Supporting Information

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SI Text

Global Vegetation Models Used in This Study

Seven global vegetation models (GVMs) were used in this study: HYBRID4 (1), JeDi (2), JULES (3), LPJmL (4, 5), ORCHIDEE (6, 7), SDGVM (8), and VISIT (9, 10). The vegetation models were used to simulate the responses of natural terrestrial vegetation to climate and CO_2 mixing ratio changes at 0.5°x0.5° (except for JULES and JeDi, which were run at 1.25°x1.85°) spatial resolution over 1951–2099.

The total time duration of the spin-up varied among the vegetation models in order to accommodate differences in reaching equilibrium for multiple state variables. As spin-up climatology, the detrended and bias-corrected daily climate inputs for three consecutive decades spanning 1951–1980 were provided for each GCM (JULES used HadGEM2-ES climate for all spin-ups). Except for JULES, if the spin-up required more than 30 y, every second 30-y period was inverted (i.e., 1980–1951), to avoid artifacts due to discontinuities in the climate data. The CO_2 mixing ratio during the spin-up and historical periods was fixed at 280 ppm for all years before 1765, and was thereafter increased linearly until 2005 (2004 for HadGEM2-ES and 2000 for fixed CO_2 runs). CO_2 mixing ratio was then changed according to the RCP until 2099 (or fixed at the 2001 value for the no CO_2 change runs).

Key GVM features relevant to the results presented in this paper are given in Table S1, and overall model descriptions are given below.

HYBRID4

HYBRID4 simulates the growth and competitive interactions of individual trees using a gap-model approach, with an herbaceous understory. Individual trees can belong to one of six generalized plant types, and the understory can be of either C_3, C_4, or mixed leaf physiology. Twenty independent plots were simulated for each terrestrial gridbox using a daily timestep. A relatively simple surface physics and hydrology routine calculates the daytime and nighttime surface temperatures and soil moisture dynamics over two soil water layers. Trees have access to both layers whereas the herbaceous layer only accesses the upper layer. A nitrogen cycle is included, which affects canopy photosynthetic capacities. Atmospheric N deposition was assumed to be spatially and temporally invariant. Individual tree mortality can occur as a result of low labile carbon, and is influenced by overall rates of photosynthesis and respiration. Photosynthesis is calculated using a standard Farquhar-type model. Stomatal conductance is calculated using empirical functions of vapor pressure deficit (VPD), temperature, CO_2, shortwave radiation, soil moisture, and photosynthetic capacity. Both photosynthesis and respiration are scaled to the canopy using a "big-leaf" approach. Maintenance respiration is a function of tissue N contents and temperature. Detailed canopy radiation transfer is calculated across foliage layers. All plant types are assumed to be available for growth in all plots, but only those that are competitively successful will survive and grow. For full details concerning HYBRID4 please refer to ref. 1.

JeDi

JeDi simulates the performance of a large number of randomly-generated plant growth strategies (~2000), constrained by eco-physiological trade-offs, within a coupled land surface hydrology module. All plant types are assumed to be available at all locations, but only those that are adequately adapted to the local conditions will survive and grow. Gridbox properties are scaled using the biomass-ratio hypothesis. This diverse representation of vegetation provides more flexibility for ecosystem composition to adapt to environmental changes. Growth and surface processes are simulated on a daily timestep. The growing period depends on soil moisture availability and surface temperature. Baseline turnover rates are fixed for each growth strategy, but there is also a senescence component which depends on overall net primary productivity (NPP). Photosynthesis is a function of absorbed shortwave radiation and photosynthetic capacity, determined by temperature, atmospheric CO_2, and canopy N. Transpiration and photosynthesis are both down-regulated by a moisture-stress factor which accounts for both soil water supply and atmospheric demand (defined using the Priestley-Taylor equation). Maintenance respiration is a function of tissue N content and temperature. The depth of the single soil moisture layer representing the rooting zone of each growth strategy is determined by plant coarse root biomass. For full details concerning JeDi please refer to ref. 2.

JULES

JULES represents the dynamics of five plant types within each gridbox using a Lotka-Volterra approach. Surface physics are simulated using a sophisticated GCM land surface scheme with a 30 to 60 min timestep. Photosynthesis of each plant type is calculated using a standard Farquhar-type approach, with a moisture stress factor applied directly to leaf photosynthesis. Stomatal conductance is calculated using an empirical function of net photosynthesis, CO_2, and VPD. Scaling to the canopy uses a big-leaf approximation with a two-stream approximation of canopy radiation interception. Maintenance respiration rates depend on tissue N contents and temperatures. For full details concerning JULES please refer to ref. 3.

