Objective biome classification across global vegetation models reveals consistent biome shifts under future climate change

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SUPPLEMENTARY MATERIALS

S1: GVMs and PFT products

PFTs, references and responsible persons for different GVMs and PFT products used in this study. For the biome classification, we only included PFTs representing natural vegetation while bare ground and managed land were excluded. The following provides includes and excluded PFTs per GVM and PFT product.

ORCHIDEE-DGVM

included: tropical broad-leaved evergreen (trbrev); tropical broad-leaved raingreen (trbrrg); temperate needleleaf evergreen (tendev); temperate broad-leaved evergreen (tebrev); temperate broad-leaved summergreen (tebrsu); boreal needleleaf evergreen (bondev); boreal broad-leaved summergreen (bobrsu); boreal needleleaf summergreen (bondsu); C3 natural grass (c3gra); C4 natural grass (c4gra)

excluded: bare soil (bare); C3 winter crop (c3win); C3 summer crop (c3sum); C4 maize (c4mai); C4 other crops (c4oth); C3 pasture (c3pas); C4 pasture (c4pas)

Main reference: Guimberteau et al. (2018)

Responsible persons:
Jinfeng Chang: changjf@zju.edu.cn, Zhejiang University (China)
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ORCHIDEE

included: tropical broad-leaved evergreen (trbrev); tropical broad-leaved raingreen (trbrrg); temperate needleleaf evergreen (tendev); temperate broad-leaved evergreen (tebrev); temperate broad-leaved summergreen (tebrsu); boreal needleleaf evergreen (bondev); boreal broad-leaved summergreen (bobrsu); boreal needleleaf summergreen (bondsu); C3 natural grass (c3gra); C4 natural grass (c4gra)

excluded: bare soil (bare); C3 winter crop (c3win); C3 summer crop (c3sum); C4 maize (c4mai); C4 other crops (c4oth); C3 pasture (c3pas); C4 pasture (c4pas)

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LPJ-GUESS

included: Boreal needleleaved evergreen (BNE); Boreal shade intolerant needleleaved evergreen (BINE); Boreal needleleved summergreen (BNS); Temperate broadleaved summergreen

(TeBS); shade intolerant broadleaved summergreen (IBS); Temperate broadleved evergreen (TeBE); Tropical broadleaved evergreen (TrBE); Tropical shade intolerant broadleaved evergreen (TrIBE); Tropical broadleaved raingreen (TrBR); C3 grass (C3G); C4 grass (C4G);

excluded: none

Main reference: Smith et al. (2014)

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CLM 4.5

included: needleleaf-evergreen-tree-temperate; needleleaf-evergreen-tree-boreal; needleleaf-deciduous-tree-boreal; broadleaf-evergreen-tree-tropical; broadleaf-evergreen-tree-temperate; broadleaf-deciduous-tree-tropical; broadleaf-deciduous-tree-temperate; broadleaf-deciduous-tree-boreal; broadleaf-evergreen-shrub-temperate; broadleaf-deciduous-shrub-temperate; broadleaf-deciduous-shrub-boreal; c3-arctic-grass; c3-non-arctic-grass; c4-grass

excluded: c3-crop-rainfed; c3-crop-irrigated; corn-rainfed; corn-irrigated; spring-cereal-temperate-rainfed; spring-cereal-temperate-irrigated; winter-cereal-temperate-rainfed; winter-cereal-temperate-irrigated; soybean-rainfed; soybean-irrigated

Main reference: Thiery et al. (2017)

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CARAIB

included: C3 herbs (humid) (c3hh); C3 herbs (dry) (c3dh); C4 herbs (c4h); Broadleaved summergreen arctic shrubs (brsuas); Broadleaved summergreen boreal or temperate cold shrubs (brsutecds); Broadleaved summergreen temperate warm shrubs (brsutewms); Broadleaved evergreen boreal or temperate cold shrubs (brevtecds); Broadleaved evergreen temperate warm shrubs (brevtewms); Broadleaved evergreen xeric shrubs (brevxs); Subdesertic shrubs (sds); Tropical shrubs (trs); Needleleaved evergreen boreal or temperate cold trees (ndevtecdt); Needleleaved evergreen temperate cool trees (ndevteclt); Needleleaved evergreen trees, drought-tolerant (ndevtedtt); Needleleaved evergreen trees, drought-tolerant, thermophilous (ndevtedttht); Needleleaved evergreen subtropical trees, drought-intolerant (ndevstdit); Needleleaved summergreen boreal or temperate cold trees (ndsutecdt); Needleleaved summergreen subtropical swamp trees (ndsustswt); Broadleaved evergreen trees, drought tolerant (brevdtt); Broadleaved evergreen trees, drought-tolerant, thermophilous (brevdttht); Broadleaved evergreen subtropical trees, drought-intolerant (brevstdit); Broadleaved summergreen boreal or temperate cold trees (brsutecdt); Broadleaved summergreen temperate cool trees (brsuteclt); Broadleaved summergreen temperate warm trees (brsutewmt); Broadleaved raingreen tropical trees (brrgtrt); Broadleaved evergreen tropical trees (brevtrt);

excluded: Maize-temperate (maizetec); Maize-tropical (maizetrc); Oil crops-groundnuts oil (groundnutc) Oil crops-rapeseed (oilrapeseedc); Soybeans (soybeanc); Sunflower (sunflowerc); Other crops-temperate (othertec); Other crops-tropical (othertrc); Pulses-temperate (pulsestec); Pulses-tropical (pulsestrc) Rice (ricec); Sugarcane (sugarcanec); Temperate cereals (cerealtec); Temperate roots (roottec); Tropical cereals (cerealtrc) Tropical roots roottrc C3 herbs - Pastures c3p C4 herbs - Pastures c4p

Main references: Minet et al. (2015); Warnant et al. (1994)

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ESACCI, Harper et al. (2023)

included: broad- leaved evergreen trees; broad-leaved deciduous trees; needle-leaved evergreen trees; needle-leaved deciduous trees; broad- leaved evergreen shrubs; broad-leaved deciduous shrubs; needle-leaved evergreen shrubs; needle-leaved deciduous shrubs;natural grasses

excluded: managed grasses; built-up areas; permanent inland-water bodies; bare soil; permanent snow-and-ice cover

Main reference: Harper et al. (2023)

Responsible persons:

Tuanmu and Jetz (2014)

included: Evergreen/deciduous needleleaf trees; Evergreen broadleaf trees; Deciduous broadleaf trees; Mixed/other trees; Shrubs; Herbaceous vegetation; Regularly flooded vegetation
excluded: Cultivated and managed vegetation; Urban/built-up; Snow/ice; Barren; Open water
Main reference: Tuanmu & Jetz (2014)

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S2: Supplementary tables and figures

Table S1: Models and scenarios included in the analysis.

