaf Longevity (Years)	1	2	0.5
Leaf Turnover (fraction/year)	1	0.5	1
DBH-Height	h1 32 50 70 h2 0.66 0.63 0.58	h1 15 25 45 h2 0.66 0.63 0.58	h1 20 30 40 h2 0.63 0.57 0.53 !
DBH-crown radios	r1 8.97 6.28 2.50 r2 0.56 0.66 0.70	r1 8.97 6.28 2.50 r2 0.56 0.66 0.70	r1 8.10 5.01 2.36 r2 0.51 0.61 0.67
DBH-Crown Volume	v1 1430 690 300 v2 1.02 1.05 1.43	v1 1430 690 300 v2 1.02 1.05 1.43	v1 1400 850 425 * v2 1.05 1.16 1.36 *

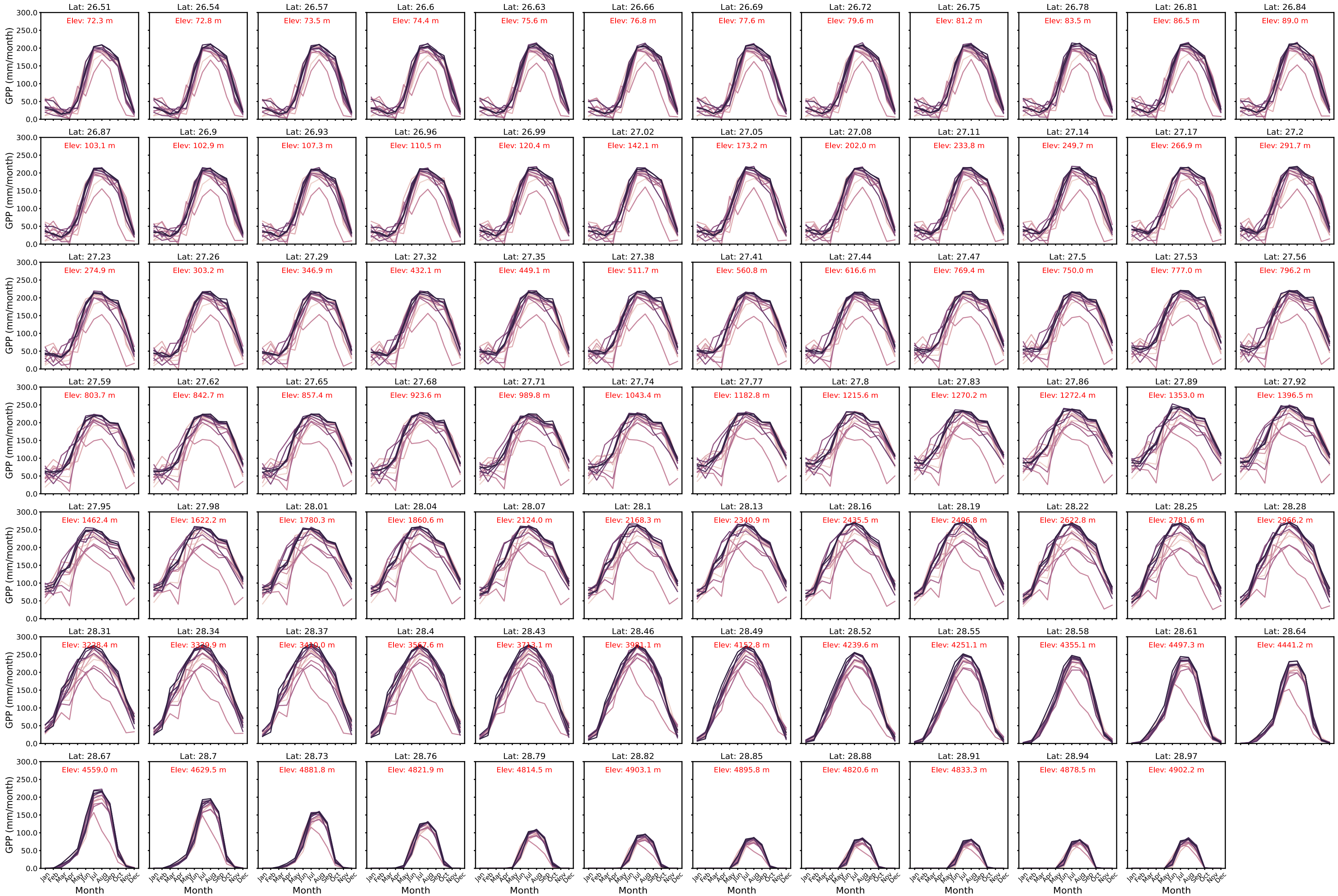
**Parameter values from all PFTs combined.*

Supplementary Table S2: Shade tolerance parameters and their values used for simulation from (Hickler et al., 2004)

