Large uncertainties in future biome changes in Africa call for flexible climate adaptation strategies

Supporting Information

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R code for ω² metric:

The following R code was used to calculate the effect size of the explanatory variables. The R code was derived from https://stats.stackexchange.com/questions/2962/omega-squared-for-measure-of-effect-in-r (website accessed on June 03, 2020, 12:55).

```
omega_sq <- function(aov_in, neg2zero=T){
   aovtab <- summary(aov_in)[[1]]
   n_terms <- length(aovtab[["Sum Sq"]]) - 1
   output <- rep(-1, n_terms)
   SSr <- aovtab[["Sum Sq"]][n_terms + 1]
   MSr <- aovtab[["Mean Sq"]][n_terms + 1]
   SSt <- sum(aovtab[["Sum Sq"]])
   for(i in 1:n_terms){
      SSm <- aovtab[["Sum Sq"]][i]
      DFm <- aovtab[["Df"]][i]
      output[i] <- (SSm-DFm*MSr)/(SSt+MSr)
      if(neg2zero & output[i] < 0){output[i] <- 0}
   }
   names(output) <- rownames(aovtab)[1:n_terms]

   return(output)
}
```

Supplementary Figures and Tables

Supplementary Table S1: General Circulation Models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) used in the ensemble experiment and the institutions and countries, where they were developed.

GCM abbreviation	Full name	Institute	Country of origin
ACCESS	Australian Community Climate and Earth System Simulator	Commonwealth Scientific and Industrial Research Organisation/ Bureau of Meteorology	Australia
CCSM4	Community Climate System Model 4	National Center for Atmospheric Research (NCAR)	USA
CNRM	CNRM Climate Model version 5 (CNRM-CM5)	Centre National de Recherches Météorologiques (CNRM)	France
GFDL	GFDL Climate Model version 3 (GFDL-CM3)	Geophysical Fluid Dynamics Laboratory (GFDL)	USA
MPI	MPI Earth System Model (MPI-ESM)	Max Planck Institute (MPI) for Meteorology	Germany
NorESM1M	Norwegian Earth System Model	Bjerknes Centre for Climate Research, Norwegian Meteorological Institute (NCC)	Norway

Supplementary Table S2: Scheme for classifying vegetation into seven different biomes, based on Scheiter et al. (2012 & 2018). Dominant trees or grasses account for >50% of tree cover or grass biomass (peak leaf biomass), respectively. '–' means that a variable was not used for the classification of a certain biome.

Biome	Tree cover	Dominant trees	Grass biomass	Dominant grasses
Desert	<10%	-	<1.5t/ha	-
C_4 grassland	<10%	-	>1.5t/ha	C_4
C_3 grassland	<10%	-	>1.5t/ha	C_3
C_4 savanna	10-80%	Savanna tree	-	C_4
C_3 savanna	10-80%	Savanna tree	-	C_3
Woodland	10-80%	Forest tree	-	-
Forest	>80%	-	-	-

Supplementary Table S3: Variability of carbon stored in continental-scale mean total aboveground biomass (in PgC) and variability of WUE (in gC / H_2O) in 2080-2099. 'GCM variability' is 2×SD of the ensemble mean per scenario. 'RCP variability' is the difference between the ensemble means of each RCP scenario per CO_2 scenario. 'CO_2 variability' is the difference between eCO_2 and fCO_2 scenarios per RCP scenario. 'x' designates which scenarios or ensemble members were used to derive the respective variability. '–' means that this category was not considered in the specific case. See Fig. 1 for the according time series.

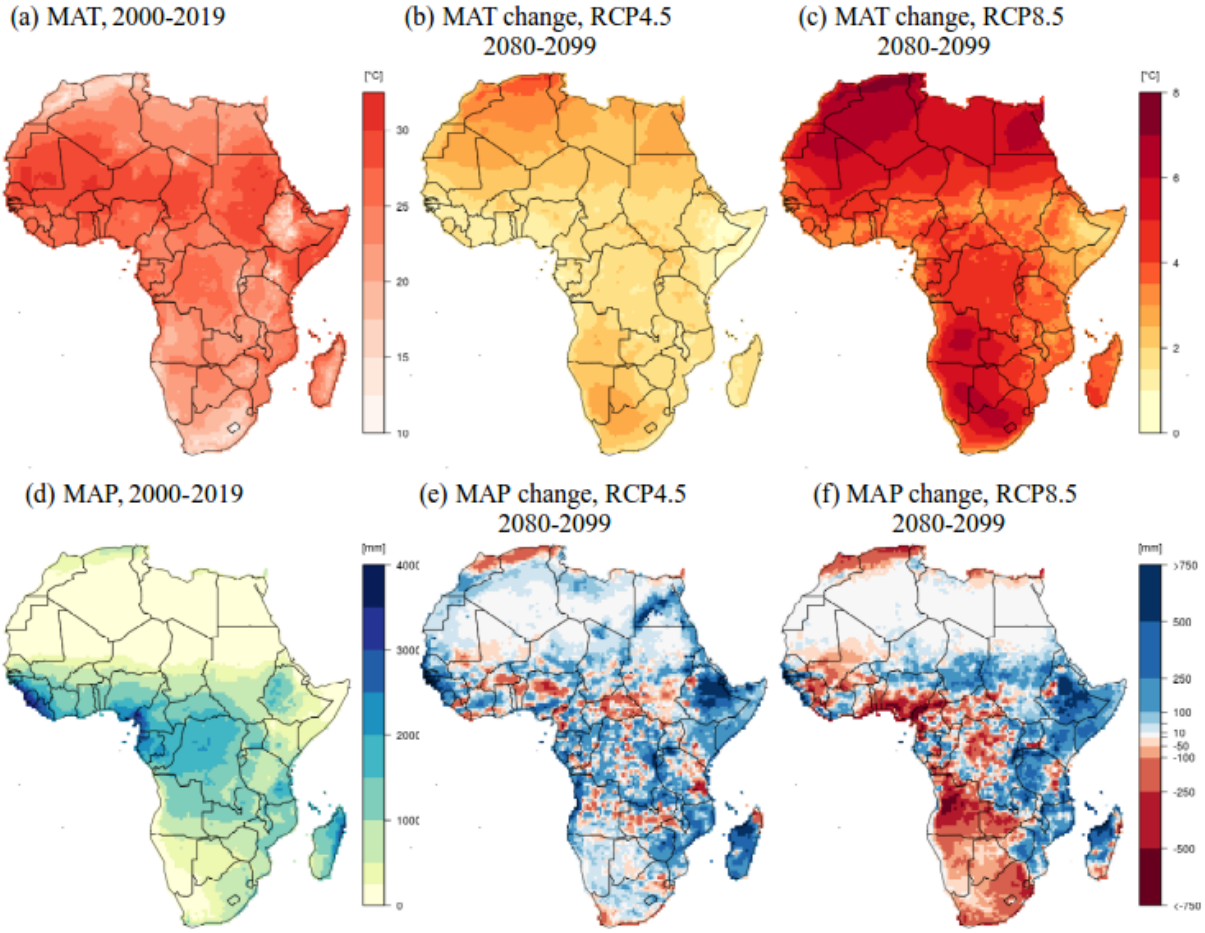
CO_2 scenario		RCP scenario		GCM variability		RCP variability		CO_2 variability	
eCO_2	fCO_2	4.5	8.5	AGB	WUE	AGB	WUE	AGB	WUE
x		x		9.7	0.048	-	-	-	-
x			x	11.2	0.085	-	-	-	-
	x	x		7.2	0.041	-	-	-	-
	x		x	7.2	0.044	-	-	-	-
x		x	x	-	-	11.2	0.327	-	-
	x	x	x	-	-	8.0	0.048	-	-
x	x	x		-	-	-	-	14.8	0.173
x	x		x	-	-	-	-	34.1	0.548