RCP	Model	Climate model	Bias correction	Land use	CO_2
RCP2.6	LPJ-GUESS	IPSL-CM5A-LR	EWEMBI	2005soc	co2
RCP2.6	ORCHIDEE	IPSL-CM5A-LR	EWEMBI	2005soc	co2
RCP2.6	ORCHIDEE-DGVM	IPSL-CM5A-LR	EWEMBI	2005soc	co2
RCP2.6	CARAIB	IPSL-CM5A-LR	EWEMBI	2005soc	co2
RCP2.6	CLM	HADGEM2-ES	EWEMBI	2005soc	co2
RCP6.0	LPJ-GUESS	IPSL-CM5A-LR	EWEMBI	2005soc	co2
RCP6.0	ORCHIDEE	IPSL-CM5A-LR	EWEMBI	2005soc	co2
RCP6.0	ORCHIDEE-DGVM	IPSL-CM5A-LR	EWEMBI	2005soc	co2
RCP6.0	CARAIB	IPSL-CM5A-LR	EWEMBI	2005soc	co2
RCP6.0	CLM	IPSL-CM5A-LR	EWEMBI	2005soc	co2
RCP8.5	LPJ-GUESS	IPSL-CM5A-LR	EWEMBI	2005soc	co2
RCP8.5	ORCHIDEE	IPSL-CM5A-LR	EWEMBI	2005soc	co2
RCP8.5	CLM	HADGEM2-ES	EWEMBI	2005soc	co2

Table S2: Strength of bioclimatic constraints for defining biome distributions. 'T-limit' denotes if biome boundaries are mainly constrained and defined by temperature or by other factors. In our analyses, biomes classified as 'Partially' were considered as 'No' (i.e., temperature is not the main constraint of the biome boundary).

Olson biome	T-limit	Notes	References
TrMBF	Yes	Require high, stable temperatures year-round (typically >18°C); temperature minima critical.	Olson et al. (2001); Mucina (2019)
TrGS	Partially	Temperature important, but fire regimes and precipitation seasonality also critical.	Olson et al. (2001)
TrDBF	Partially	Temperature important but distribution also strongly shaped by dry season precipitation.	Olson et al. (2001)
TrCF	Partially	Temperature important, particularly seasonal cold limits, but precipitation also key.	Olson et al. (2001)
FlGS	No	Limits mainly controlled by hydrology and flooding patterns rather than temperature.	Olson et al. (2001)
DeXS	Partially	Temperature extremes matter (hot or cold deserts), but severe moisture limitation dominates.	Olson et al. (2001); Mucina (2019)
MoGS	Yes	Temperature drops with altitude define upper tree lines and biome limits.	Olson et al. (2001)
MeFWS	Partially	Temperature influences drought stress, but summer dry period and soils also critical.	Olson et al. (2001)
TeBMF	Yes	Temperature (cold winters) strongly limits range; growing season length is temperature-dependent.	Olson et al. (2001); Conradi et al. (2020)
TeCF	Yes	Strongly constrained by winter cold extremes and growing season length.	Olson et al. (2001)
TeGS	Yes	Temperature extremes (cold winters, warm summers) strongly influence distribution.	Olson et al. (2001)
BoFT	Yes	Long cold winters and short summers sharply define limits; temperature is primary driver.	Olson et al. (2001); Mucina (2019)
Tun	Yes	Primarily defined by extreme low temperatures, permafrost, and short growing season.	Olson et al. (2001); Mucina (2019); Conradi et al. (2020)

Table S3: Linear regression models between the number of biome types in the F31 biome maps and κ.

Model	Slope	R2	p value
CARAIB	0.00051929	0.02162	0.42993
CLM	-0.00137083	0.03119	0.34187
LPJ-GUESS	-0.00112037	0.01595	0.49839
ORCHIDEE	-0.00054955	0.00513	0.70184
ORCHIDEE-DGVM	0.00018983	0.00066	0.89071
ESACCI	-0.00096713	0.11253	0.06506
Touanmu	-0.00048656	0.14269	0.03617

Table S4: Linear regression models between the proportion of the land surface affected by biome shifts under climate change and κ.

Model	Slope	R2	p value
CARAIB	-0.21327034	0.3529	0.00043
CLM	-1.84027664	0.67317	0
LPJ-GUESS	-0.62708825	0.24688	0.00446
ORCHIDEE	-0.72792962	0.36964	0.00029
ORCHIDEE-DGVM	-0.54408676	0.4039	0.00012

Table S5: Linear regression models between the proportion of the land surface affected by biome shifts under climate change and the number of biomes in F31 biome map.

Model	Slope	R2	p value
CARAIB	0.00051929	0.02162	0.42993
CLM	-0.00137083	0.03119	0.34187
LPJ-GUESS	-0.00112037	0.01595	0.49839
ORCHIDEE	-0.00054955	0.00513	0.70184
ORCHIDEE-DGVM	0.00018983	0.00066	0.89071

Table S6: Biome coverage and change for Olson map. Columns are LP – LPJ-GUESS; OR – ORCHIDEE; OD – ORCHIDEE-DGVM; CA – CARAIB; CL – CLM4.5; c – current; f – future; s – shift between current and future.

biome	LPc	LPf	LPs	ORc	ORf	ORs	ODc	ODf	ODs	CAc	CAf	CAs	CLc	CLf	CLs
TrMBF	11.8	11.7	-0.1	12.5	12.6	0.1	12.4	16.5	4.1	11.7	13.1	1.4	11.9	11.7	-0.2
TrGS	15.4	18.0	2.6	12.7	13.5	0.7	13.5	12.3	-1.2	11.5	14.8	3.3	13.7	13.6	-0.1
TrDBF	0.2	0.0	-0.2	1.1	0.5	-0.6	0.6	0.1	-0.5	1.7	0.8	-0.9	0.0	0.0	-0.0
TrCF	0.0	0.0	-0.0	0.2	0.3	0.0	0.2	0.1	-0.2	0.4	0.1	-0.4	0.1	0.0	-0.1
FlGS	0.0	0.0	-0.0	0.2	0.1	-0.1	0.2	0.1	-0.2	0.6	0.1	-0.6	0.1	0.1	-0.0
DeXS	19.8	20.1	0.3	16.2	16.4	0.2	17.7	16.6	-1.0	17.2	16.7	-0.6	11.6	12.0	0.5
MoGS	1.1	1.4	0.3	2.4	1.6	-0.9	2.4	3.4	0.9	3.2	1.7	-1.5	2.2	2.1	-0.1
MeFWS	0.4	0.5	0.1	1.8	1.4	-0.3	2.1	2.0	-0.1	2.2	2.0	-0.2	1.4	1.4	-0.0
TeBMF	10.8	16.5	5.7	10.6	12.1	1.5	10.0	14.8	4.8	10.2	16.6	6.4	10.6	11.1	0.6
TeCF	1.2	1.0	-0.2	2.8	2.0	-0.8	3.8	3.6	-0.2	3.0	2.2	-0.8	1.8	1.6	-0.1
TeGS	7.0	5.5	-1.5	8.3	8.2	-0.2	7.8	6.8	-1.0	8.1	10.6	2.5	9.1	8.7	-0.4
BoFT	19.4	18.2	-1.1	20.0	21.3	1.3	16.0	18.1	2.1	17.1	15.3	-1.8	19.2	20.3	1.1
Tun	12.8	7.0	-5.8	11.2	10.1	-1.1	13.3	5.7	-7.6	13.0	6.0	-7.0	18.3	17.3	-1.0

Table S7: Abbreviations of Olson et al. (2001) biomes.

