Climate change and elevated CO_2 favor forest over savanna under different future scenarios in South Asia

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SUPPLEMENTARY MATERIALS

aDGVM2 model description

The aDGVM2 is an individual-based dynamic vegetation model that simulates growth, reproduction and mortality of individual plants at representative 1 ha stands. The design of aDGVM2 allows tracking of state variables such as biomass, height, leaf area and photosynthetic rates of individual plants. In aDGVM2, each plant is characterized by a specific and potentially unique combination of trait values that influence how a plant performs under given biotic and abiotic conditions. It allows plant communities to adapt to their environment by dynamically changing their trait composition constrained by trade-offs between traits. These traits describe plant type (grassy or woody), leaf characteristics (specific leaf area, leaf longevity), leaf phenology (evergreen or deciduous), hydraulic characteristics (risk of xylem cavitation), plant architecture (carbon allocation strategy, root and crown shape, wood density), response to fire, reproduction and mortality (Langan et al., 2017; Scheiter et al., 2013). The aDGVM2 implements plant physiology models typically used in DGVMs (Prentice et al., 2007). Fire systematically removes aboveground grass biomass while aboveground tree biomass removal is related to tree height (Higgins et al., 2008; Scheiter and Higgins, 2009). Plants with trait combinations that allow sufficient growth and reproduction rates can produce seeds and contribute their trait values to the community trait pool. Seeds can randomly mutate or exchange trait values, thereby allowing recombination within the community trait pool. Seeds are randomly drawn from the community trait pool and added to the plant population as seedlings. Plants with insufficient performance fail to contribute seeds to the seed bank and disappear from the population. Plant growth is constrained by light and water competition. Light competition is simulated by considering the impacts of neighboring plants on the light available to a target plant. Water competition is simulated via water uptake of plants from a common layered soil water pool. The probability of an individual's mortality increases if its annual carbon balance is negative. The aDGVM2 also includes a representation of shrubs as multi-stemmed woody plants, which emerge as adaption to dry conditions (Gaillard et al., 2018).

Table S1. List and description of traits that are optimized by the genetic optimization algorithm during model simulation. Values for trees and C_4 grasses were taken from Langan at al. (2017). C_3 grasses were included for this study and values of C_4 grasses were taken for model parametrization. 'na' indicates that this trait is not used for grasses.

Description of traits	Tree		C_4-grass		C_3-grass	
	min	max	min	max	min	max
Matric potential at 50% loss of conductance	-3	-0.2	-3	-0.2	-3	-0.2
Allocation to roots	0.2	0.4	0.2	0.8	0.2	0.8
Allocation to leaves	0.35	0.5	0.2	0.8	0.2	0.8
Allocation to stem	0.25	0.35	0	0	0	0
Allocation to bark	0.001	0.05	0	0	0	0
Allocation to storage	0.1	0.4	0.1	0.4	0.1	0.4
Allocation to reproduction	0.05	0.2	0.05	0.2	0.05	0.2
Phenology (rain/summer green, evergreen)	0	1	0	1	0	1
Phenology (deciduous or evergreen)	0	1	1	1	1	1
Rain threshold for plant activity	-3	-0.2	-3	-0.2	-3	-0.2
Rain threshold for plant dormancy	-3	-0.2	-3	-0.2	-3	-0.2
Light threshold for plant activity	0.1	2	0.1	2	0.1	2
Light threshold for plant dormancy	6	14	6	14	6	14
Parameter for height calculation	0.4	0.4	na	na	na	na
Parameter for height calculation	0.4	0.5	na	na	na	na
Parameter for root form	0.01	10	0.01	10	0.01	10
Parameter for root form	-1	20	1	20	1	20
Maximum rooting depth	0.3	3.6	0.3	2.4	0.3	2.4
Seed weight	0.001	0.05	0.001	0.05	0.001	0.05
Parameter for canopy form	21	25	20	60	20	60
Storage to stem allocation after fire	0.2	0.4	0	0	0	0
Storage to leaf allocation after fire	0.6	0.9	0.6	0.9	0.6	0.9
Stem Count	1	10	1	1	1	1

Table S2. List and description of traits that are constant during the model simulation and are not optimized by the genetic optimization algorithm. Values for trees and C_4 grasses were taken from Langan at al. (2017). C_3 grasses were included for this study and values of C_4 grasses were taken for model parametrization. 'na' indicates that this trait is not used for grasses and '*' denotes new parameters