Supplementary Table S4: Change in aboveground biomass (AGB) and WUE from 2000-2019 to 2080-2099 for the six GCMs in each RCP-CO_2 scenario.

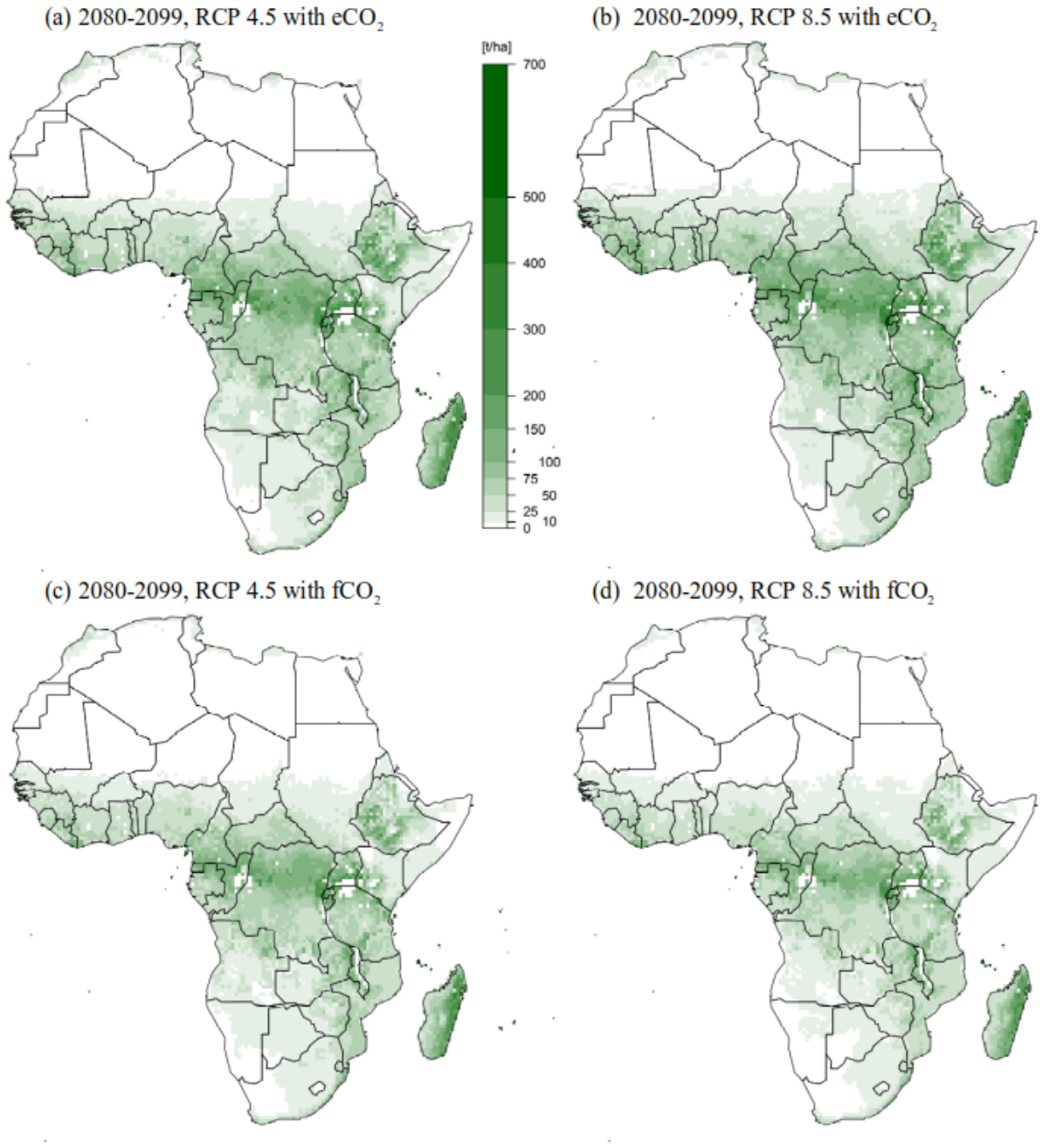
Scenario	GCM	AGB change	WUE change
RCP4.5, eCO_2	ACCESS	31.0%	20.0%
	CCSM4	43.4%	20.2%
	CNRM	33.3%	22.7%
	GFDL	17.7%	15.3%
	MPI	28.7%	21.4%
	NorESM1M	35.7%	24.7%
RCP8.5, eCO_2	ACCESS	59.6%	64.0%
	CCSM4	60.1%	72.2%
	CNRM	61.2%	73.0%
	GFDL	36.4%	61.3%
	MPI	48.4%	65.6%
	NorESM1M	55.2%	73.7%
RCP4.5, fCO_2	ACCESS	3.6%	-4.7%
	CCSM4	11.2%	-4.1%
	CNRM	5.7%	-2.6%
	GFDL	-7.5%	-9.1%
	MPI	2.4%	-3.7%
	NorESM1M	7.5%	-0.9%
RCP8.5, fCO_2	ACCESS	-6.1%	-12.5%
	CCSM4	-7.4%	-9.4%
	CNRM	-6.0%	-8.8%
	GFDL	-22.2%	-15.7%
	MPI	-13.4%	-12.5%
	NorESM1M	-9.8%	-9.0%