Biome	Biome full name
TrMBF	Tropical and subtropical moist broadleaf forest
TrGS	Tropical and subtropical grassland savanna and shrubland
TrDBF	Tropical and subtropical dry broadleaf forest
TrCF	Tropical and subtropical coniferous forest
FlGS	Flooded grassland and savanna
DeXS	Deserts and xeric shrubland
MoGS	Montane grassland and shrubland
MeFWS	Mediterranean forest woodland and scrub
TeBMF	Temperate broadleaf and mixed forest
TeCF	Temperate conifer forest
TeGS	Temperate grassland savanna and shrubland
BoFT	Boreal forest/taiga
Tun	Tundra

Table S8: Confusion matrix LPJ-GUESS vs Olson et al. (2001) biome map. Overall $\kappa = 0.73$. See Table S7 for full biome names.

Biome	κ	1	2	3	4	5	6	7	8	9	10	11	12	13
1 TrMBF	0.79	82.8	12.8	0.0	0.0	0.0	0.6	0.1	0.0	3.8	0.0	0.0	0.0	0.0
3 TrGS	0.70	8.7	85.5	0.0	0.0	0.0	5.7	0.0	0.1	0.0	0.0	0.0	0.0	0.0
4 TrDBF	0.20	17.8	68.2	11.2	0.0	0.0	2.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0
5 TrCF	0.12	23.0	51.2	0.0	6.2	0.0	12.1	0.0	2.0	3.9	0.0	1.6	0.0	0.0
6 FlGS	0.10	7.1	55.8	0.0	0.0	5.3	12.1	0.0	0.0	11.4	0.0	6.6	0.8	1.0
7 DeXS	0.78	0.1	8.1	0.0	0.0	0.0	87.2	0.1	0.0	0.2	0.1	1.6	0.1	2.6
8 MoGS	0.42	3.7	5.6	0.0	0.0	0.0	22.0	28.2	0.2	1.8	0.9	4.0	4.1	29.5
9 MeFWS	0.26	4.4	10.1	0.0	0.0	0.0	49.3	0.2	16.2	16.3	0.4	3.1	0.0	0.0
10 TeBMF	0.78	2.5	0.6	0.0	0.0	0.0	3.4	0.0	0.2	82.3	0.2	4.6	6.3	0.1
11 TeCF	0.47	6.5	0.3	0.0	0.0	0.0	6.2	0.6	0.2	18.1	32.8	2.3	27.8	5.3
12 TeGS	0.76	1.0	2.2	0.0	0.0	0.0	13.2	0.0	0.3	6.7	0.2	71.9	3.6	0.9
13 BoFT	0.81	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.0	1.4	0.0	0.1	89.5	8.8
14 Tun	0.75	0.0	0.0	0.0	0.0	0.0	1.5	0.5	0.0	0.0	0.3	0.0	15.3	82.3

Table S9: Confusion matrix ORCHIDEE vs Olson et al. (2001) biome map. Overall $\kappa = 0.87$. See Table S7 for full biome names.

Biome	κ	1	2	3	4	5	6	7	8	9	10	11	12	13
1 TrMBF	0.91	94.8	3.8	0.2	0.0	0.0	0.1	0.1	0.0	0.6	0.1	0.4	0.0	0.0
3 TrGS	0.86	4.5	90.1	0.0	0.0	0.0	4.0	0.0	0.0	0.4	0.1	0.9	0.0	0.0
4 TrDBF	0.69	23.7	17.5	56.0	0.0	0.0	1.0	0.1	0.0	1.3	0.0	0.5	0.0	0.0
5 TrCF	0.70	10.6	7.1	8.2	54.5	0.0	10.2	0.0	1.2	6.7	1.2	0.4	0.0	0.0
6 FlGS	0.40	10.1	30.7	0.5	0.0	25.6	16.6	0.0	0.5	8.5	0.8	6.8	0.0	0.0
7 DeXS	0.90	0.3	3.3	0.1	0.0	0.0	93.9	0.1	0.2	0.2	0.6	1.2	0.0	0.0
8 MoGS	0.78	2.6	3.0	0.1	0.0	0.1	14.4	65.7	0.2	3.1	2.5	6.4	1.0	1.2
9 MeFWS	0.82	0.2	0.9	0.0	0.0	0.0	7.6	0.1	73.3	10.5	1.1	6.2	0.0	0.0
10 TeBMF	0.89	1.4	0.1	0.0	0.0	0.1	0.9	0.0	0.2	90.8	0.8	1.8	3.8	0.1
11 TeCF	0.77	0.2	0.0	0.0	0.0	0.0	3.7	0.9	0.3	5.5	70.6	2.2	15.6	1.0
12 TeGS	0.86	0.0	2.0	0.0	0.0	0.0	2.2	0.0	0.2	3.6	0.7	87.7	3.4	0.2
13 BoFT	0.89	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.1	97.0	2.5
14 Tun	0.90	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	12.4	87.5

Table S10: Confusion matrix ORCHIDEE-DGVM vs Olson et al. (2001) biome map. Overall $\kappa = 0.89$. See Table S7 for full biome names.

Biome	κ	1	2	3	4	5	6	7	8	9	10	11	12	13
1 TrMBF	0.87	93.1	6.2	0.3	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0
3 TrGS	0.80	8.5	89.2	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.1	0.0	0.0
4 TrDBF	0.44	36.2	33.5	29.7	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 TrCF	0.62	16.4	21.5	3.1	47.3	0.0	9.8	0.0	0.4	0.4	1.2	0.0	0.0	0.0
6 FlGS	0.44	11.8	44.1	0.0	0.0	29.8	10.0	0.0	0.0	2.3	0.0	2.0	0.0	0.0
7 DeXS	0.91	0.3	6.5	0.1	0.1	0.0	91.7	0.1	0.1	0.1	0.7	0.2	0.0	0.3
8 MoGS	0.73	2.4	4.7	0.2	0.1	0.0	11.0	62.7	0.2	1.2	3.4	2.5	0.2	11.6
9 MeFWS	0.94	0.0	0.0	0.0	0.0	0.1	5.4	0.0	91.2	2.0	0.9	0.3	0.0	0.0
10 TeBMF	0.95	0.3	0.1	0.0	0.1	0.3	0.6	0.0	0.2	95.3	1.4	0.6	0.5	0.6
11 TeCF	0.89	0.2	0.0	0.0	0.0	0.0	0.9	1.3	0.3	1.1	95.9	0.0	0.1	0.3
12 TeGS	0.94	0.0	0.3	0.0	0.0	0.0	2.0	0.0	0.2	2.1	1.5	93.2	0.5	0.1
13 BoFT	0.95	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.5	0.3	0.5	93.0	5.1
14 Tun	0.93	0.0	0.0	0.0	0.0	0.0	0.2	0.9	0.0	0.0	0.1	0.0	0.1	98.7

Table S11: Confusion matrix CLM vs Olson et al. (2001) biome map. Overall $\kappa = 0.69$. See Table S7 for full biome names.