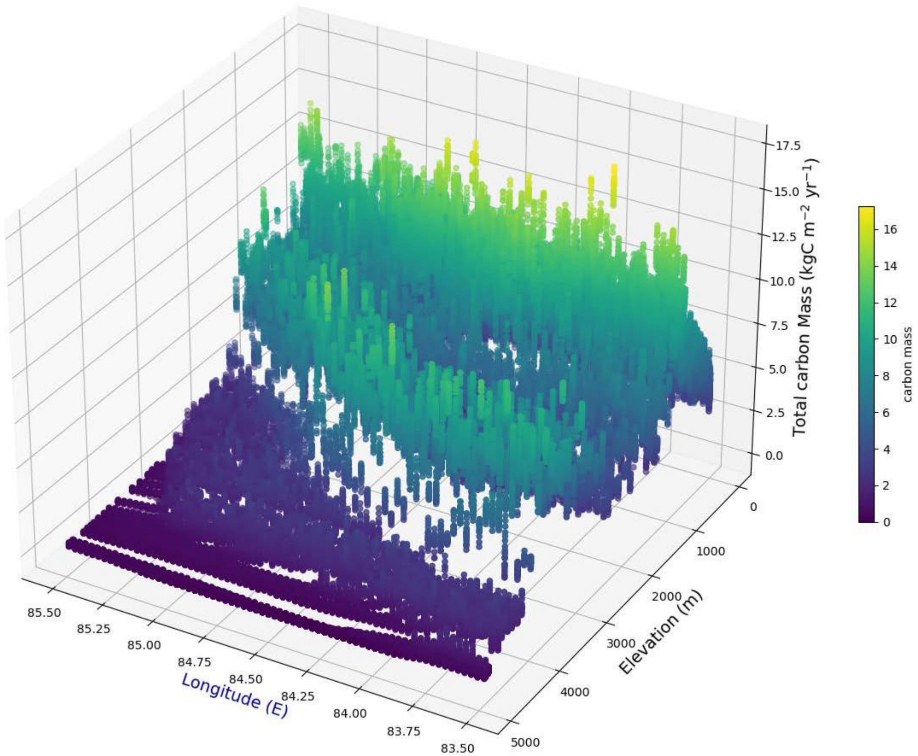
Shade tolerance category	Parameters				
	Min forest floor PAR (J m^{-2} day^{-1})	Shape parameter for recruitment	Threshold for growth suppression mortality (kgC m^{-2} leaf yr^{-1})	Sapwood turnover (fraction/year)	Max sapling establishment rate (individual m^{-2} $year^{-1}$)
Tolerant	35000	2.0	0.03	0.05	0.05
Intermediate tolerant	200000	7.0	0.05	0.075	0.1
Intolerant	250000	11.0	0.1	0.1	0.2



Supplementary Figure S3: Simulated GPP by months along the elevation gradient from 2010 to 2022. The figure indicates that the growth seasons start with March and June, and July and August have maximum productivity. Productivity is higher at the end of the gradient, becoming almost zero in the winter months (Nov-Feb).



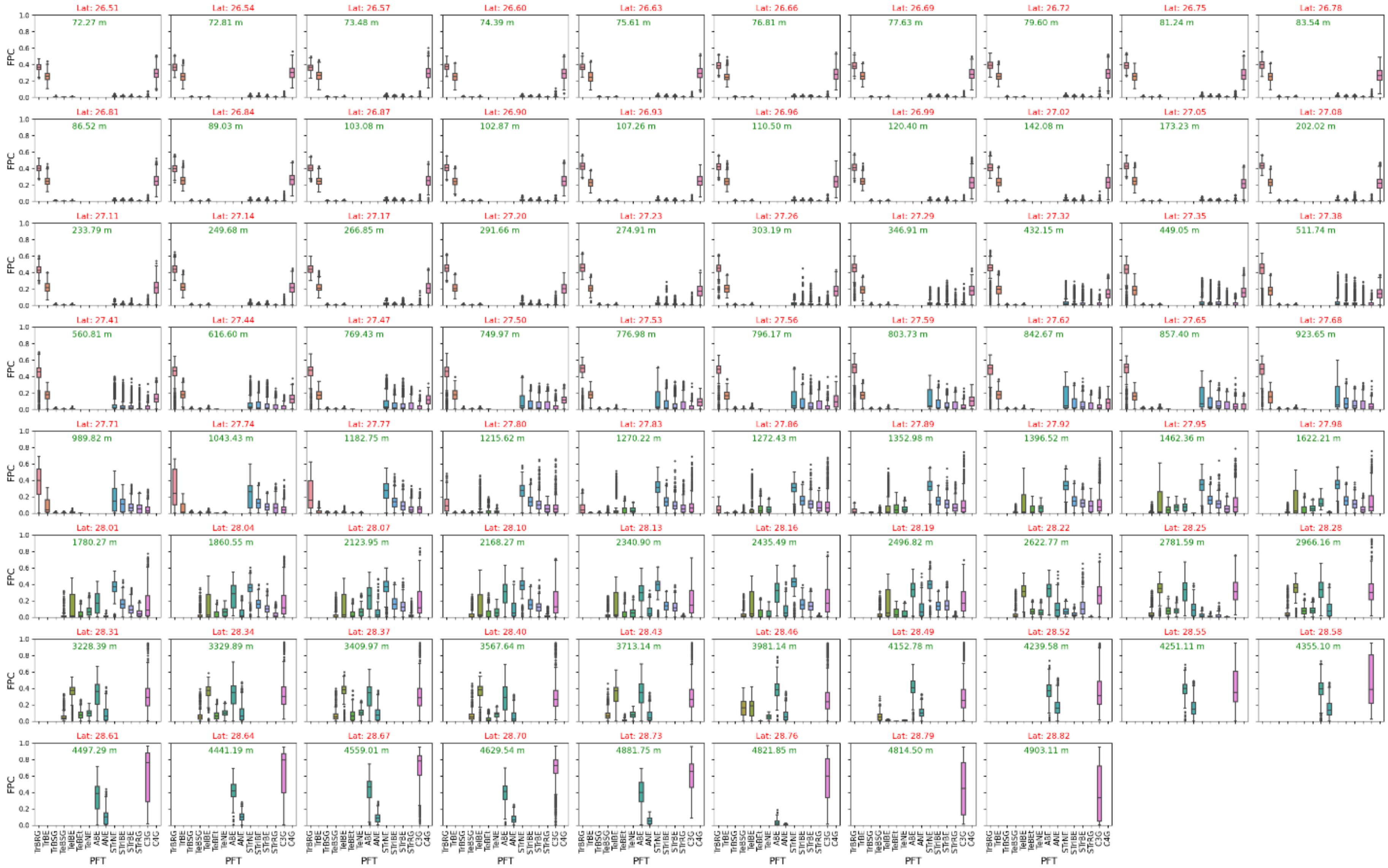
Supplementary Figure S4: Simulated monthly GPP along the simulated latitudinal grid showing variability in productivity (narrow and sharp peaks suggest a short growing season, whereas a flat peak suggests a wider growing season). In lower elevations, the growth period is wider, and productivity is higher compared to higher elevations.



