

1 **Supplementary information**

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3 **How do afforestation and BECCS differ in their impacts on the land**
4 **carbon cycle and surface climate?**

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11 Supplementary information contains Supplemenary Text S1, Figures S1 to S24, and
12 Table S1.

Text S1. AR-favored and BECCS-favored areas under SSP5-3.4-OS

Under the IAM framework, the climate-driven variables may have to some extent impacted the allocation of bioenergy crops (e.g., using relatively low carbon density areas that have high potential yields), and such procedures were not applied for allocating AR. This may have some limited impact on the comparison between the two climate change mitigation options. We clarified the impact in the analysis as follows.

We used the 2015–2100 afforestation areas of the SSP1-1.9 and SSP1-2.6 pathways and bioenergy crop expansion areas of the SSP5-3.4-OS to label the global gridboxes as “AR-favored”, “BECCS-favored”, “AR-/BECCS-favored”, and “noAR-/noBECCS-favored”, depending on the climate mitigation applied in the three scenarios (Figure S16). We then analyzed the gridboxes where crop expansion/AR occurred after 2040 in the IPSL-CM6A-LR simulations and found that 43.6% of the gridboxes corresponded to the “AR-/BECCS-favored”, 15.4% to the “AR-favored”, 15.0% to the “BECCS-favored” and 26.0% to the “noAR-/noBECCS-favored” labels, respectively. Finally, we compared the land carbon budget, including CDR of BECCS, over these four regions in the BECCS and AR SSP5-3.4-OS experiments from the COU and BGC simulations over the 2040–2100 period globally and regionally (Figures 5 and S17–20).

The carbon sequestration benefits of bioenergy crops in the areas BECCS-favored are similar to those when all areas are combined (although with a much smaller magnitude of CDR). The carbon sequestration benefits of AR are comparable to those of BECCS when only the AR-favored areas are considered, both globally and subregionally, due to the relatively low CDR of bioenergy crops in those areas. When only AR-/BECCS-favored areas are considered, the carbon sequestration benefits of bioenergy crops are enhanced globally and regionally, particularly in the subregions of Middle-East and Africa, and OECD countries, although the CDR benefits of BECCS over AR are slightly reduced in the target areas of Latin America. The noAR-/noBECCS-favored areas are dominated by ecosystems with

low aboveground biomass increases. In these target areas, the carbon sequestration capacity of BECCS is slightly higher than AR globally but not regionally – AR may be equally beneficial in the subregions of Latin America, Middle-East and Africa, and OECD countries

