

Supplementary materials for

# Vegetation Patterns and Competitive Dynamics along Elevation Gradients: Interactions between Environmental Factors and Vegetation in the Central Himalayas

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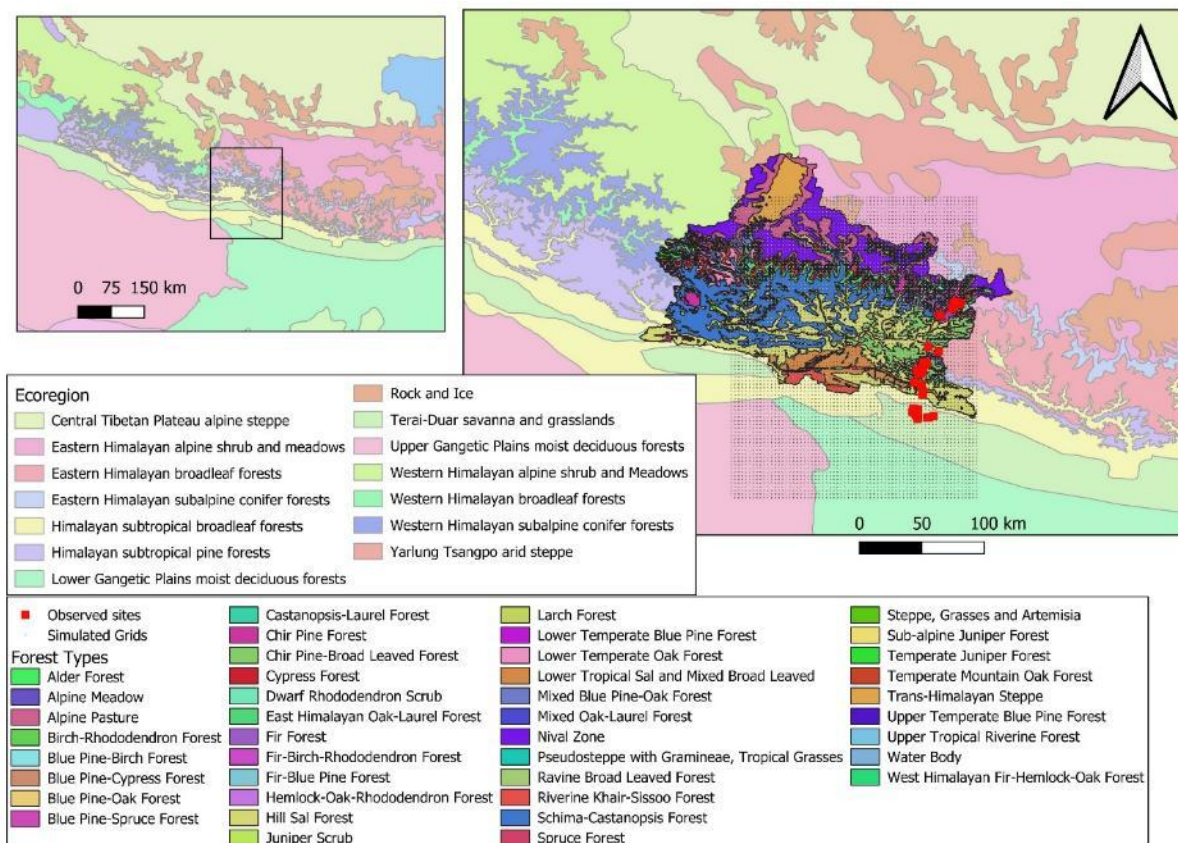