Supplementary Table S5: ANOVA for change in carbon in aboveground biomass (AGB) and water use efficiency (WUE) between 2000-2019 and 2080-2099. The table presents F-values from ANOVA for the dependent variables “aboveground biomass change” and “water use efficiency”, and independent variables “CO_2 scenario”, “RCP scenario” and “GCM” that were used for the omega-squared metric. Two-way interaction effects are included in the model and are denoted with ‘:’.

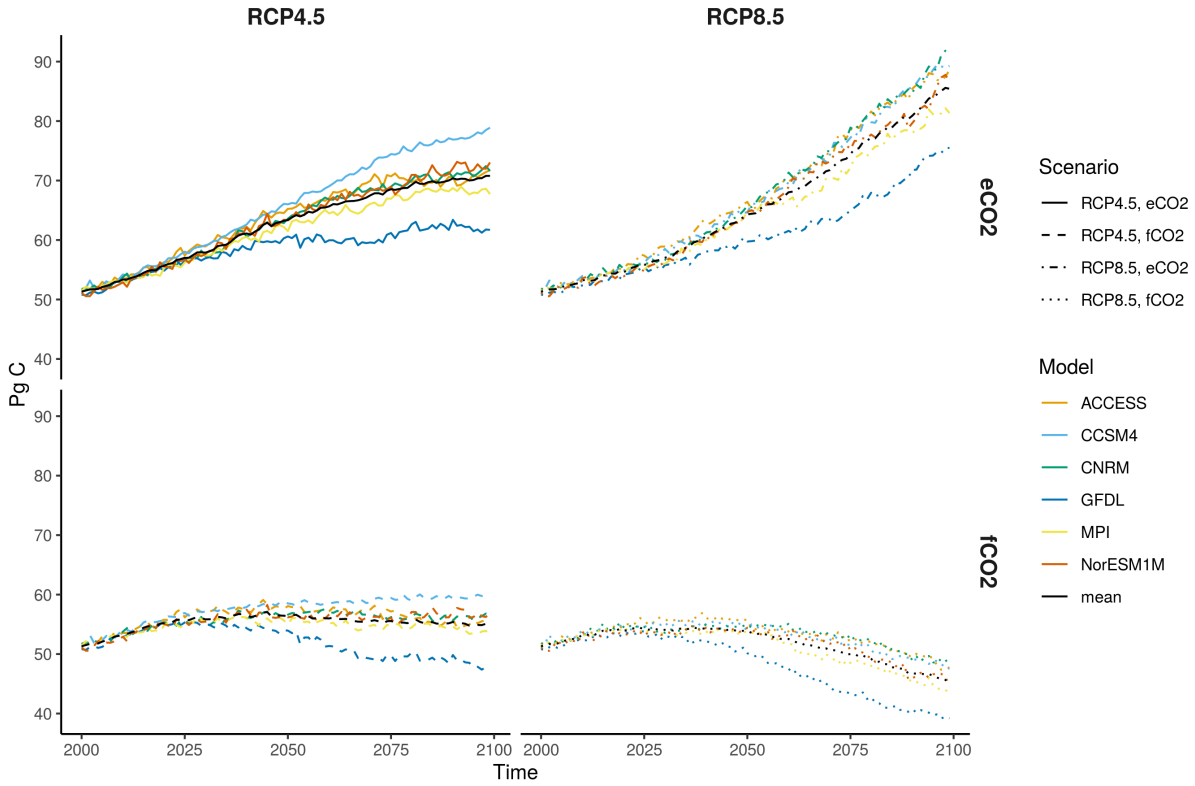
Independent variables & interaction effects	F-value	
	AGB	WUE
CO_2	8330	7992
RCP	50	1210
GCM	146	23
CO_2:RCP	1293	2198
CO_2:GCM	12	3
RCP:GCM	6	2