Biome	κ	1	2	3	4	5	6	7	8	9	10	11	12	13
1 TrMBF	0.83	85.0	10.8	0.0	0.0	0.0	0.4	0.0	0.0	2.6	0.1	0.5	0.0	0.5
3 TrGS	0.59	6.3	68.6	0.0	0.0	0.0	18.6	0.0	0.1	0.1	0.0	1.6	0.0	4.7
4 TrDBF	0.03	34.1	60.5	1.7	0.0	0.0	2.3	0.1	0.0	0.0	0.0	1.0	0.0	0.4
5 TrCF	0.38	17.2	33.2	0.0	23.8	0.0	6.2	0.0	6.6	3.1	0.4	9.4	0.0	0.0
6 FlGS	0.27	4.3	47.0	0.0	0.0	15.4	11.1	0.0	0.0	7.3	0.0	9.2	0.0	5.7
7 DeXS	0.54	0.2	11.4	0.0	0.0	0.0	54.4	0.5	0.2	0.1	0.1	4.2	1.2	27.7
8 MoGS	0.67	1.6	7.2	0.0	0.0	0.0	9.6	54.1	1.3	0.5	0.1	8.9	6.3	10.5
9 MeFWS	0.63	0.1	4.5	0.0	0.0	0.0	16.6	0.5	50.9	5.2	0.0	18.0	0.1	4.1
10 TeBMF	0.85	0.6	0.8	0.0	0.0	0.0	0.9	0.1	0.5	86.5	0.1	5.4	4.1	0.9
11 TeCF	0.63	0.6	0.6	0.0	0.0	0.0	1.9	1.3	0.5	9.4	47.7	2.9	32.5	2.6
12 TeGS	0.74	0.0	4.4	0.0	0.0	0.0	6.4	1.0	0.5	3.8	0.3	78.5	3.2	2.0
13 BoFT	0.79	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.9	0.1	0.1	85.5	13.2
14 Tun	0.64	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	12.4	87.3

Table S12: Confusion matrix CARAIB vs Olson et al. (2001) biome map. Overall $\kappa = 0.96$. See Table S7 for full biome names.

Biome	κ	1	2	3	4	5	6	7	8	9	10	11	12	13
1 TrMBF	0.99	99.6	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3 TrGS	0.98	1.4	98.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4 TrDBF	0.96	3.5	3.6	92.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 TrCF	0.98	3.5	0.4	0.0	96.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6 FlGS	0.96	0.5	6.9	0.0	0.0	92.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7 DeXS	1.00	0.0	0.3	0.0	0.0	0.0	99.4	0.2	0.0	0.0	0.0	0.0	0.0	0.1
8 MoGS	0.90	0.0	0.0	0.0	0.0	0.0	0.0	86.1	0.0	0.0	0.0	0.0	1.6	12.3
9 MeFWS	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0
10 TeBMF	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	99.8	0.0	0.0	0.1	0.0
11 TeCF	0.95	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	90.2	0.0	5.9	2.6
12 TeGS	0.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	99.1	0.7	0.1
13 BoFT	0.92	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	92.4	7.6
14 Tun	0.88	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	5.6	93.9

Table S13: Confusion matrix ESACCI vs Olson et al. (2001) biome map. Overall $\kappa = 0.94$. See Table S7 for full biome names.

Biome	κ	1	2	3	4	5	6	7	8	9	10	11	12	13
1 TrMBF	0.99	98.1	1.5	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3 TrGS	0.88	0.2	88.7	0.0	0.0	0.0	10.7	0.0	0.0	0.0	0.0	0.0	0.0	0.3
4 TrDBF	0.96	2.1	4.0	92.1	0.0	0.0	1.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0
5 TrCF	0.99	2.0	0.0	0.0	98.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6 FlGS	0.77	0.0	26.9	0.0	0.0	63.1	9.8	0.0	0.0	0.0	0.0	0.0	0.0	0.3
7 DeXS	0.87	0.0	1.4	0.0	0.0	0.0	94.0	0.1	0.0	0.0	0.0	0.2	0.0	4.2
8 MoGS	0.93	0.1	4.3	0.0	0.0	0.0	5.2	89.1	0.1	0.0	0.0	0.2	0.0	1.2
9 MeFWS	0.90	0.0	5.4	0.0	0.0	0.0	7.9	0.2	81.9	0.1	0.0	0.2	0.4	4.0
10 TeBMF	0.98	0.0	0.1	0.0	0.0	0.0	2.7	0.0	0.0	96.2	0.2	0.3	0.3	0.2
11 TeCF	0.95	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.1	0.5	92.8	0.5	5.4	0.1
12 TeGS	0.93	0.0	2.0	0.0	0.0	0.0	5.7	0.2	0.0	0.1	0.0	88.7	0.2	3.1
13 BoFT	0.98	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	99.4	0.5
14 Tun	0.93	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.8	97.7

Table S14: Confusion matrix Tuanmu et al. vs Olson et al. (2001) biome map. Overall κ = 0.99. See Table S7 for full biome names.

Biome	κ	1	2	3	4	5	6	7	8	9	10	11	12	13
1 TrMBF	1.00	99.8	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3 TrGS	0.98	0.0	97.8	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.6
4 TrDBF	1.00	0.0	0.0	99.9	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 TrCF	1.00	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6 FlGS	0.99	0.0	0.8	0.0	0.0	98.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7 DeXS	0.97	0.0	0.4	0.0	0.0	0.0	98.5	0.0	0.0	0.0	0.0	0.1	0.0	1.1
8 MoGS	0.98	0.0	0.9	0.0	0.0	0.0	3.1	96.0	0.0	0.0	0.0	0.0	0.0	0.1
9 MeFWS	0.98	0.0	0.0	0.0	0.0	0.0	3.3	0.0	96.7	0.0	0.0	0.0	0.0	0.0
10 TeBMF	1.00	0.0	0.1	0.0	0.0	0.0	0.4	0.0	0.0	99.6	0.0	0.0	0.0	0.0
11 TeCF	1.00	0.0	0.0	0.0	0.0	0.0	0.5	0.1	0.0	0.0	99.4	0.0	0.0	0.0
12 TeGS	0.99	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	98.8	0.0	0.0
13 BoFT	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
14 Tun	0.98	0.0	0.1	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	99.3