Description of traits	Tree	C_4 Grass	C_3 Grass
Mortality due to negative carbon balance	0.3	0.2	0.2
Mortality due to low height	0.1	0.05	0.05
Mortality due to mechanic instability	10	5	5
Mortality due to mechanic instability	6	6	6
Topkill constants parameter 1 (Higgins et al. 2012)	1.48	0	0
Topkill constants parameter 2 (Higgins et al. 2012)	3.30698	0	0
Topkill constants parameter 3 (Higgins et al. 2012)	0.02618	0	0
Ball berry equation parameter 1	9	5.48	9
Ball berry equation parameter 2	0.01	0.02	0.01
Maintenance respiration parameter	0.015	0.025	0.015
Growth respiration parameter	0.35	0.35	0.35
Fraction of leaf biomass that respires	1	0.01	0.01
Fraction of wood biomass that respires	0.1	0.01	0.01
Fraction of root biomass that respires	0.01	0.01	0.01
Parameter for respiration model	0.218	0.218	0.218
C:N ratio of woody biomass	150	120	120
C:N ratio of woody biomass	60	120	120
Lower temperature limits for efficient carboxylation	-10*	15*	-10*
Upper temperature limits for efficient carboxylation	36*	45*	36*

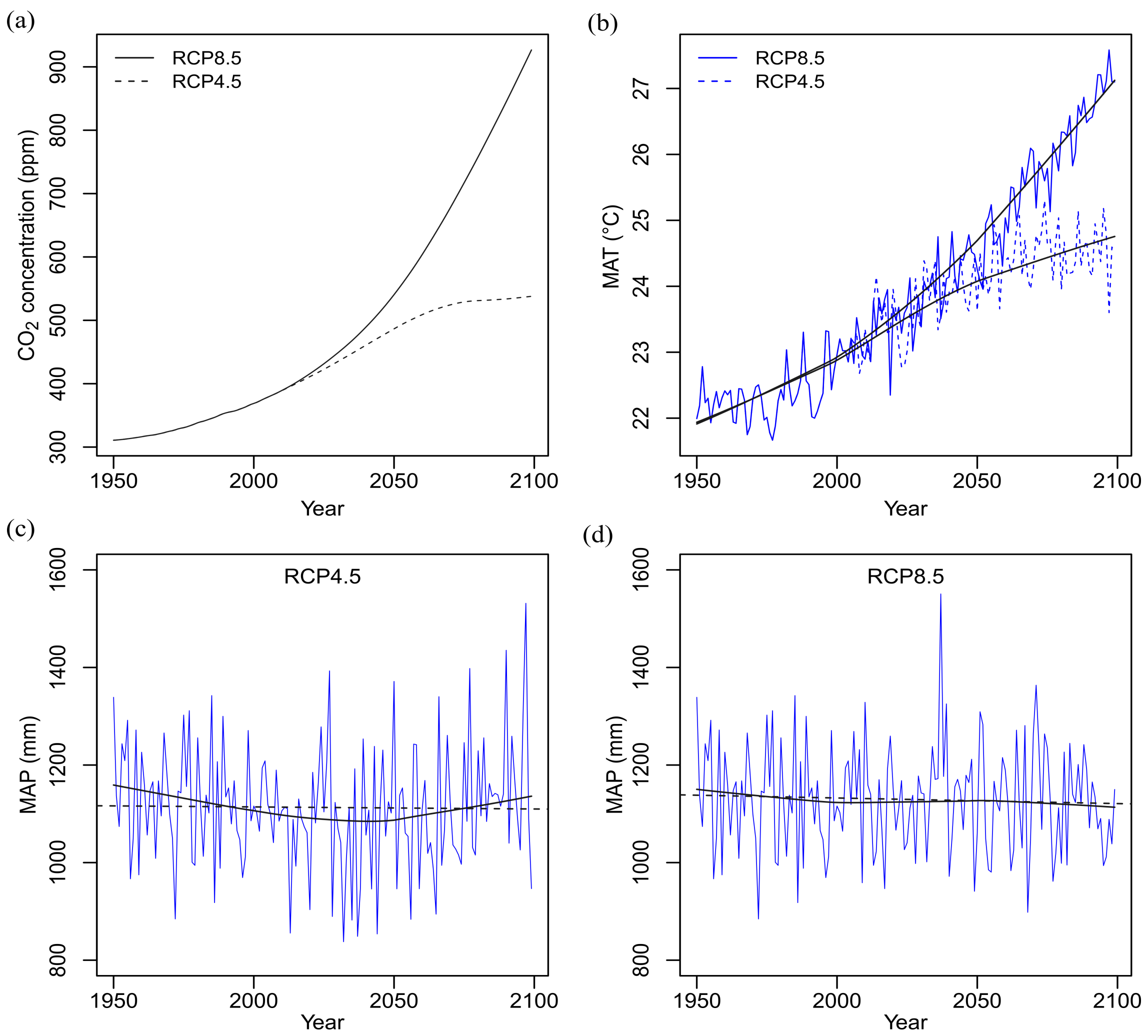

Figure S1. Time series represent (a) CO_2 concentration under RCP4.5 and RCP8.5; (b) mean annual temperature under RCP4.5 and RCP8.5; (c) mean annual precipitation for RCP4.5 and (d) mean annual precipitation for RCP8.5 for South Asia between 1951 and 2099. In (b), (c) and (d) the black solid line represents a smoothed non-linear fit (LOWESS), and in (c) and (d) the black dashed line represents a linear smoothed fit (LOWESS) to the data. Mean annual precipitation and mean annual temperature were derived from GFLDM2M simulations.

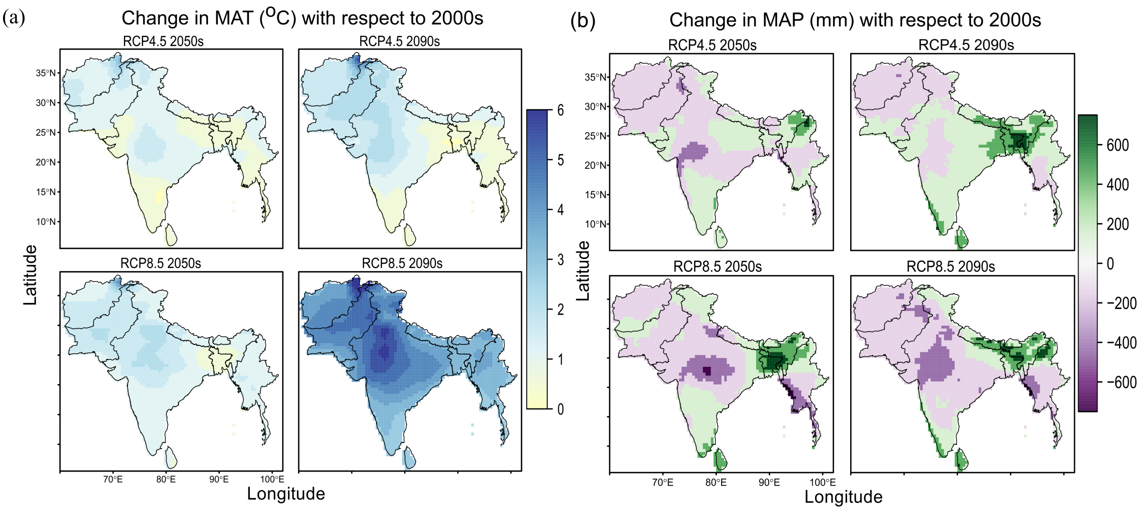

Figure S2. Projected change in (a) mean annual temperature (MAT) and (b) mean annual precipitation (MAP) until the 2050s and 2090s, relative to the 2000s.