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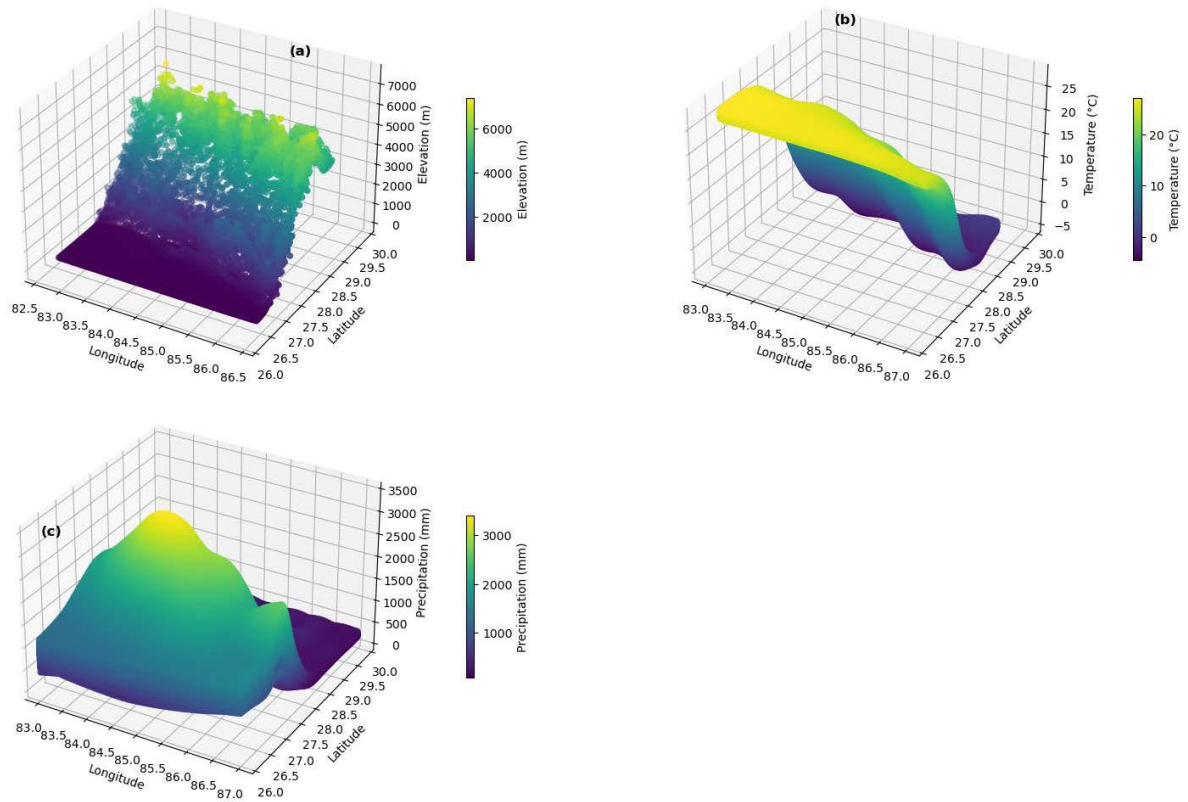
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Supplementary Figure S1: Spatial distribution of forest area (by Land Resource Mapping Project, 1986) with ecoregion (from Olson et al., 2001) along the elevation gradient of the Himalayas.