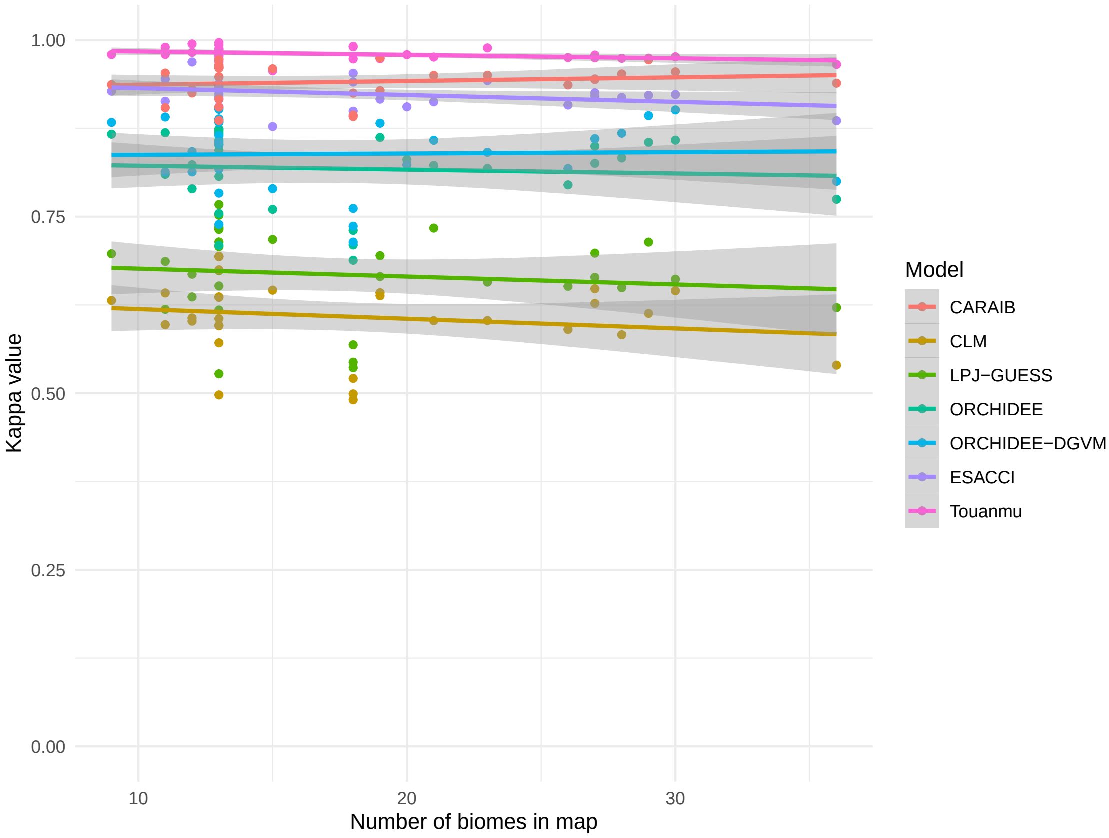

Figure S1: Data-model agreement in relation to the number of biomes in F31 biome maps. Each point represents the κ value of the biome classification with one of the F31 biome maps. Lines are linear regressions.

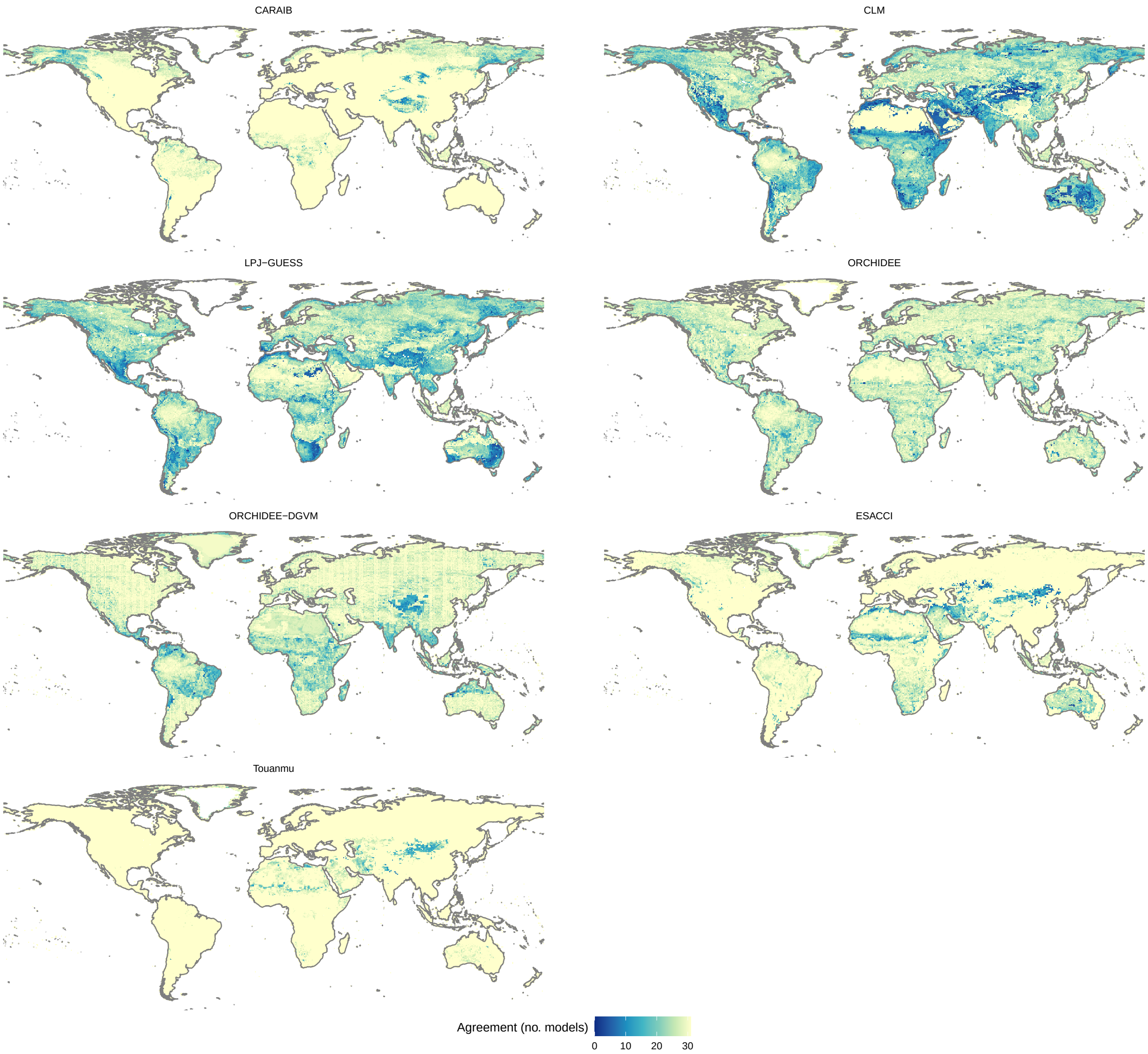

Figure S2: Data-model agreement for each GVM and PFT product. The figure shows the number of maps where the observation-based and modeled biome type agree for all combinations of the F31 biome maps, each of the five GVMs and the two PFT products. Dark blue indicates areas with low agreement.