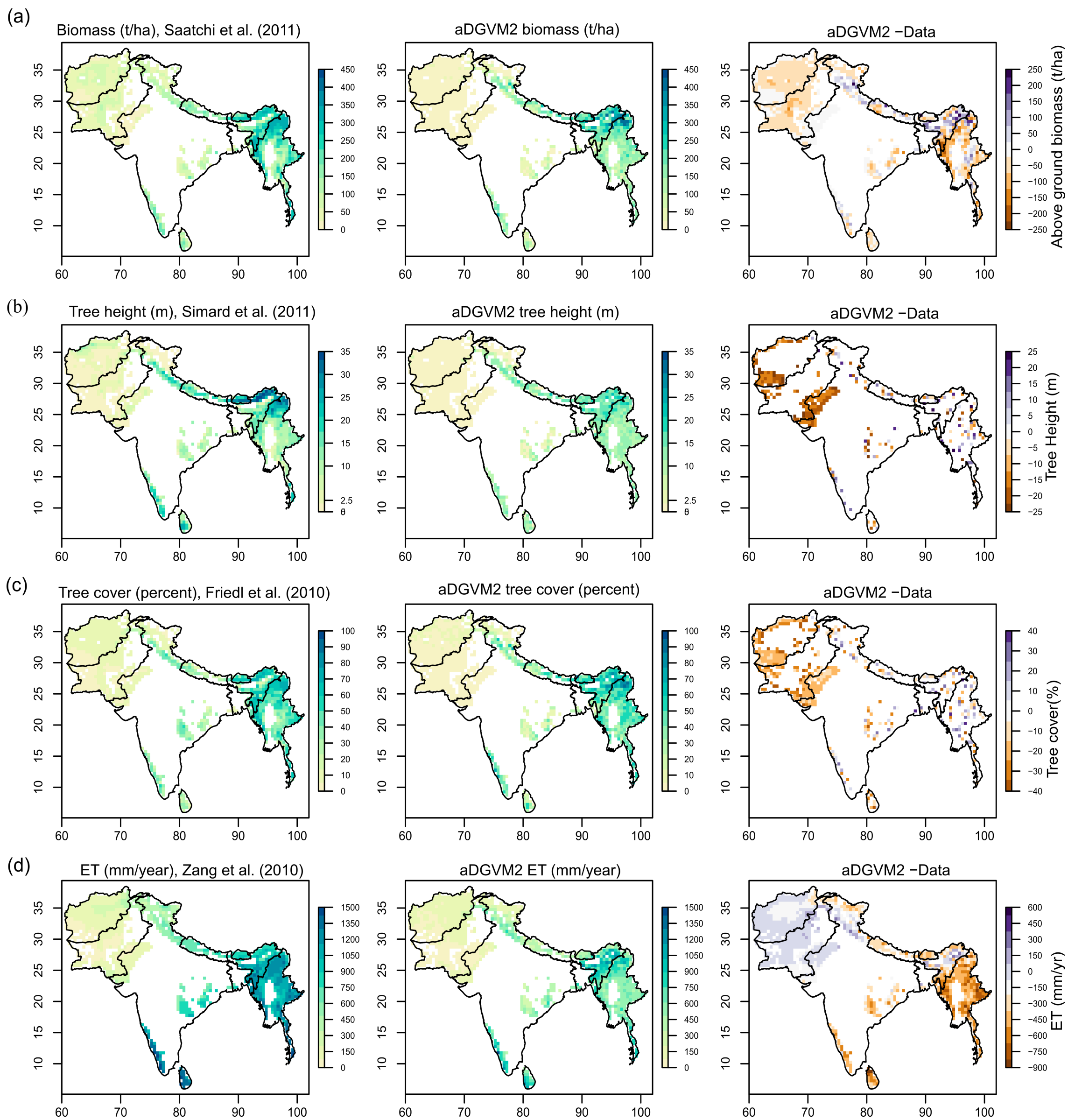

Figure S3. Comparison between aDGVM2 results and remote sensing products when removing areas with more than 50% land use cover for (a) simulated biomass and Saatchi et al. (2011) biomass and their difference, (b) simulated tree height and Simard et al. (2011) and their difference, (c) simulated tree cover and Friedl et al. (2011) tree cover and their difference and (d) simulated evapotranspiration and Zang et al. (2010) evapotranspiration and their difference. In the figure the first column shows the remote sensing products, the second column shows aDGVM2 results and the third column shows the difference between simulation and data.