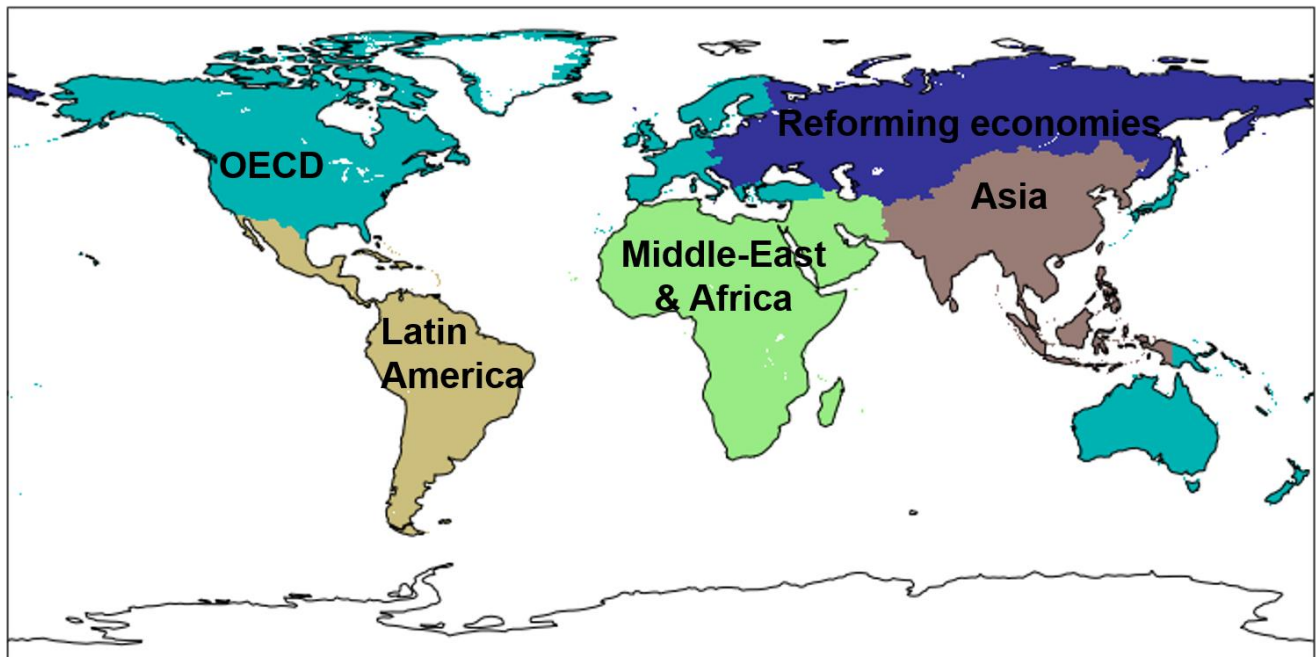


Figure S1. Five regions from Representative Concentration Pathway used in this study: Asia, Latin America, the Middle East and Africa, the Organisation for Economic Co-operation and Development (OECD) countries (North America, Western Europe, and Pacific OECD), Reforming Economies (Eastern Europe and Former Soviet Union).