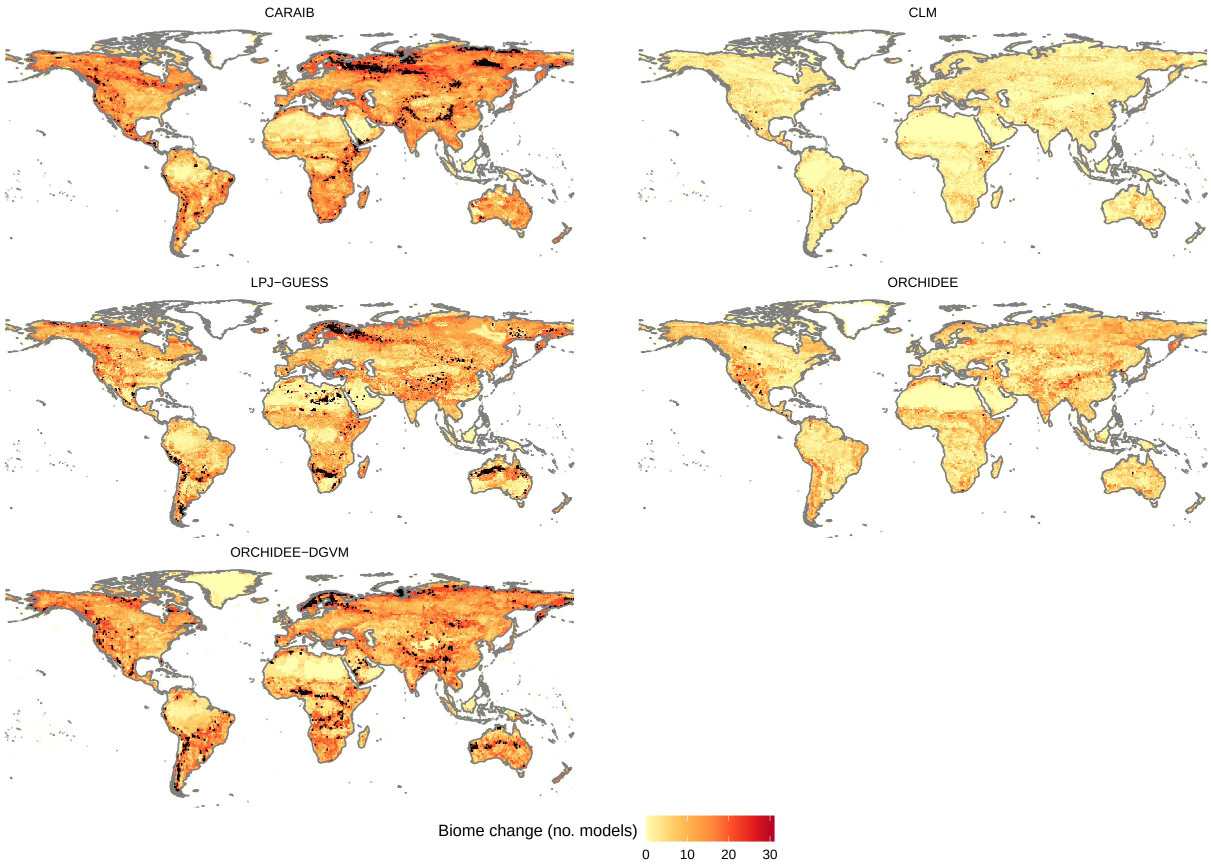

Figure S3: Susceptibility to biome change for each GVM under RCP6.0. The figure shows the number of models that project a biome change until the end of the century for all combinations of the F31 biome maps and each of the five GVMs. Dark red indicates areas with high susceptibility to biome change.

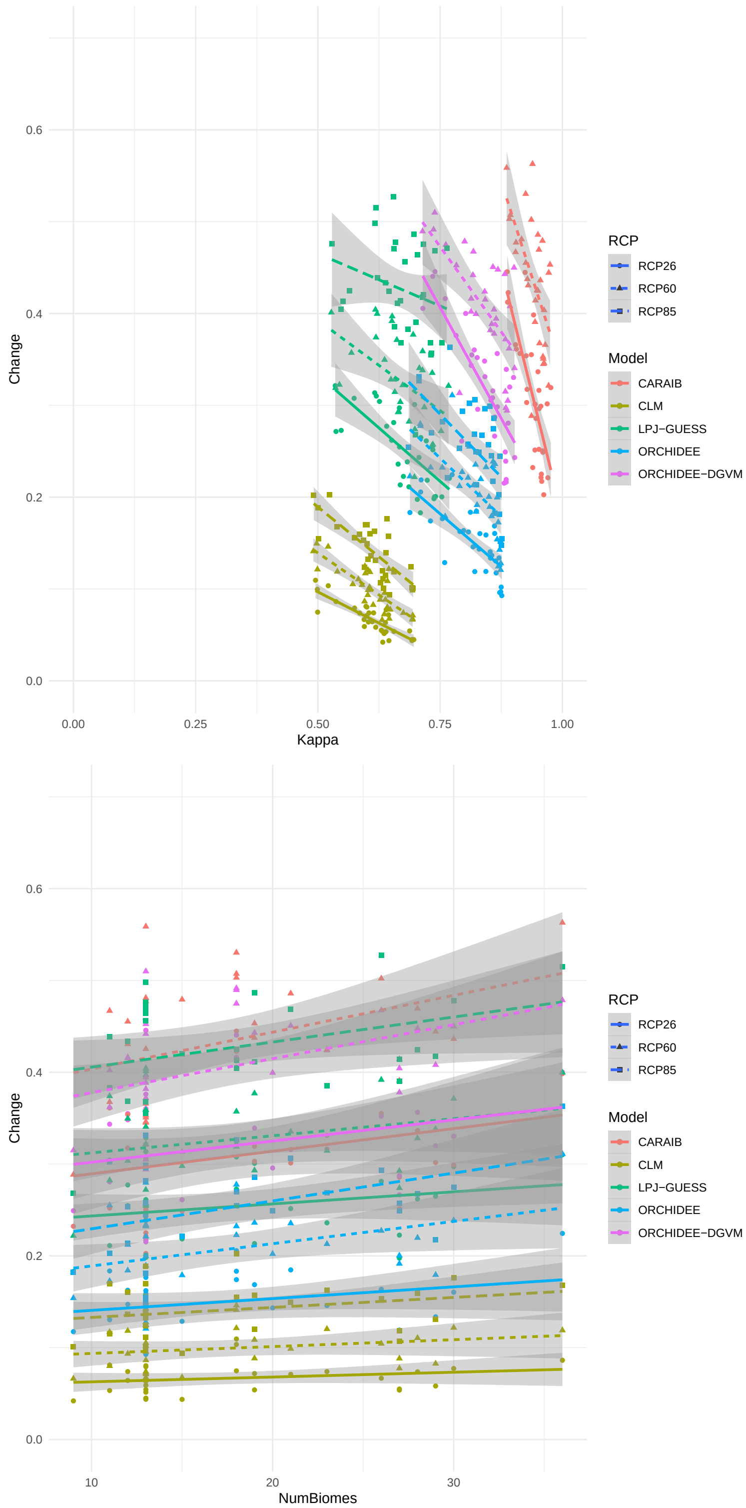

Figure S4: Rate of biome change in relation to data-model agreement and the number of biomes. Each point represents a biome classification for one of the F31 biome maps. The κ values were calculated for all biomes in the respective data-model combination. Different point and line types represent different RCPs. Change represents the proportion of grid cells undergoing biome transitions until the end of the century for a given GVM and biome classification.