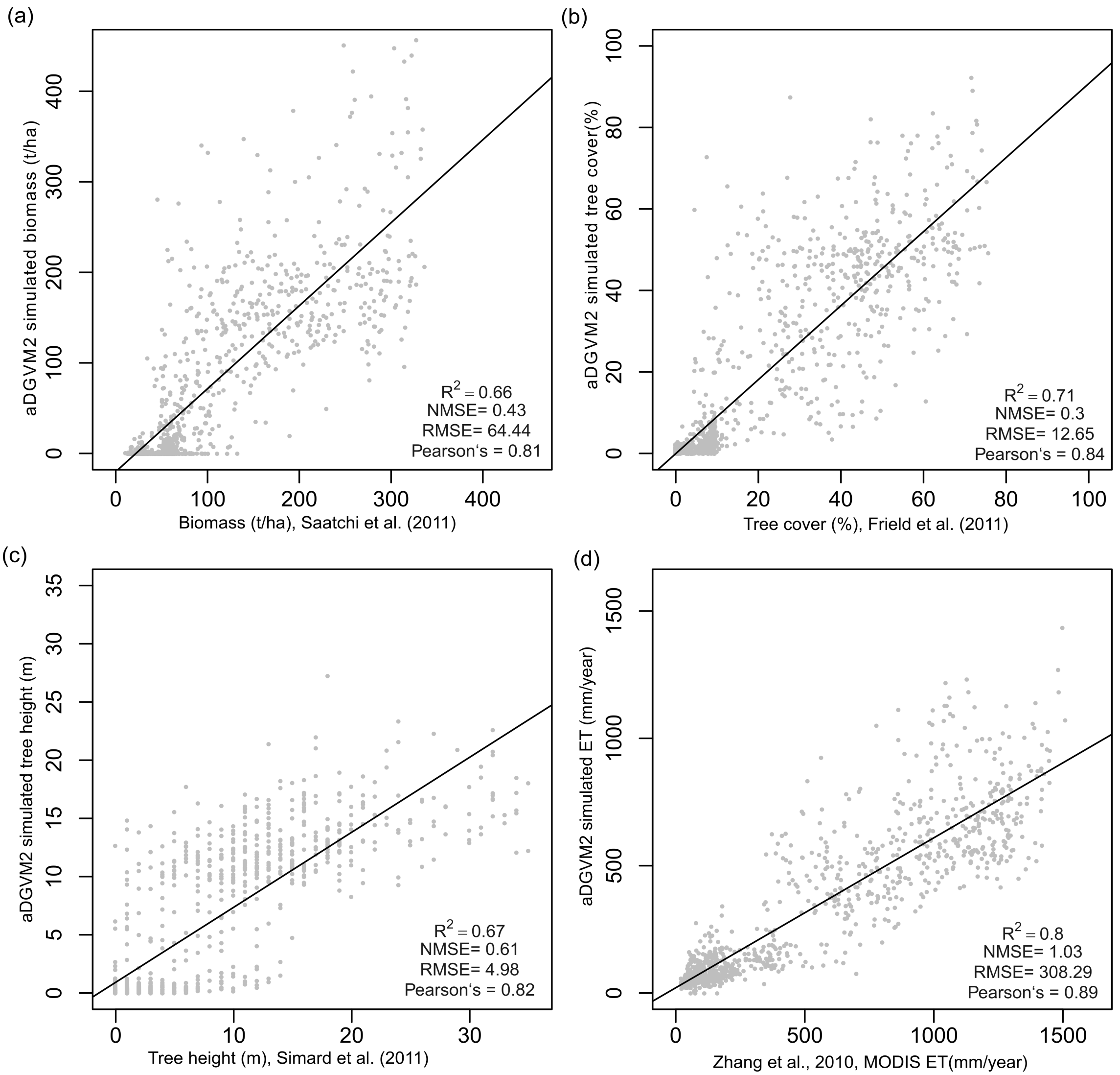

Figure S4. Scatterplots for simulated state variables against benchmarking data after removing the area with more than 50% of land use. (a) Simulated biomass and Saatchi et al. (2011) biomass, (b) simulated tree cover and Frield et al. (2010) tree cover, (c) simulated tree height and Simard et al. (2011) tree height, and (d) simulated evapotranspiration and MODIS ET (Zhang et al., 2010). NMSE and RMSE are normalized mean square error and root mean square error, respectively.

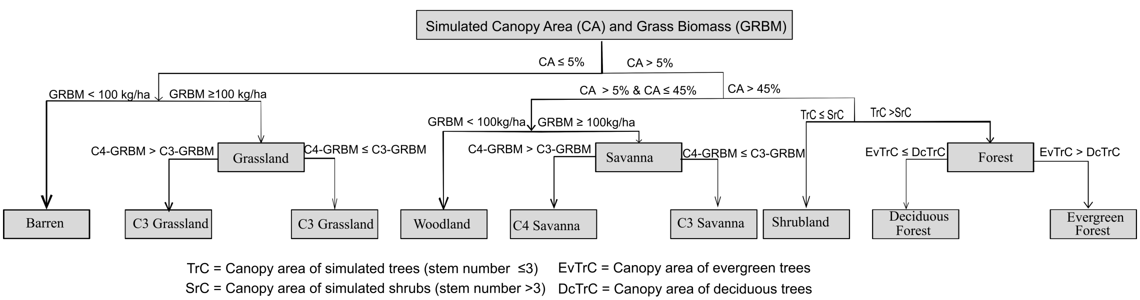

Figure S5. Flow chart illustrating classification of simulated vegetation into biomes using canopy area of different woody vegetation types and grass biomass. Simulated stem numbers were used to distinguish between shrubs and trees.