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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 tree 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 phenological and morphological characteristics 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 of 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                | <i>Rhododendron arboreum</i> v1, <i>Rhododendron barbatum</i> ,<br><i>Rhododendron campanulatum</i> , <i>Rhododendron arboreum</i> ,<br><i>Rhododendron arboreum</i> var. <i>cinnamomeum</i> | <i>Abies spectabilis</i> , <i>Juniperus recurva</i>                                       |
| Leaf Phenology                     | Broadleaved                                                                                                                                                                                  | Needleleaved                                                                              |
| Bioclimatic limit                  | Boreal<br>tcmin_surv -21<br>tcmin_est -16<br>tcmax_est 3<br>twmin_est 5                                                                                                                      | Boreal<br>tcmin_surv -31<br>tcmin_est -30<br>tcmax_est 3<br>twmin_est - 1000 ! no limited |
| Leaf Deciduousness                 | Evergreen                                                                                                                                                                                    | Evergreen                                                                                 |
| Shade tolerance                    | Intolerant                                                                                                                                                                                   | Tolerant                                                                                  |
| Drought tolerance                  | Sensitive                                                                                                                                                                                    | Sensitive                                                                                 |
| Wood density (kgC/m <sup>3</sup> ) | 273                                                                                                                                                                                          | 280                                                                                       |
| SLA (m <sup>2</sup> /kgC)          | 13                                                                                                                                                                                           | 9                                                                                         |
| Leaf Longevity (Years)             | 2                                                                                                                                                                                            | 3                                                                                         |
| Leaf Turnover (fraction/year)      | 0.5                                                                                                                                                                                          | 0.33                                                                                      |
| DBH-Height                         | h1 12 20 33.09<br>h2 0.67 0.53 0.48                                                                                                                                                          | h1 13.6 30.68 46.45<br>h2 0.59 0.55 0.51                                                  |
| DBH-crown radios                   | r1 8.42 5.90 3.94<br>r2 0.55 0.60 0.63                                                                                                                                                       | r1 6.67 4.75 3.60<br>r2 0.51 0.65 0.85                                                    |
| DBH-Crown Volume                   | v1 1400 850 425 *<br>v2 1.05 1.16 1.36 *                                                                                                                                                     | v1 1210 700 550<br>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 | <i>Lyonia ovalifolia</i> , <i>Betula utilis</i>           | <i>Quercus lamellosa</i> , <i>Quercus lanata</i> ,<br><i>Quercus semecarpifolia</i> | <i>Myrica esculenta</i> Buch., <i>Eurya acum,inata</i> DC. <i>Pieris formosa</i> | <i>Pinus wallichiana</i> , <i>Tsuga dumosa</i> |
| Leaf phenology      | Broadleaved                                               | Broadleaved                                                                         | Broadleaved                                                                      | Needleleaved                                   |
| Bioclimatic limit   | Temperate<br>tcmin_surv -1                                | Temperate<br>tcmin_surv -10                                                         | Temperate<br>tcmin_surv -10                                                      | Temperate<br>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<br>tcmax_est 18.8<br>twmin_est 5              | tcmin_est 0<br>tcmax_est 18.8<br>twmin_est 5 | tcmin_est 0<br>tcmax_est 18.8<br>twmin_est 10 | tcmin_est -2<br>tcmax_est 10<br>twmin_est 5 |
| Leaf Deciduousness                 | Summergreen                                               | Evergreen                                    | Evergreen                                     | Evergreen                                   |
| Shade tolerance                    | Intolerant                                                | Intolerant                                   | Tolerant                                      | Intolerant                                  |
| Drought tolerance                  | -                                                         | Resistant                                    | -                                             | -                                           |
| Wood density (kgC/m <sup>3</sup> ) | 265                                                       | 282                                          | 281                                           | 235                                         |
| SLA (m <sup>2</sup> /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<br>h2 0.63 0.46 0.43                       | h1 22 29 41<br>h2 0.70 0.64 0.55             | h1 10 24 35 !<br>h2 0.55 0.50 0.45 !          | h1 30 35 55 !<br>h2 0.65 0.62 0.57 !        |
| DBH-crown radios                   | r1 6.42 5.85 4.59<br>r2 0.45 0.56 0.61                    | r1 10.80 8.16 4.20<br>r2 0.54 0.58 0.65      | r1 6.16 3.71 2.50<br>r2 0.53 0.63 0.69        | r1 8.50 6.30 4.42<br>r2 0.53 0.63 0.75      |
| DBH-Crown Volume                   | v1 1400 850 425 *<br>v2 1.05 1.16 1.36 *                  | v1 1580 665 360<br>v2 1.20 1.25 1.34         | v1 1400 850 425 *<br>v2 1.05 1.16 1.36 *      | v1 850 490 380<br>v2 1.13 1.25 1.51         |