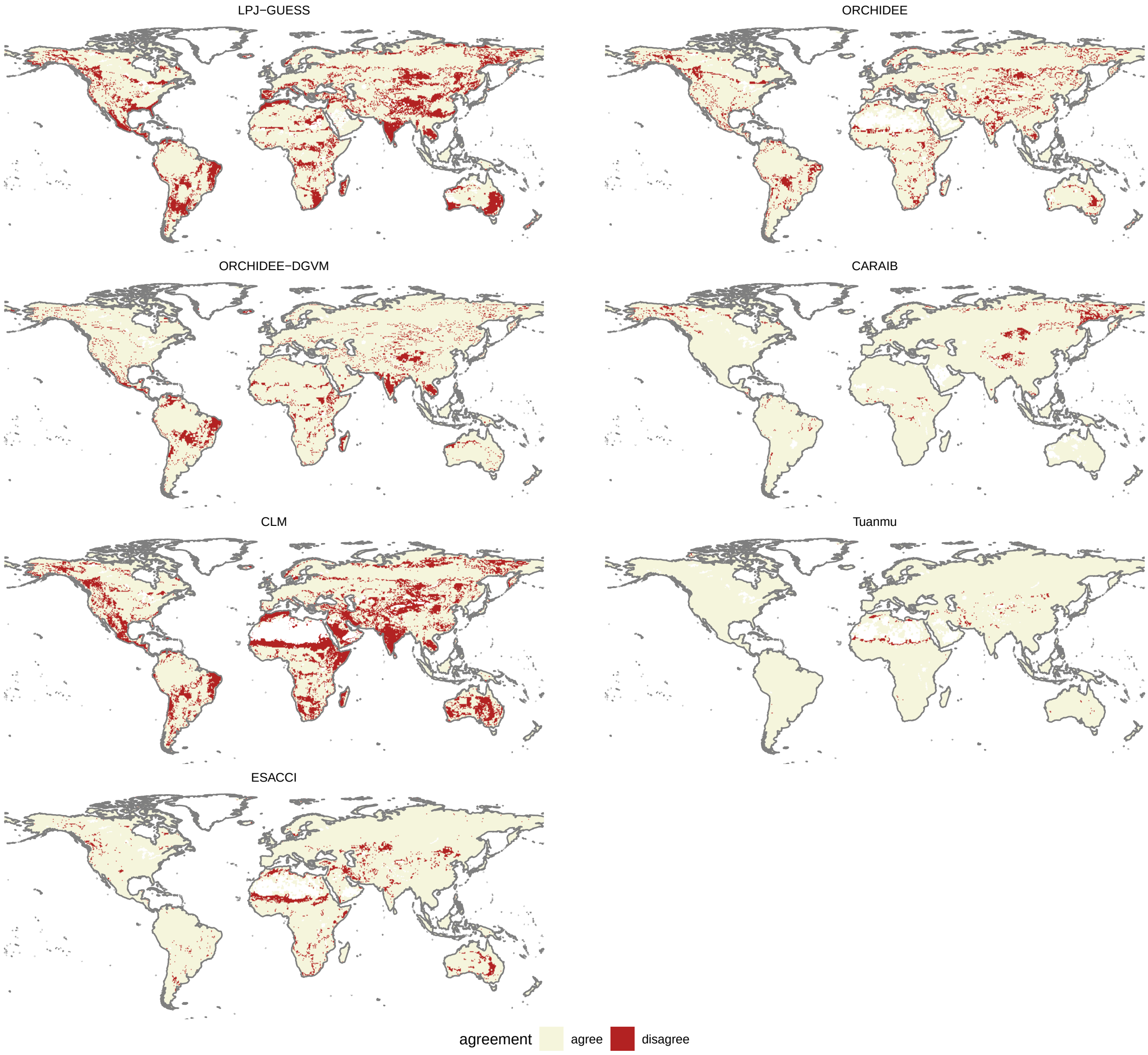

Figure S5: Agreement between Olson et al. (2001) biomes and modeled biomes. Biome maps for current conditions for different models are provided in Fig. 4 in the main text.

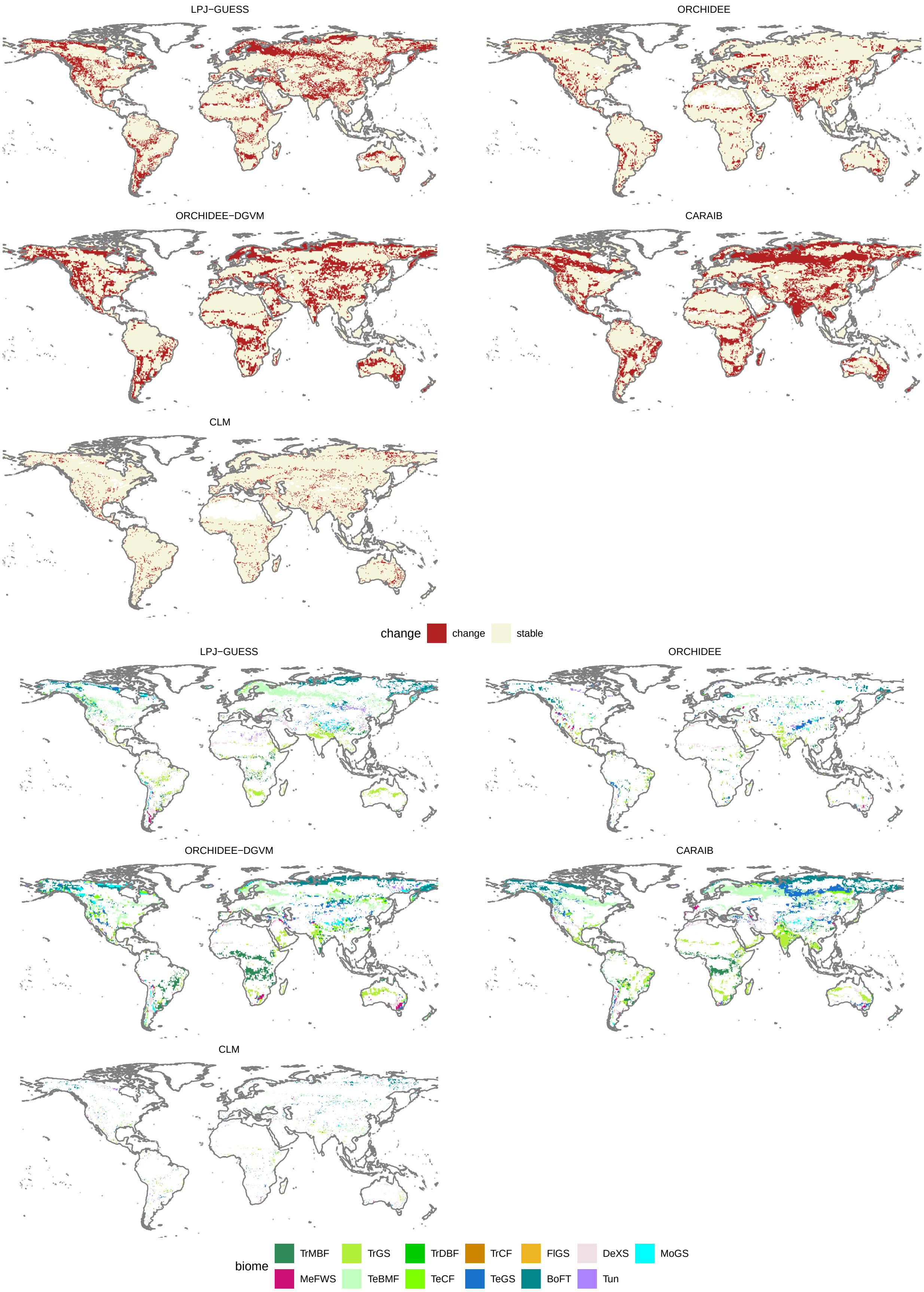

Figure S6: Biome changes projected by GVMs. Here, biome classification schemes fitted for the Olson et al. (2001) biome map were used. The upper panels indicate areas where biome shifts are projected, the lower panels show the biome type at the end of the century for areas where biome shifts are projected. See Table S7 for full biome names.