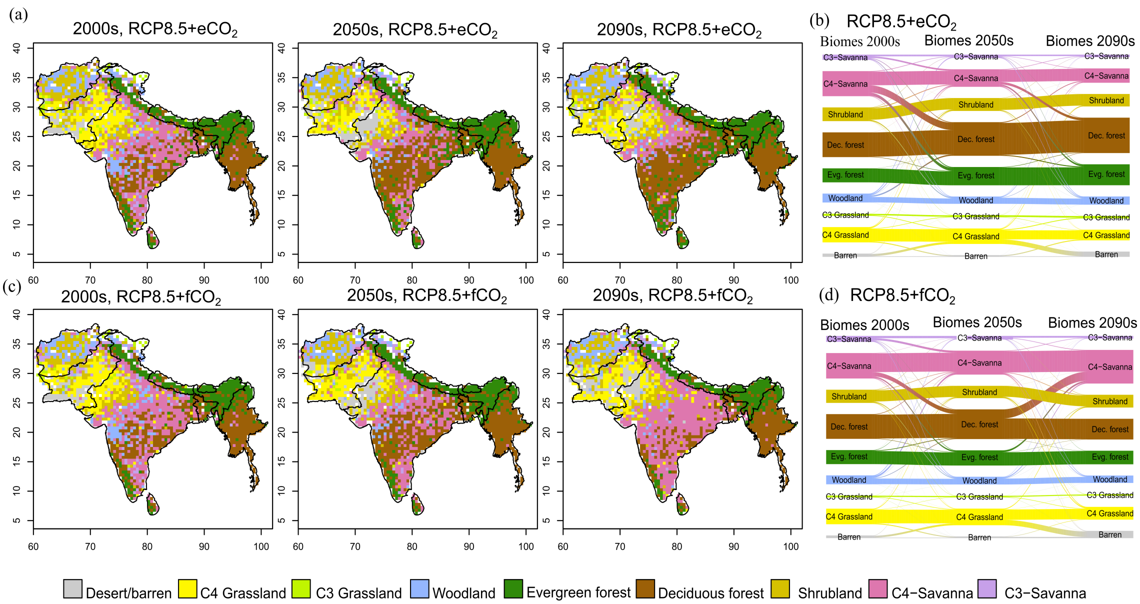

Figure S6. Simulated biome distribution for the 2000s, 2050s and 2090s under (a) RCP8.5+eCO_2 and (c) RCP8.5+fCO2, and Sankey diagrams showing the transition between biomes from the 2000s to the 2050s and the 2050s to the 2090s under (b) RCP8.5+eCO_2 and (d) RCP8.5+fCO2. See Figure 4 for simulated biome distribution under RCP4.5.