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### 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                | <i>Pinus roxburghii</i>                                                                                    | <i>Schima wallichii</i>                                                                                    | Ficus and other fodder species                                                                             | <i>Alnus nepalensis</i>                                                                                    |
| Leaf phenology                     | Needle leaved                                                                                              | Boeadleaved                                                                                                | Broad leaved                                                                                               | broadleaved                                                                                                |
| Bioclimatic limit                  | Sub-tropical<br>tcmin_surv 8.0<br>tcmin_est 8.0<br>tcmax_est 1000 ! no limit<br>twmin_est -1000 ! no limit | Sub-tropical<br>tcmin_surv 8.0<br>tcmin_est 8.0<br>tcmax_est 1000 ! no limit<br>twmin_est -1000 ! no limit | Sub-tropical<br>tcmin_surv 8.0<br>tcmin_est 8.0<br>tcmax_est 1000 ! no limit<br>twmin_est -1000 ! no limit | Sub-tropical<br>tcmin_surv 8.0<br>tcmin_est 8.0<br>tcmax_est 1000 ! no limit<br>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/m <sup>3</sup> ) | 210                                                                                                        | 265                                                                                                        | 145                                                                                                        | 200                                                                                                        |
| SLA (m <sup>2</sup> /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<br>h2 0.71 0.64 0.60                                                                           | h1 17 28 40<br>h2 0.66 0.63 0.58                                                                           | h1 9.81 20.81 40<br>h2 0.72 0.63 0.61                                                                      | h1 12.50 20 40.85<br>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<br>v2 1.15 1.30 1.51 | v1 1180 700 450<br>v2 1.08 1.0 1.20                                     | v1 1400 850 425 *<br>v2 1.05 1.16 1.36 *   | v1 1400 850 425 *<br>v2 1.05 1.16 1.36 *   |