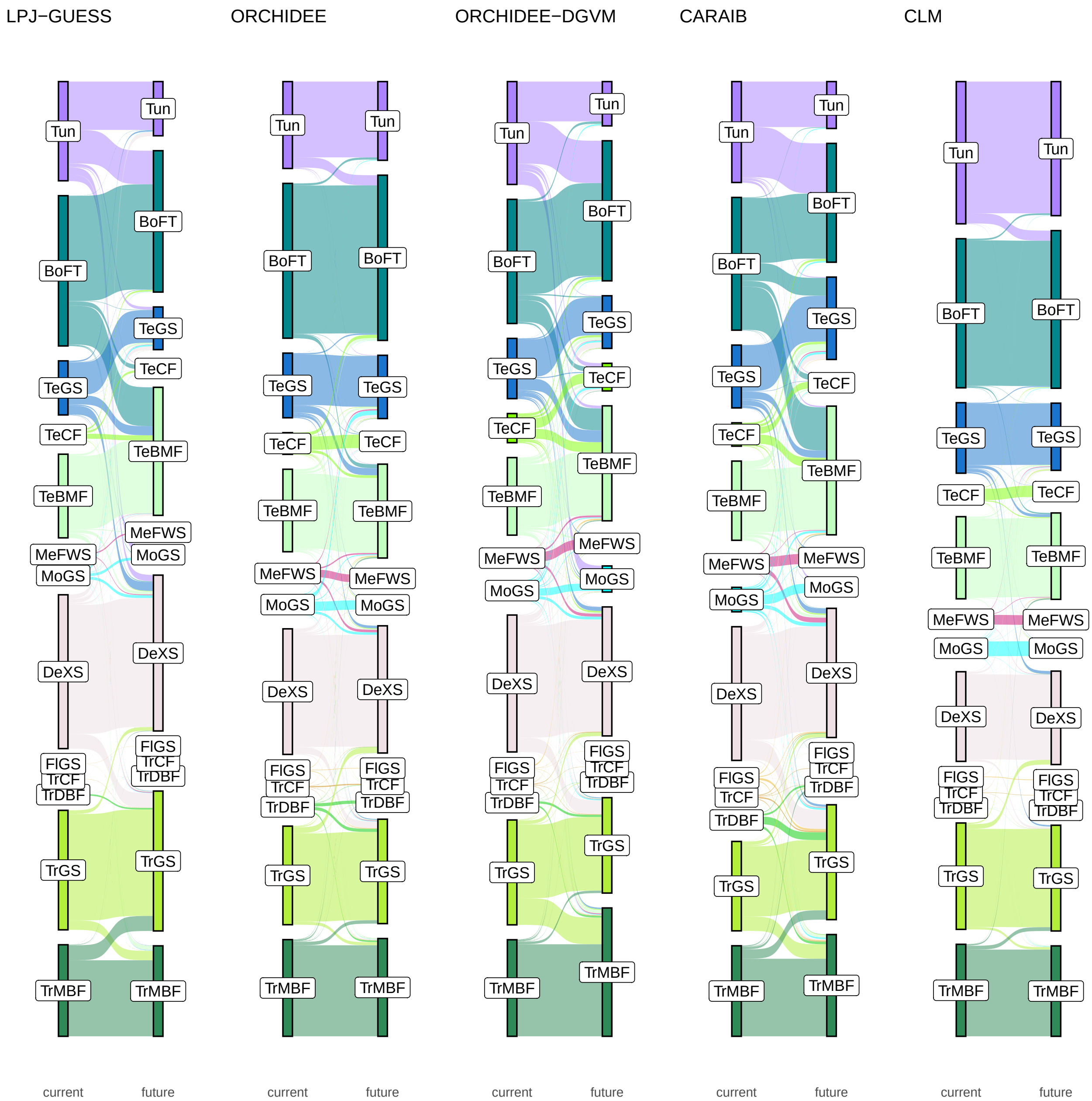

Figure S7: Biome changes projected by GVMs. The Sankey diagrams illustrate transitions between different biomes between current and future conditions for different GVMs and biome classification informed by the Olson et al. (2001) map. The height of the rectangles represents the biome coverage under current or future conditions, the width of the links represents the number of transitions between biomes. See Table S7 for full biome names.

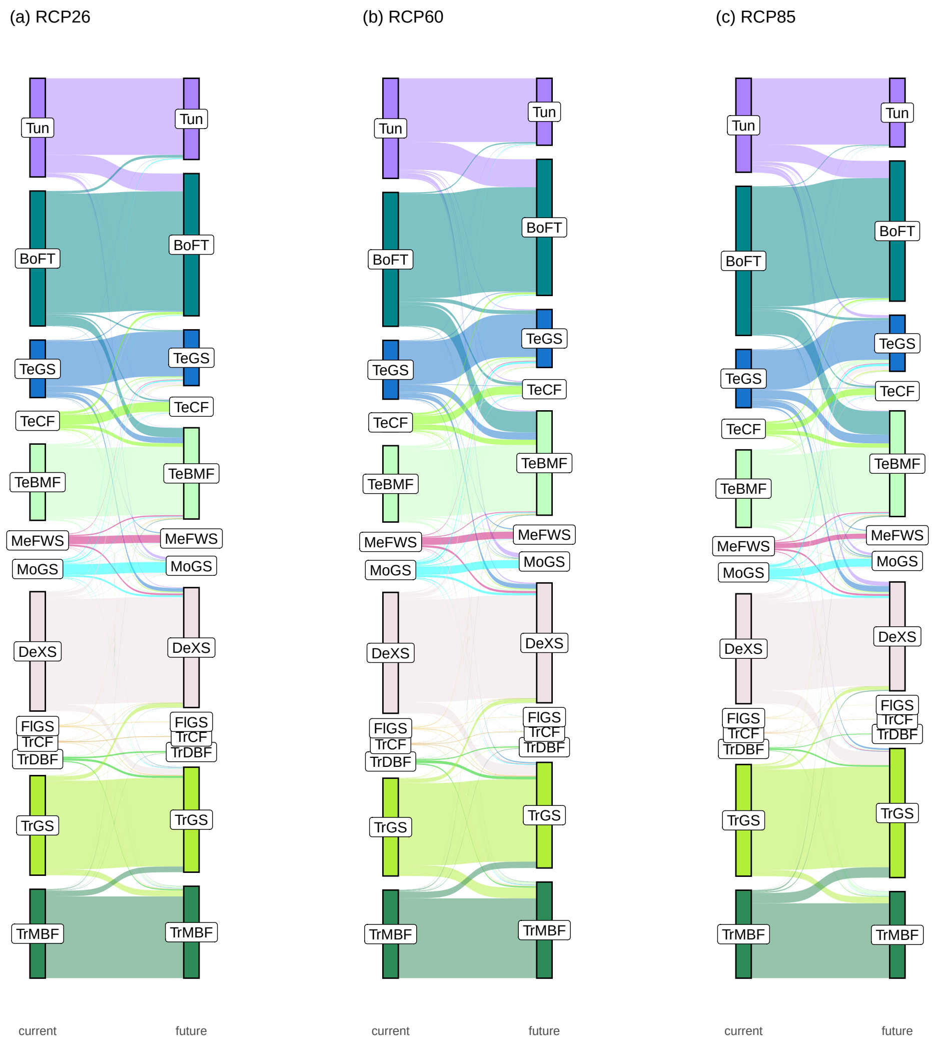

Figure S8: Biome changes projected by GVMs for different RCPs. The Sankey diagrams illustrate transitions between different biomes between current and future conditions and biome classification informed by the Olson et al. (2001) map. For each scenario, all available GVMs were included. See Fig. S8 for plots of individual models for RCP6.0. The height of the rectangles represents the biome coverage under current or future conditions, the width of the links represents the number of transitions between biomes. See Table S7 for full biome names.