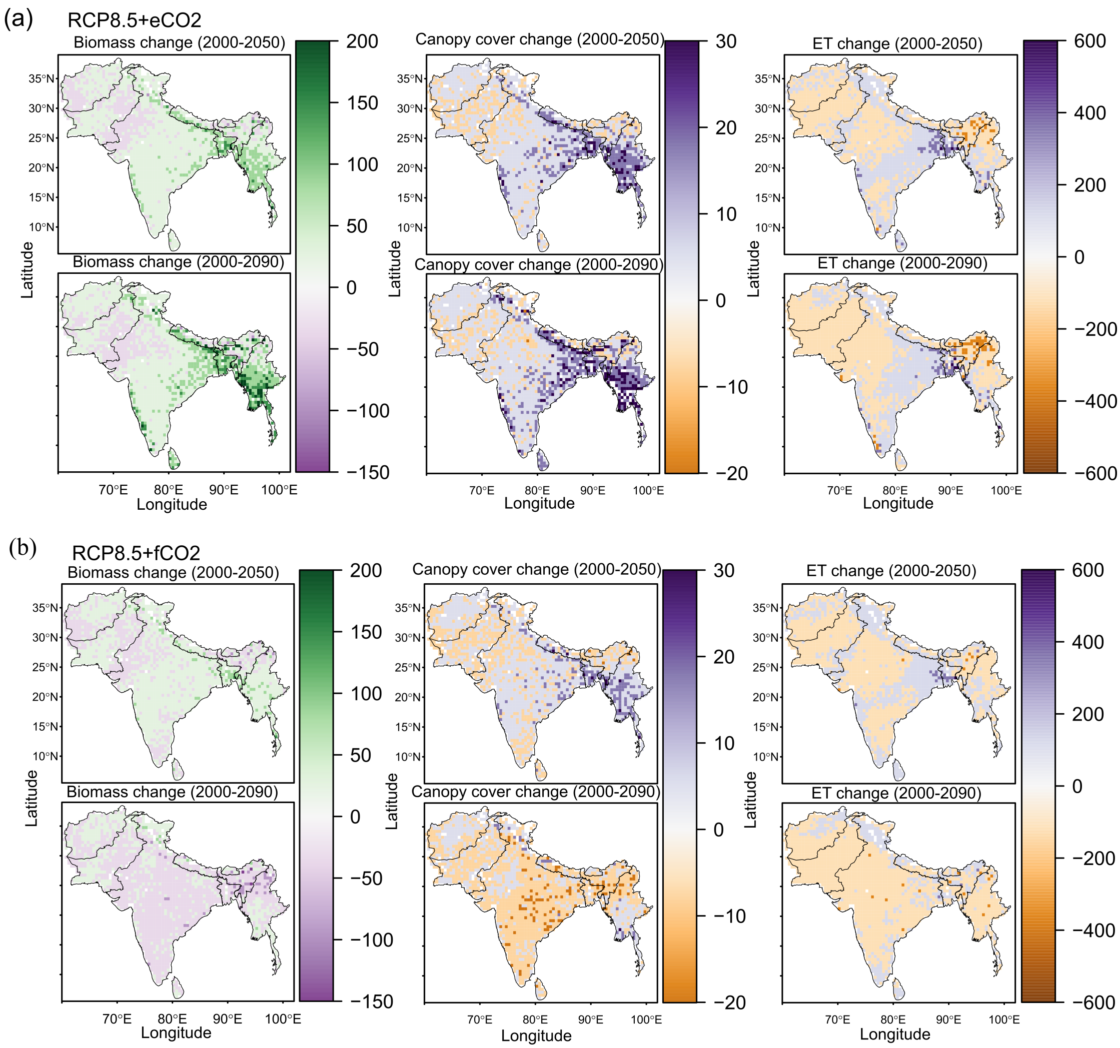

Figure S7. Projected change in biomass, canopy area and ET between the 2000s and 2050s, and between the 2000s and 2090s under (a) RCP84.5+eCO_2 and (b) RCP8.5+fCO_2.