#### D. Tropical group

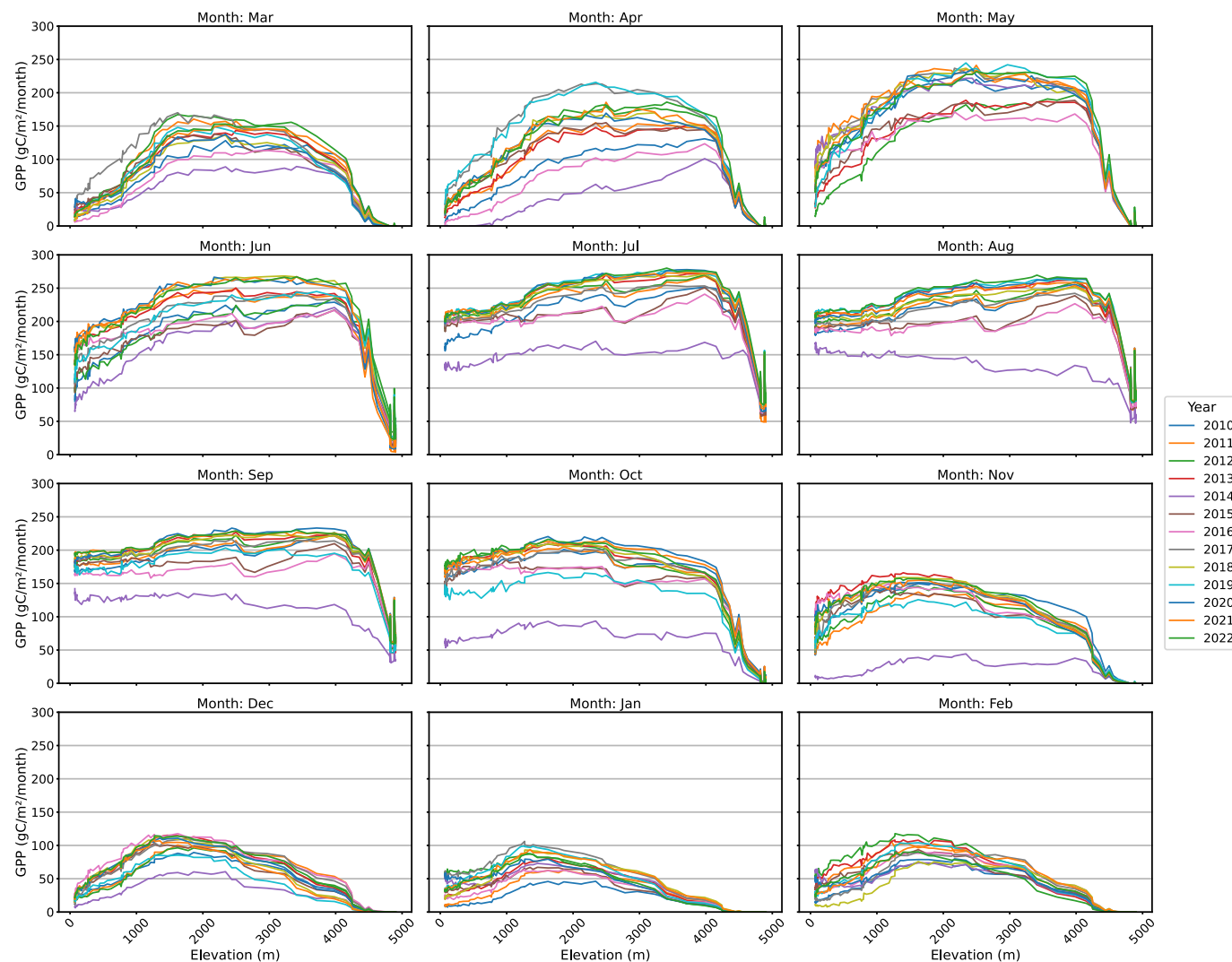
| Parameters and                | Tropical Broadleaved Summer green (TrBRG)                                                                | Tropical Broadleaved Evergreen (TrBE)                                                                    | Tropical Broadleaved Summer Green (TrBSG)                                                                |
|-------------------------------|----------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Represented Species           | <i>Shorea robusta, Terminalia alata</i>                                                                  | <i>M.philippensis, Syzygium cumini, Largerstomia parviflora</i>                                          | <i>Dalbergia latifolia, Aegle Marmelos; Bombax ceiba, Dalbergia Sisoo, Haldina cordifolia</i>            |
| Leaf phenology                | Broad leaved                                                                                             | Broad leaved                                                                                             | Broad leaved                                                                                             |
| Bioclimatic limit             | Tropical<br>tcmin_surv 13.5<br>tcmin_est 12.5<br>tcmax_est 1000 ! no limit<br>twmin_est -1000 ! no limit | Tropical<br>tcmin_surv 13.5<br>tcmin_est 12.5<br>tcmax_est 1000 ! no limit<br>twmin_est -1000 ! no limit | Tropical<br>tcmin_surv 13.5<br>tcmin_est 12.5<br>tcmax_est 1000 ! no limit<br>twmin_est -1000 ! no limit |
| Leaf Deciduousness            | Rain green                                                                                               | Evergreen                                                                                                | Summer green                                                                                             |
| Shade tolerance               | Intolerant                                                                                               | Tolerant                                                                                                 | Intolerant                                                                                               |
| Drought tolerance             | Resistant                                                                                                | Resistant                                                                                                | Resistant                                                                                                |
| Wood density (kgC/m³)         | 250                                                                                                      | 290                                                                                                      | 247                                                                                                      |
| SLA (m²/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<br>h2 0.66 0.63 0.58                                                                         | h1 15 25 45<br>h2 0.66 0.63 0.58                                                                         | h1 20 30 40<br>h2 0.63 0.57 0.53 !                                                                       |
| DBH-crown radius              | r1 8.97 6.28 2.50<br>r2 0.56 0.66 0.70                                                                   | r1 8.97 6.28 2.50<br>r2 0.56 0.66 0.70                                                                   | r1 8.10 5.01 2.36<br>r2 0.51 0.61 0.67                                                                   |
| DBH-Crown Volume              | v1 1430 690 300<br>v2 1.02 1.05 1.43                                                                     | v1 1430 690 300<br>v2 1.02 1.05 1.43                                                                     | v1 1400 850 425 *<br>v2 1.05 1.16 1.36 *                                                                 |

\*Parameter values from all PFTs combined.