LPJmL

LPJmL simulates the dynamics of nine plant types on a daily timestep, each with different physiological tolerances. The relative contribution of plant types to overall gridbox properties is based on its relative fractional coverage. This cover is proportional to the leaf area index and crown area of an average individual of each woody plant type in the gridbox, together with its population density, and the herbaceous understory. Each plant type also has bioclimatic limits that determine whether it can survive and/or regenerate under a particular climatic regime. The permafrost model includes an energy balance model, including one-dimensional heat conduction, convection of latent heat, freezing, and thawing mechanics. Soil hydrology is calculated using 5 layers with different rooting distributions for different plant types. The Farquhar-based photosynthesis is calculated from absorbed radiation, temperature, CO_2, and soil moisture status. Maintenance respiration is proportional to tissue N contents and temperature. Plant tissues turn over at fixed rates but there is also a calculation of annual mortality of individuals. Competition-driven mortality occurs if the total space available is insufficient for the sum of the fractional covers. Mortality also occurs in proportion to growth efficiency (i.e., the ratio of biomass increment to leaf area) and in response to heat stress. A fire module is included, which depends on fuel load and litter moisture. Establishment of new plant is filtered depending in bioclimatic limits. LPJmL's agricultural modules simulating fractions of crop and bioenergy plants were deactivated for these runs. For full details concerning LPJmL please refer to refs. 4 and 5.

ORCHIDEE

ORCHIDEE was applied in this project using a prescribed plant functional type distribution corresponding to pre-industrial land cover, which was kept constant for the duration of the simulations. The model therefore simulated no change in vegetation distribution. Twelve plant types are represented, and photosynthesis is simulated using a standard Farquhar-model approach coupled to the Ball-Berry stomatal conductance model. Photosynthetic capacity is directly affected by soil moisture stress (a scaling factor that decreases linearly to zero when root extractable water drops below a threshold of 0.4), and leaf age, as well as plant type, and indirectly through the atmospheric stress impacting the Ball-Berry conductance. Scaling of photosynthesis and stomatal conductance to the canopy level is achieved using a big-leaf approximation. Maintenance respiration is a function of tissue biomass and temperature. Turnover occurs due to phenological responses of leaves and fine roots, herbivory (fixed rates), and leaf aging. Mortality is prescribed as a fixed ratio of standing biomss. For full details concerning ORCHIDEE please refer to ref. 6. The ORCHIDEE AR5 version used in this study contains an improved description of phenology (7).

SDGVM

Like ORCHIDEE, SDGVM also used a fixed vegetation distribution for this study. Seven plant types are simulated, with photosynthesis proportional to leaf area and internal leaf CO_2. The latter is calculated as a function of N uptake rate, shortwave radiation, temperature, and VPD. Soil moisture affects leaf area. Maintenance respiration is a function of N uptake and tissue temperature. A surface physics routine calculates temperatures and soil moisture dynamics. Fire is simulated as a function of moisture stress and vegetation state. For full details concerning SDVGM please refer to ref. 8.

VISIT

VISIT was also run with a fixed prescribed vegetation distribution. The Olson vegetation data map was used for biome type reference. The carbon dynamics of 16 plant types are simulated, with photosynthesis an empirical function of the incident shortwave radiation, canopy leaf area index, attenuation coefficient, leaf-level light-use efficiency, and maximum photosynthetic rate. The light-use efficiency and maximum photosynthetic rate are functions of temperature, intercellular CO_2 concentration, and soil water content, taking into account biome-specific ecophysiological characteristics. The growth respiration rate is proportional to the amount of carbon allocated to each organ, whereas the maintenance respiration rate increases linearly with standing biomass and exponentially with temperature. Growth and maintenance respirations are separately estimated for leaves, stems, and roots. Stomatal conductance is calculated using the Leuning version of the Ball-Berry model. A leaf area optimization routine is used to determine allocation of labile carbon to the canopy. Fixed rates of turnover are applied to all tissues. A simple soil hydrology routine simulates the dynamics of two soil water layers. For full details concerning VISIT please refer to refs. 9 and 10.