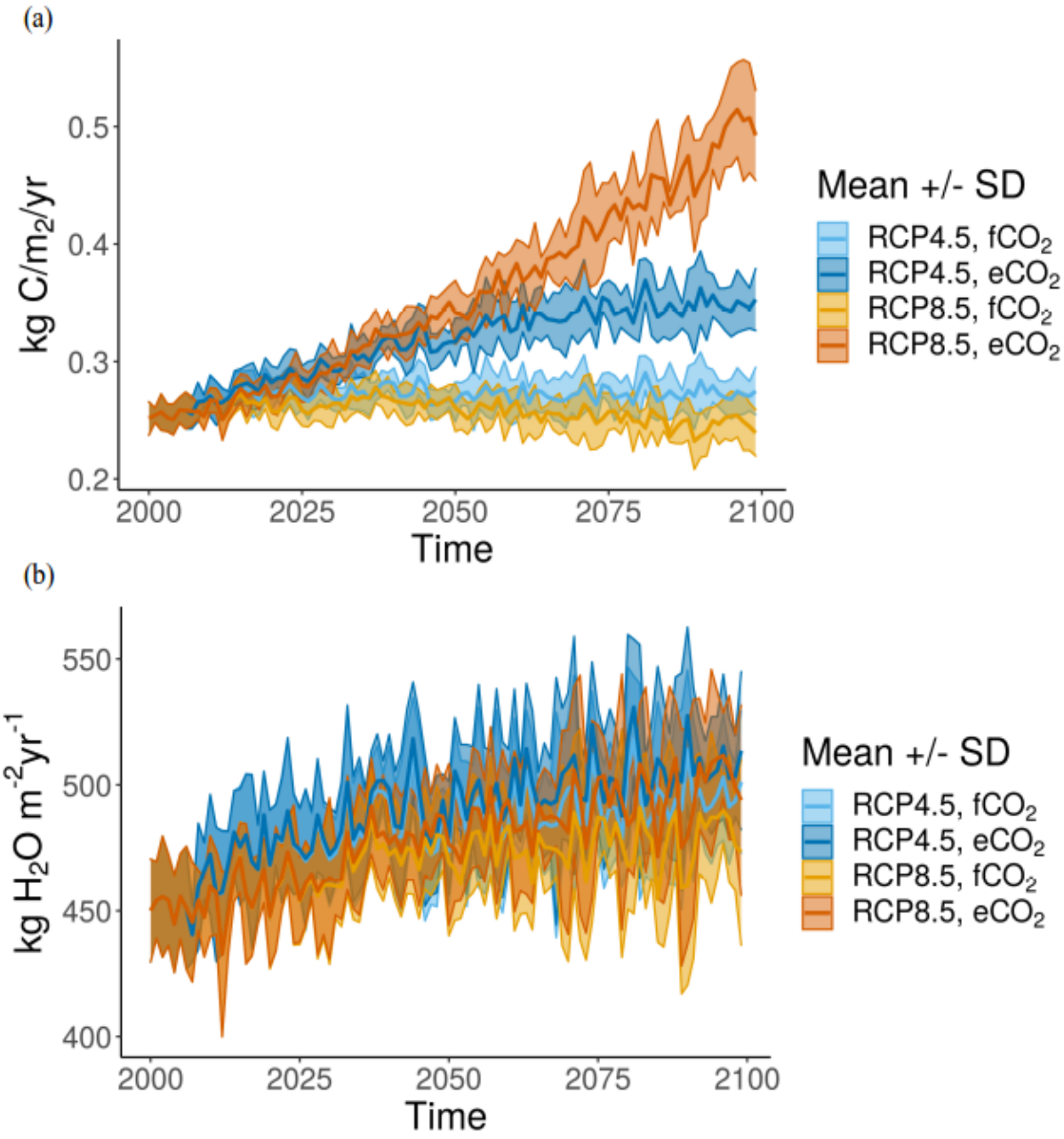
Supplementary Figure S1: Mean annual temperature (MAT) and precipitation (MAP) in 2000-2019 and change by 2080-2099. MAT in 2000-2019 (a) is the mean across all six GCMs under RCP4.5. Change in MAT for RCP4.5 (b) and RCP8.5 (c) is the difference between the periods 2080-2099 and 2000-2019 in °C. MAP in 2000-2019 (d) is the mean across all six GCMs under RCP4.5. Change in MAP for RCP4.5 (e) and RCP8.5 (f) is the difference between the periods 2080-2099 and 2000-2019 in mm.



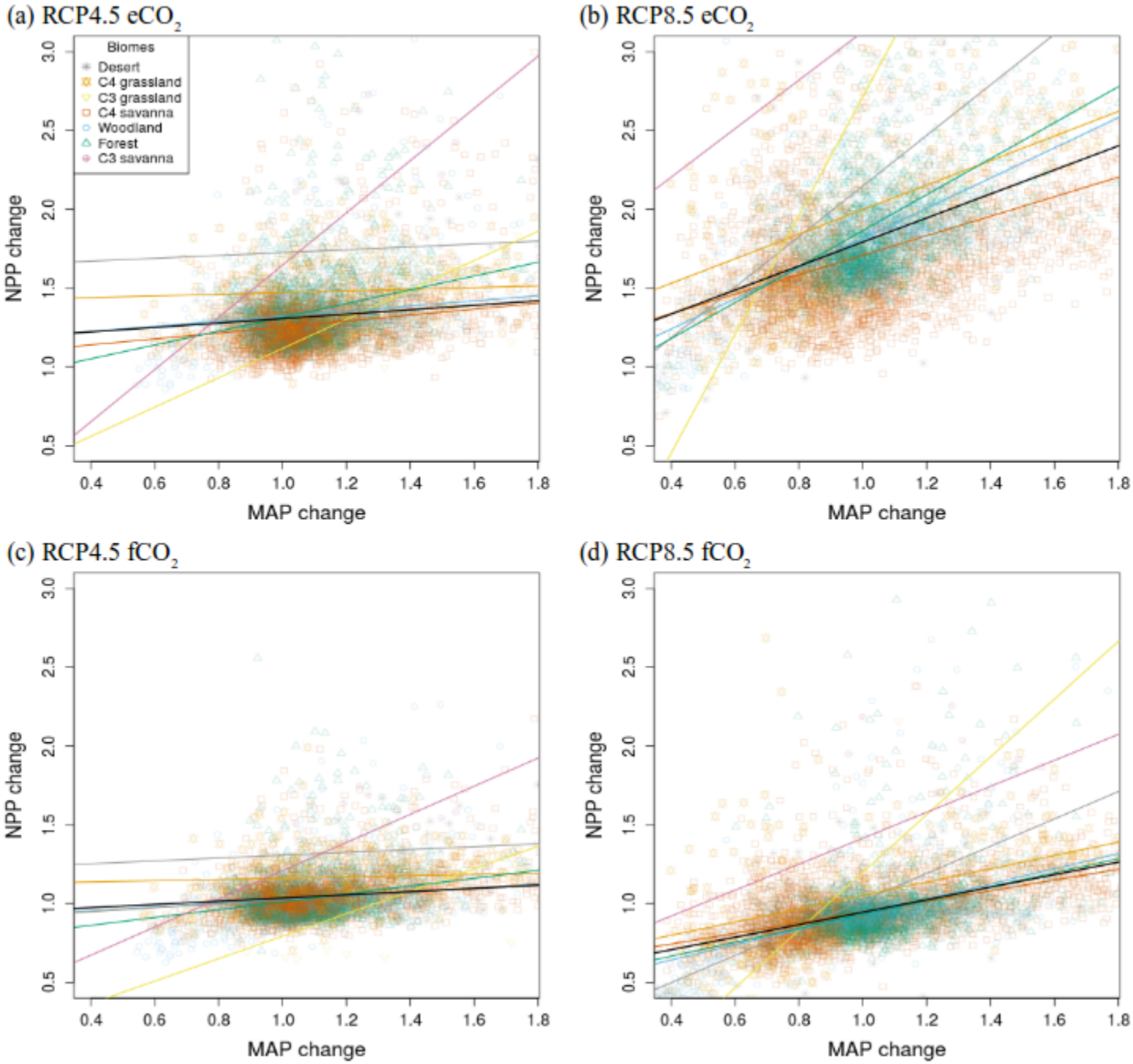
Supplementary Figure S2: Simulated aboveground biomass in t/ha for 2080-2099. The maps show the ensemble mean in 2080-2099 across all six ensemble members under eCO_2 (a, b) and fCO_2 (c, d) with RCP4.5 (a, c) and RCP8.5 (b, d).