16      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 <sup>-2</sup> day <sup>-1</sup> ) | Shape parameter for recruitment | Threshold for growth suppression mortality (kgC m <sup>-2</sup> leaf yr <sup>-1</sup> ) | Sapwood turnover (fraction/year) | Max sapling establishment rate (individual m <sup>-2</sup> year <sup>-1</sup> ) |
| 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                                                                             |

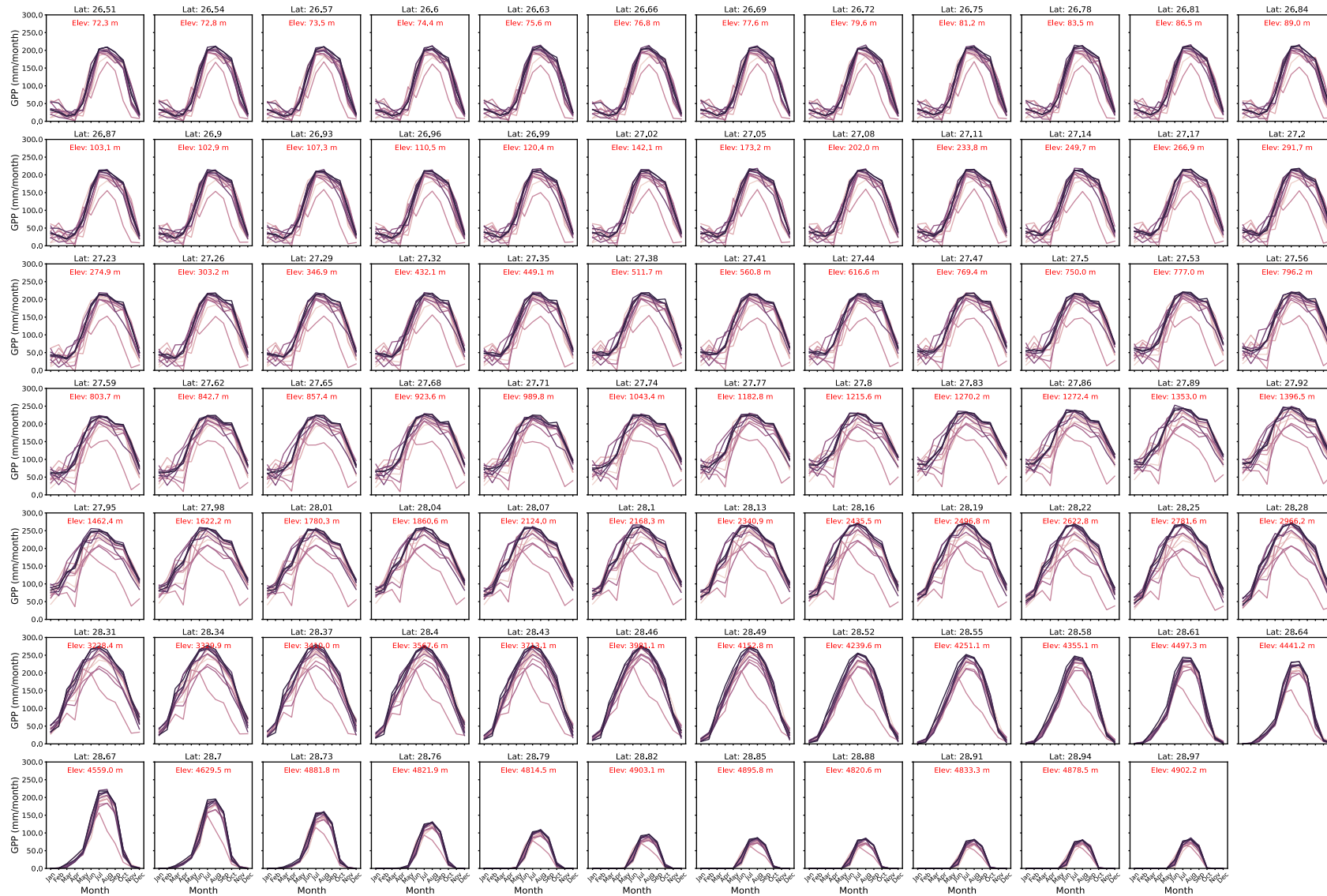
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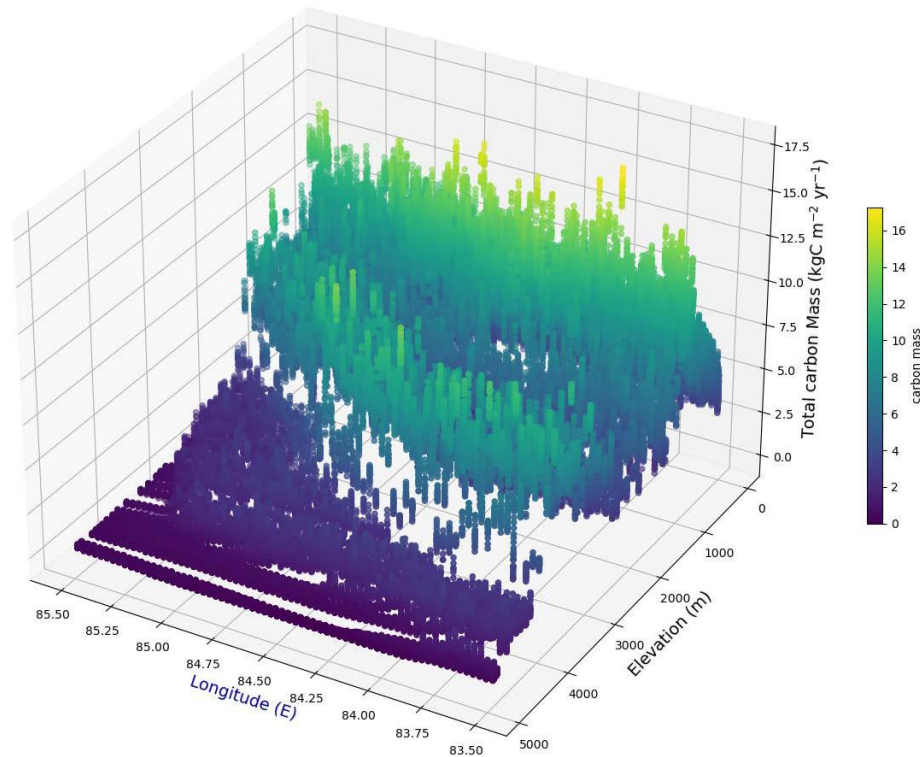
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19 Supplementary Figure S3: Simulated GPP by months along the elevation gradient from 2010 to 2022. The figure indicates that the growth  
 20 seasons start with March and June, and July and August have maximum productivity. Productivity is higher at the end of the gradient,  
 21 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.