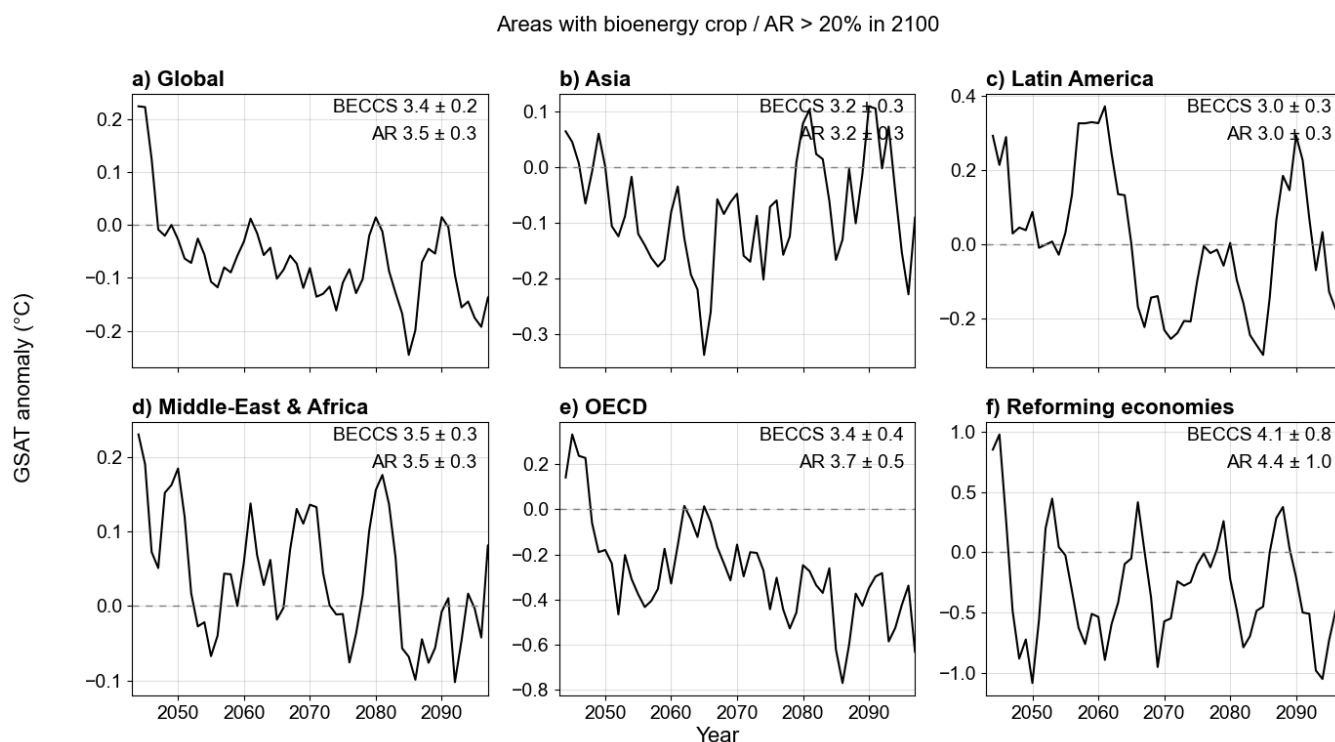


Figure S2. (a) Global and (b-f) subregional differences in land mean surface temperature (°C) between BECCS and AR experiments over gridboxes with over 20% of bioenergy crops in 2100 by IPSL-CM6A-LR given as 5-year moving averages. Positive values indicate larger values in the BECCS than in the AR experiment. Each panel shows 2040–2100 mean $\pm$ interannual variation via one standard deviation in BECCS and AR experiments.