Supplementary Figure S3: Total aboveground carbon in Africa between 2000 and 2099 simulated by all six ensemble members and their mean (black lines) under RCP4.5 and RCP8.5 with eCO_2 and fCO_2.

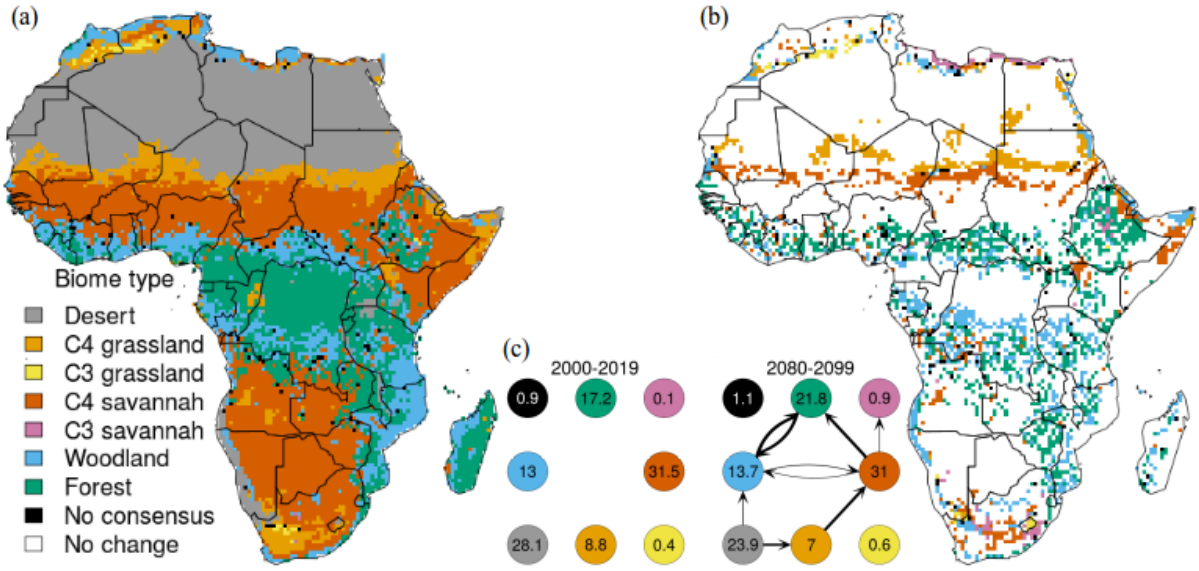


Supplementary Figure S4: Mean NPP (a) and mean total transpiration (b) from vegetation in Africa between 2000 and 2099 across all six ensemble members under RCP4.5 and RCP8.5 with eCO_2 and fCO_2. Shaded areas are the mean +/- standard deviation of the six ensemble members per scenario. NPP and transpiration are used to calculate water use efficiency (WUE).