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

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33 Figure (Supplementary Figure 6) shows the spatial distribution of FPC for all simulated PFTs along the elevation gradient, which shows  
34 clear turnover in vegetation composition with elevation. It also indicates that both environmental filtering and interspecific interactions  
35 (patterns and elevation range of dominance) are shaping the distribution of PFTs. The shift in dominant PFTs across the gradient reflects  
36 strong niche differentiation and abiotic filtering driven by decreasing temperature. For example, at lower elevations, the landscape is  
37 dominated by tropical broadleaved raingreen (TrBRG) and temperate deciduous (TeBSG) PFTs, which exhibit high PFC values, while at  
38 mid to higher elevations, temperate needle-leaved evergreen (TeNE) and subalpine PFTs (e.g., ABE and BBE) become increasingly  
39 dominant.

40 In terms of vegetation composition within the simulated grids, the difference in the relative abundance of PFTs indicates varying degrees  
41 of dominance and competitive interactions. At the lower end of the gradient, only a few PFTs dominate in FPC (Supplementary Figure 6),  
42 resulting in low evenness (Figure 9) and indicating strong competitive exclusion. In contrast, toward the upper end of the gradient,  
43 although only a limited number of cold-adapted PFTs persist (Supplementary Figure 6) - due to temperature conditions - their relative  
44 contributions to FPC are similar, resulting in higher evenness (Figure 9). This pattern suggests that under increasingly harsh conditions,  
45 environmental filtering reduces the total number of species able to survive, but competitive asymmetries decrease, resulting in a more  
46 even distribution.



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