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Table S1. Effects of atmospheric humidity and temperature on processes responsible for major differences in *NPP* and residence time responses among seven analyzed GVMs

	Atmospheric temperature on turnover			Atmospheric temperature on mortality components					Atmospheric vapor pressure deficit on stomatal closure	
GVM	roots	stems	leaves	background	competition	C balance	fire	other	incl.	description
HYBRID4	✓	✓	✓	o	✓	✓	x	embolism	✓	stomatal closure as a direct function of *inter alia* vapor pressure deficit
JeDi	o	o	o	o	x	✓	x	none	x	water stress factor on GPP instead determined by evaporative demand and supply
JULES	✓	✓	✓	✓	x	x	x	none	x	Ball-Berry model
LPJmL	o	o	o	✓	✓	✓	✓	heat stress	x	water stress factor on GPP instead determined by soil moisture only
ORCHIDEE	o	o	o	x	x	x	x	none	x	Ball-Berry model
SDGVM	o	o	o	o	x	x	✓	none	✓	stomatal closure as a function of relative humidity and temperature
VISIT	o	o	o	x	x	x	x	none	x	Ball-Berry model

A "✓" means that the formulation is dependent on the respective variable, while an "o" means that the process is incorporated but not dependent on the respective variable, and an "x" means the process is not explicitly treated.

Table S2. Number of decades of each GVMxGCMxRCP combination in each mean-decadal 1-degree wide land temperature change bin classified by GCM, RCP, and temperature bin

ΔT (°C) CO_2min (ppm) CO_2max (ppm)	RCP	GFDL-ESM2M	HadGEM2-ES	IPSL-CM5A-LR	MIROC-ESM-CHEM	NorESM1-M	Total
+1	2.6	60	14	12	12	20	118
370	4.5	16	12	15	10	12	65
510	6.0	30	14	15	15	16	90
	8.5	18	14	12	12	15	71
	Total	124	54	54	49	63	344
+2	2.6	0	56	48	42	30	176
391	4.5	24	12	10	15	16	77
594	6.0	10	21	10	10	12	63
	8.5	18	7	12	12	10	59
	Total	52	96	80	79	68	375
+3	2.6	0	0	0	6	0	6
426	4.5	0	12	25	15	12	64
594	6.0	10	14	15	10	12	61
	8.5	12	14	6	6	10	48
	Total	22	40	46	37	34	179
+4	2.6	0	0	0	0	0	0
510	4.5	0	24	0	10	0	34
758	6.0	0	14	10	10	0	34
	8.5	12	7	12	6	5	42
	Total	12	45	22	26	5	110
+5	2.6	0	0	0	0	0	0
610	4.5	0	0	0	0	0	0
926	6.0	0	7	0	5	0	12
	8.5	0	7	6	12	10	35
	Total	0	14	6	17	10	47
+6	2.6	0	0	0	0	0	0
684	4.5	0	0	0	0	0	0
844	6.0	0	0	0	0	0	0
	8.5	0	14	6	6	0	26
	Total	0	14	6	6	0	26
+7	2.6	0	0	0	0	0	0
853	4.5	0	0	0	0	0	0
926	6.0	0	0	0	0	0	0
	8.5	0	7	6	6	0	19
	Total	0	7	6	6	0	19

The CO_2 mixing ratio ranges are given for each bin. The range of CO_2 mixing ratios for each temperature bin reflects the different climate sensitivities of the five GCMs as well as the different trajectories of RCP forcings (i.e., warming continues after forcing is halted due to lagged responses in RCPs 2.6 and 4.5).

Table S3. Number of simulations for each GVMxGCMxRCP combination

GCM	RCP	HYBRID4	JeDi	JULES	LPJmL	ORCHIDEE	SDGVM	VISIT	Total
GFDL-ESM2M	2.6	1	1	1	1	0	1	1	6
	4.5	0	1	1	1	0	1	0	4
	6.0	1	1	1	1	0	1	0	5
	8.5	1	1	1	1	0	2	1	7 (6)
HadGEM2-ES	2.6	2	2	2	2	2	1	1	12 (7)
	4.5	2	2	2	2	0	1	1	10 (6)
	6.0	2	2	2	2	1	1	1	11 (7)
	8.5	2	2	2	2	2	2	2	14 (7)
IPSL-CM5A-LR	2.6	1	1	1	1	0	1	1	6
	4.5	1	1	1	1	0	1	0	5
	6.0	1	1	1	1	0	1	0	5
	8.5	1	1	1	1	0	2	1	7 (6)
MIROC-ESM-CHEM	2.6	1	1	1	1	0	1	1	6
	4.5	1	1	1	1	0	1	0	5
	6.0	1	1	1	1	0	1	0	5
	8.5	1	1	1	1	0	2	1	7 (6)
NorESM1-M	2.6	1	1	1	1	0	0	1	5
	4.5	1	1	1	1	0	0	0	4
	6.0	1	1	1	1	0	0	0	4
	8.5	1	1	1	1	0	0	1	5
	Total	23 (19)	24 (20)	24 (20)	24 (20)	5 (3)	20 (16)	13 (12)	133 (110)

When two runs are listed for a single combination, the additional run was with fixed CO_2 mixing ratio from 2001 onwards. The total number is given with (without) the number of runs with fixed CO_2 mixing ratio.