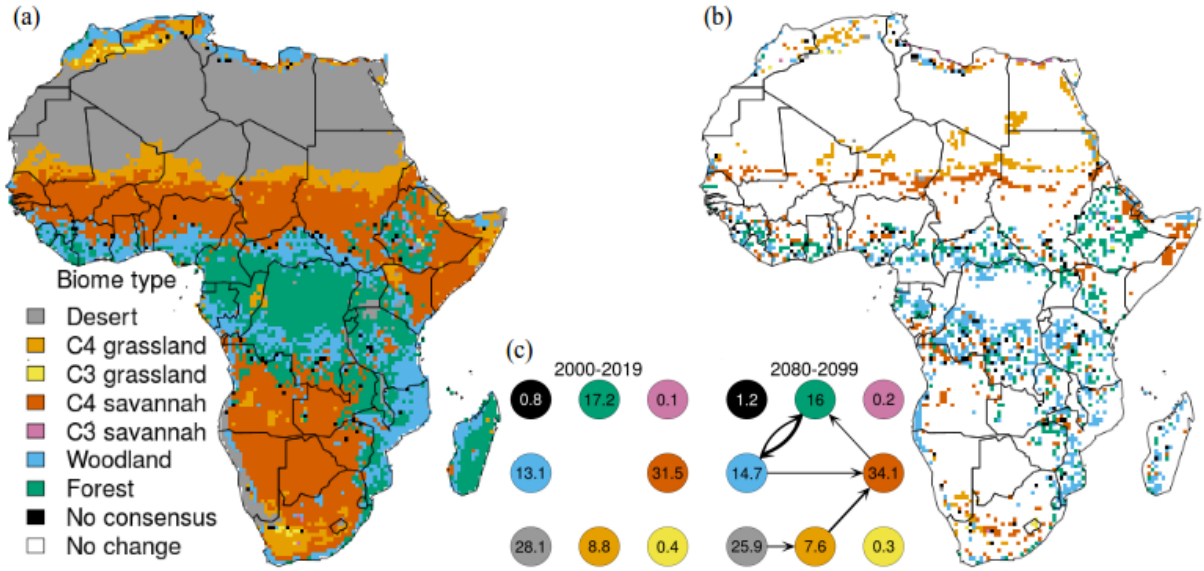


Supplementary Figure S5: MAP change versus NPP change per grid cell between 2000-2019 and 2080-2099 for eCO_2 (a,b) and fCO_2 (c,d) under RCP4.5 (a,c) and RCP8.5 (b,d). Change is the ratio between 2000-2019 and 2080-2099. Black lines are regression lines for all data points of a scenario. Coloured lines are regression lines for the respective biomes per

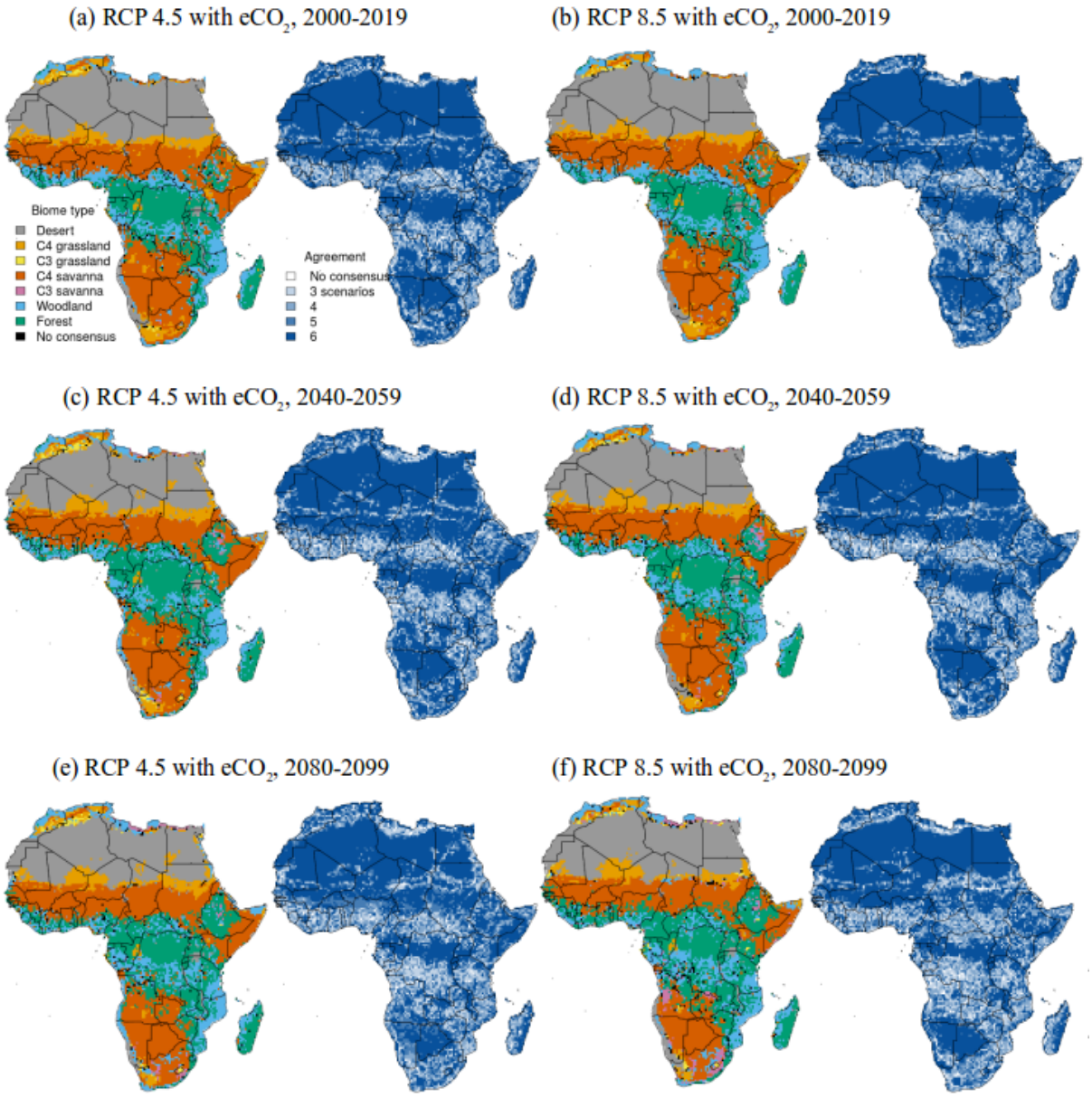
scenario. Points have the colour and shape of the biome in 2000-2019. See Fig. 4 for overall regression lines of MAP-NPP change of all four scenarios in one figure.