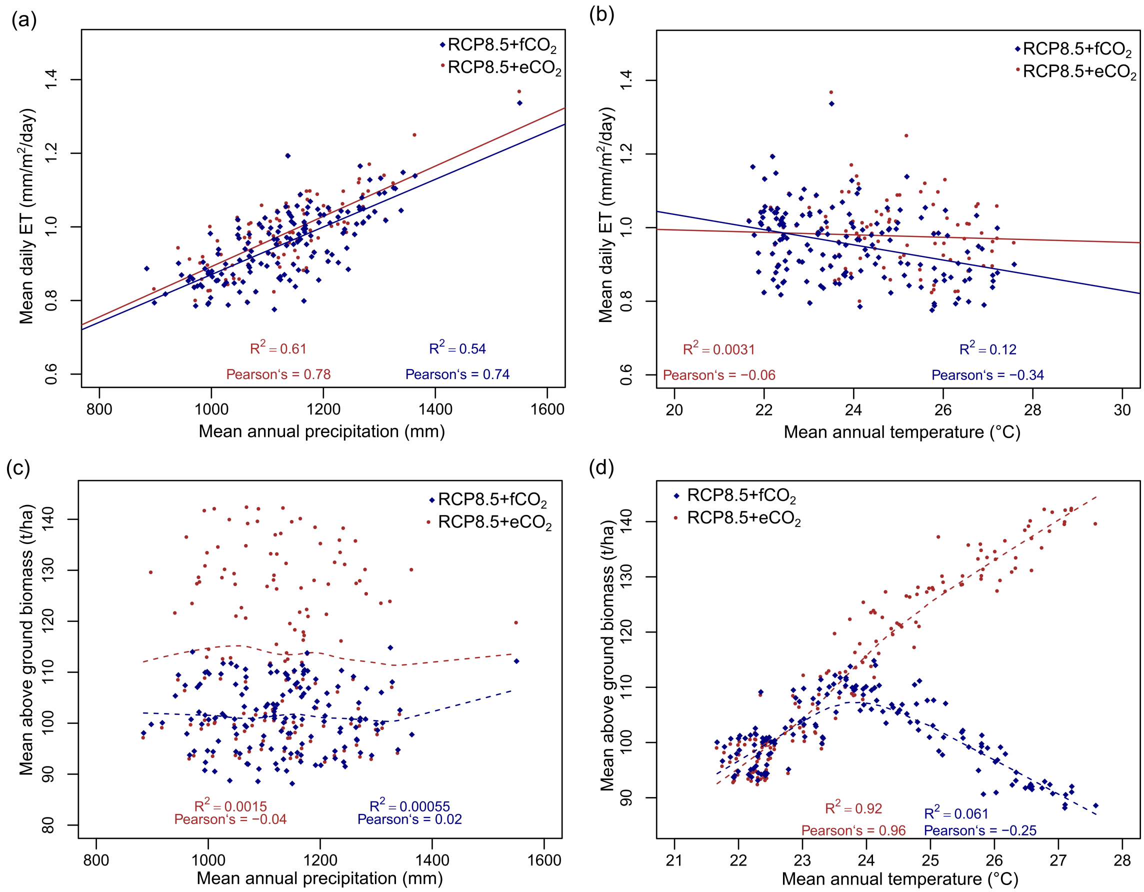

Figure S8. Relationship between (a) evapotranspiration (ET) and mean annual precipitation (MAP), (b) ET and mean annual temperature (MAT), (c) mean above ground biomass and MAP and (d) mean above ground biomass and MAT under RCP8.5.. The lines (both solid and dotted) in all figures represent the best-fit regression line. The dots represent spatially averaged ET (a, b) and biomass (c, d) for each year from 1950 to 2099. See Figure 6 for these relation between ET, biomass, MAP and MAT under RCP4.5.

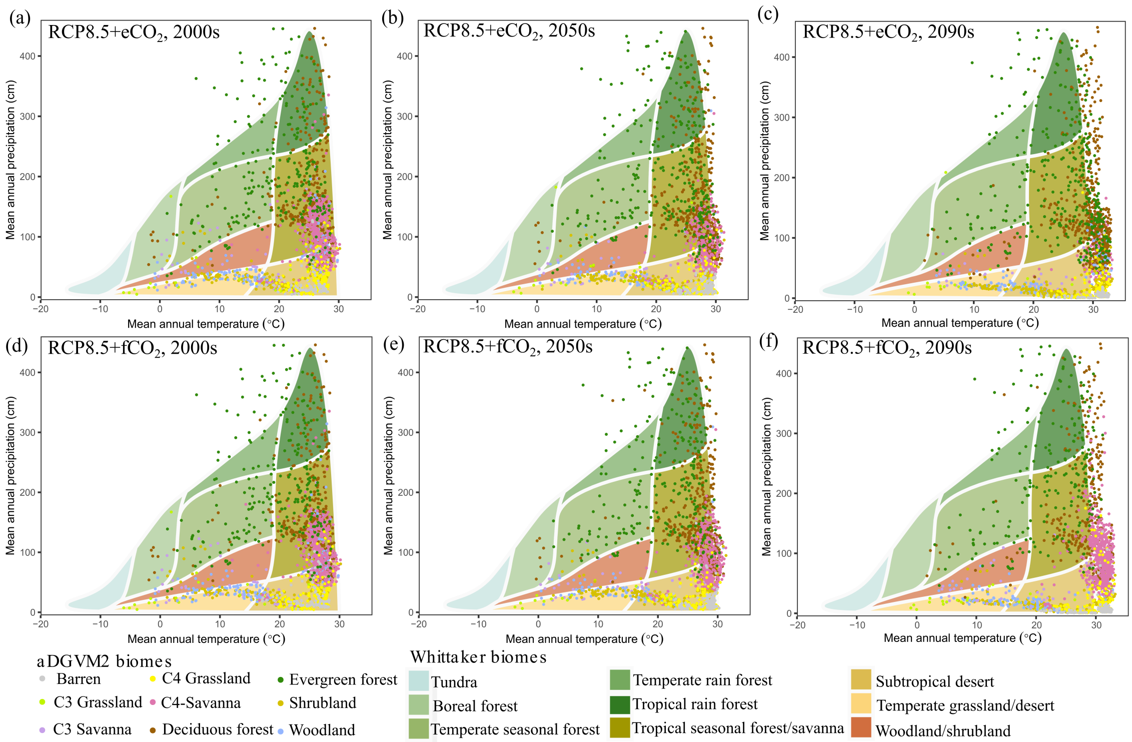

Figure S9. Simulated climatic niches of biomes for the period of (a) 2000s, (b) 2050s and (c) 2090s under RCP8.5+ eCO_2 and (d) 2000s, (e) 2050s and (f) 2090s under RCP8.5+fCO_2. The simulated biomes are overlaid on the climate envelopes of Whittaker's biomes and are plotted following Ricklefs (2008) and Whittaker (1975).