Supplementary Figure S5. Simulated total Carbon mass production (ecosystem level) along the elevation gradient. It shows that carbon mass production clearly follows temperature patterns. Some fluctuation in total carbon mass production along the elevation gradient resembles the landscape, where the higher Himalayas, the lesser Himalayas, and the Siwalik range create differences in growth conditions, including valleys and river gorges.

Figure (Supplementary Figure S6) shows the spatial distribution of FPC for all simulated PFTs along the elevation gradient, which shows clear turnover in vegetation composition with elevation. It also indicates that both environmental filtering and interspecific interactions (patterns and elevation range of dominance) are shaping the distribution of PFTs. The shift in dominant PFTs across the gradient reflects strong niche differentiation and abiotic filtering driven by decreasing temperature. For example, at lower elevations, the landscape is dominated by tropical broadleaved raingreen (TrBRG) and temperate deciduous (TeBSG) PFTs, which exhibit high PFC values, while at mid to higher elevations, temperate needle-leaved evergreen (TeNE) and subalpine PFTs (e.g., ABE and BBE) become increasingly dominant.

In terms of vegetation composition within the simulated grids, the difference in the relative abundance of PFTs indicates varying degrees of dominance and competitive interactions. At the lower end of the gradient, only a few PFTs dominate in FPC (Supplementary Figure S6), resulting in low evenness (Figure 9) and indicating strong competitive exclusion. In contrast, toward the upper end of the gradient, although only a limited number of cold-adapted PFTs persist (Supplementary Figure S6) - due to temperature conditions - their relative contributions to FPC are similar, resulting in higher evenness (Figure 9). This pattern suggests that under increasingly harsh conditions, environmental filtering reduces the total number of species able to survive, but competitive asymmetries decrease, resulting in a more even distribution.



Supplementary Figure S6: PFTs composition and distribution in terms of FPC along the simulated latitude with mean elevation ranges across simulated longitude.

References

Araghi, A. and Martinez, C. J.: Evaluation of CRU-JRA gridded meteorological dataset for modeling of wheat production systems in Iran, Int. J. Biometeorol., 68, 1201–1211, https://doi.org/10.1007/s00484-024-02659-9, 2024.

Earth Resources Observation and Science (EROS) Center: Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global, https://doi.org/10.5066/F7PR7TFT, 2000.

Hickler, T., Smith, B., Sykes, M. T., Davis, M. B., Sugita, S., and Walker, K.: USING A GENERALIZED VEGETATION MODEL TO SIMULATE VEGETATION DYNAMICS IN NORTHEASTERN USA, Ecology, 85, 519–530, https://doi.org/10.1890/02-0344, 2004.

Land Resource Mapping Project: Land Resource Mapping Project, Land systems maps and reports (scale 1:50,000), His Majesty's Government of Nepal, Kathmandu, 1986.

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P., and Kassem, K. R.: Terrestrial Ecoregions of the World: A New Map of Life on Earth, BioScience, 51, 933, https://doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2, 2001.