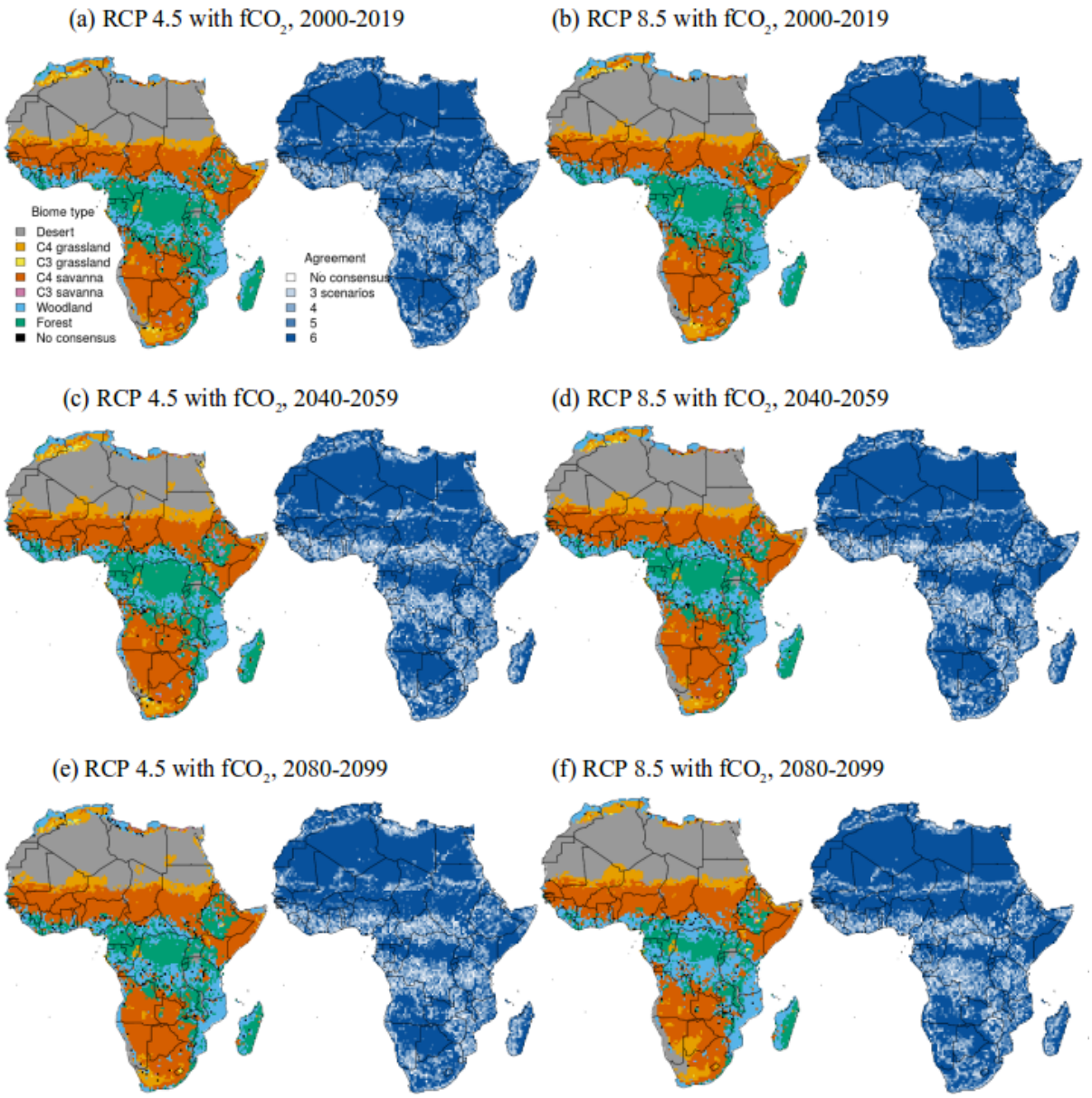
Supplementary Figure S6: Consensus biome type under eCO_2 RCP4.5 in 2000-2019 (a), biome changes in 2080-2099 (b) and transitions and fractional cover of biomes (c). The consensus biome type is the biome simulated by most ensemble members of the scenario. Grid cells with an agreement of less than three ensemble members do not have a higher probability than an outcome by chance and are marked as 'No consensus'. The biomes shown in (b) are the biomes that were simulated for 2080-2099, shown only for grid cells where biome transitions were simulated for the consensus biome. Numbers in each coloured circle (c) represent the percentage of area covered by each biome at the respective time step in the consensus map. Arrows show biome changes with regard to the previous time step. Thicker arrows indicate that a higher proportion of the total area changed. In panel (c), only changes that affect more than 0.5% of the African land surface are shown. See Fig. 5 for RCP8.5.



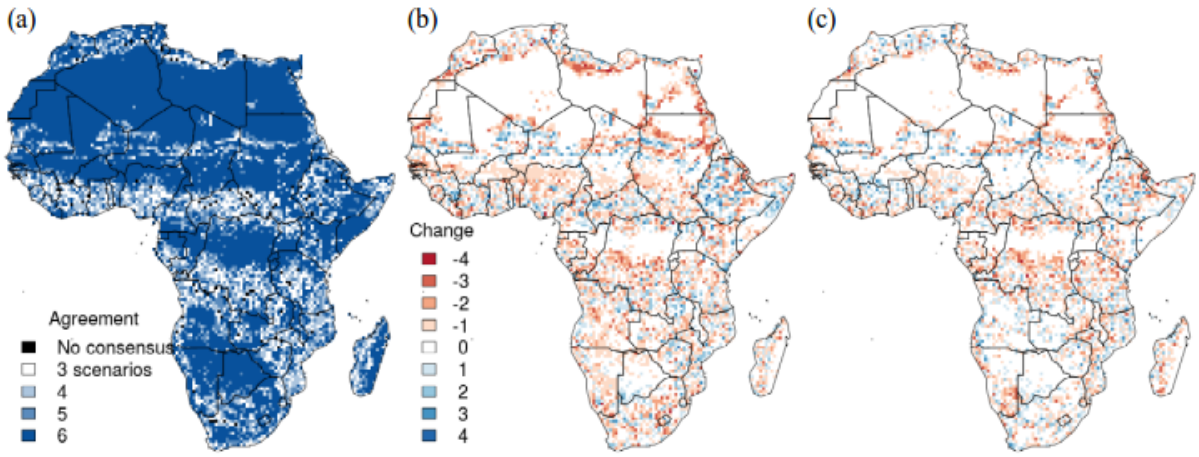
Supplementary Figure S7: Consensus biome type under fCO_2 RCP4.5 in 2000-2019 (a), biome changes in 2080-2099 (b) and transitions and fractional cover of biomes (c). The consensus biome type is the biome simulated by most ensemble members of the scenario. Grid cells with an agreement of less than three ensemble members do not have a higher probability than an outcome by chance and are marked as 'No consensus'. The biomes shown in (b) are the biomes that were simulated for 2080-2099, shown only for grid cells where biome transitions were simulated for the consensus biome. Numbers in each coloured circle (c) represent the percentage of area covered by each biome at the respective time step in the consensus map. Arrows show biome changes with regard to the previous time step. Thicker arrows indicate that a higher proportion of the total area changed. In panel (c), only changes that affected more than 0.5% of the African land surface are shown. See Fig. 6 for RCP8.5.



Supplementary Figure S8: Consensus biome type and number of scenarios simulating the consensus type for eCO_2 simulations under RCP4.5 (left, a, c, e) and RCP8.5 (right, b, d, f). The consensus biome type is the biome simulated by the majority of ensemble members. The number of ensemble members simulating the consensus type is denoted as 'Agreement'. Grid cells with less than three agreeing ensemble members are marked as 'No consensus'.



Supplementary Figure S9: Consensus biome type and number of scenarios simulating the consensus type for fCO_2 simulations under RCP4.5 (left, a, c, e) and RCP8.5 (right, b, d, f). The consensus biome type is the biome simulated by the majority of ensemble members. The number of ensemble members simulating the consensus type is denoted as 'Agreement'. Grid cells with an agreement of less than three ensemble members are marked as 'No consensus'.



Supplementary Figure S10: Simulation agreement in 2000-2019, under eCO_2 (a) and change in agreement in 2080-2099 under eCO_2 (b) and fCO_2 (c) for RCP4.5. The number of ensemble members simulating the consensus type is denoted as 'Agreement'. Grid cells with an agreement of less than three ensemble members are marked as 'No consensus'.We only displayed the number of ensemble members simulating the consensus type in 2000-2019 for eCO_2, because agreement is almost identical for eCO_2 and fCO_2 (see Fig. S8a and S9a). The consensus biome type is the biome simulated by the majority of ensemble members of the scenarios. See Fig. 8 for RCP8.5.

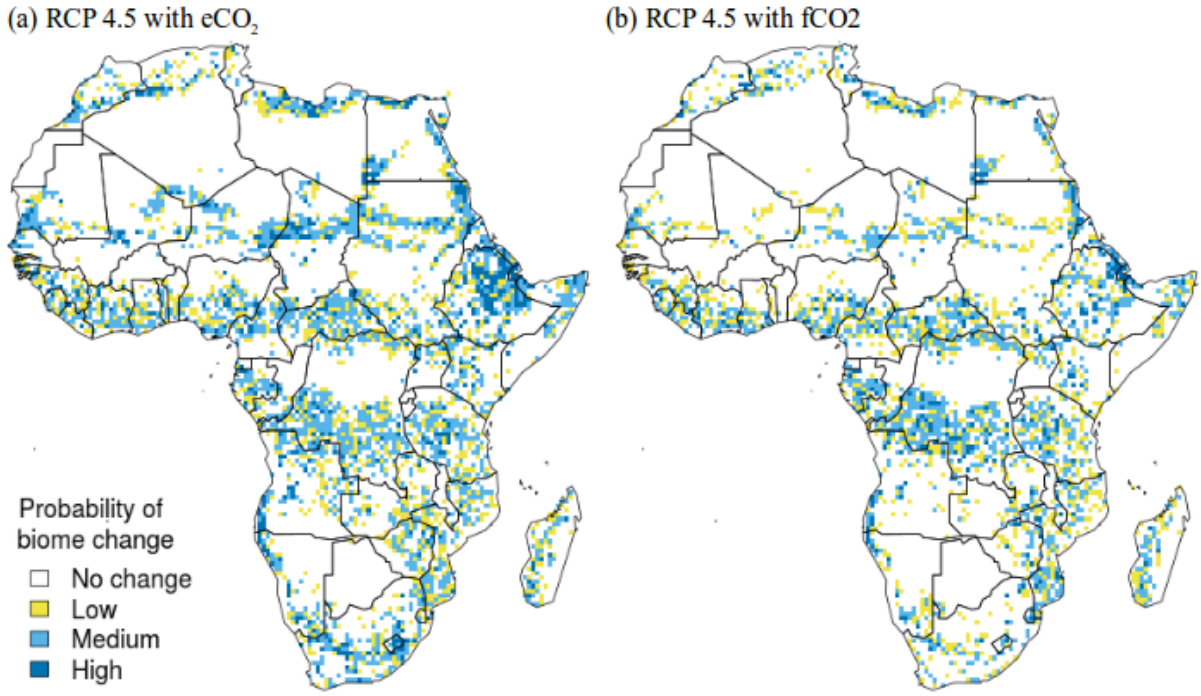


Figure S11: Probability of biome change between 2000-2019 and 2080-2099. The number of the six GCM ensemble members per scenario (here RCP4.5, eCO_2 and fCO_2) that showed a biome change from 2000-2019 to 2080-2099 was used as a measure of probability of biome change. The more ensemble members projected a biome change per grid cell, the higher its probability of biome change. High probability of biome change – all 6 simulations project biome changes; medium probability of biome change – 4-5 simulations with biome changes; low probability of biome change – 3 simulations with biome changes; no change – 0-2 simulations with changes. Grid cells with 2 or fewer simulations with biome changes do not have a higher probability than an outcome by chance and were therefore regarded as 'no change'. Whether the ensemble members simulated the same type of biome transition was not considered here. See Fig. 9 for RCP8.5.