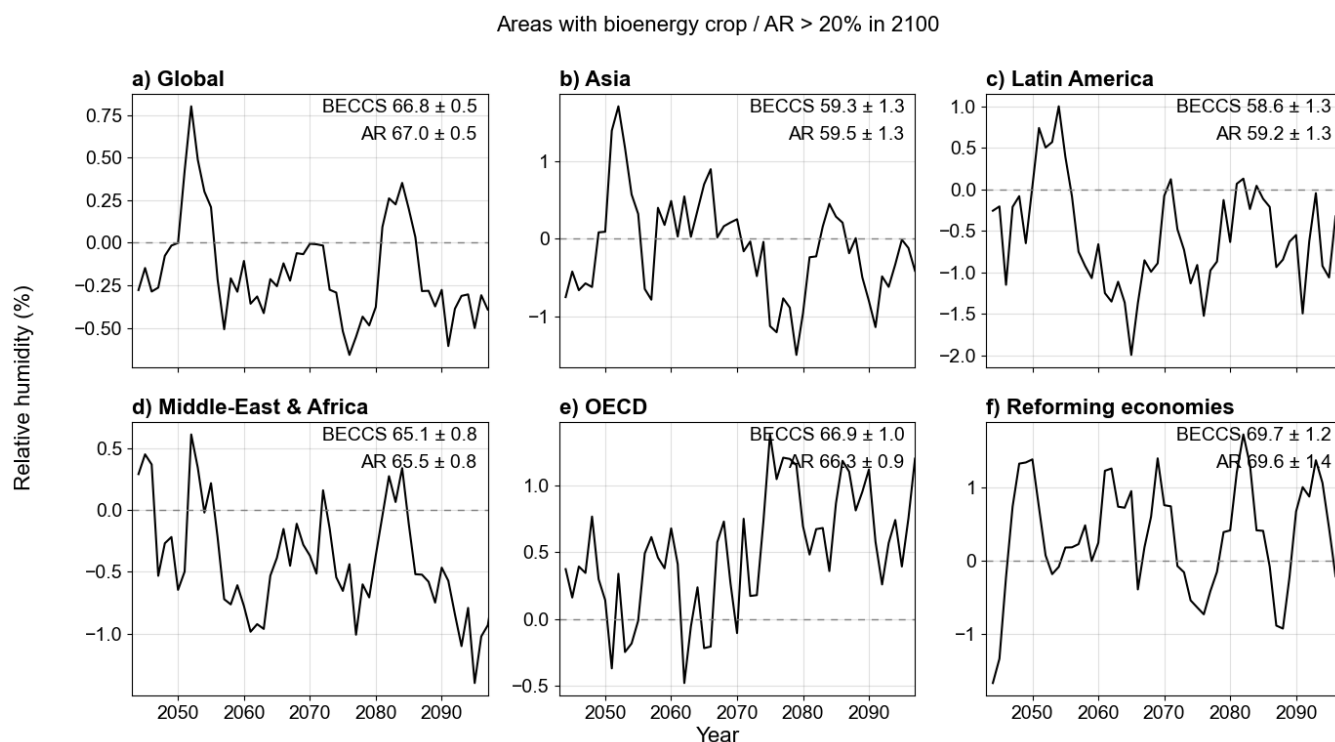


Figure S3. (a) Global and (b–f) subregional differences in land relative humidity (%) between BECCS and AR experiments over gridboxes with over 20% of 2G bioenergy crops in 2100 by simulated by IPSL-CM6A-LR given as 5-year moving averages. Positive values indicate larger values in the BECCS than in the AR experiment. Each panel shows 2040–2100 mean $\pm$ interannual variation via one standard deviation in BECCS and AR experiments.

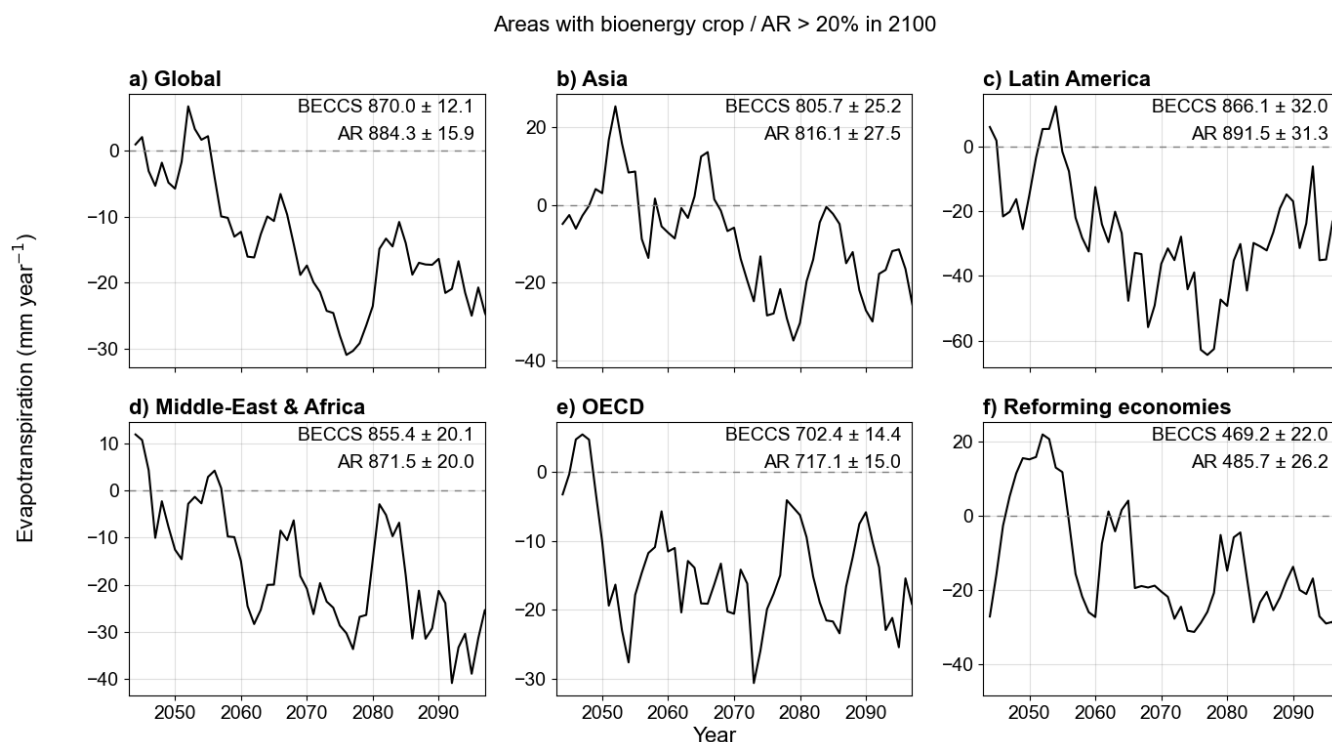
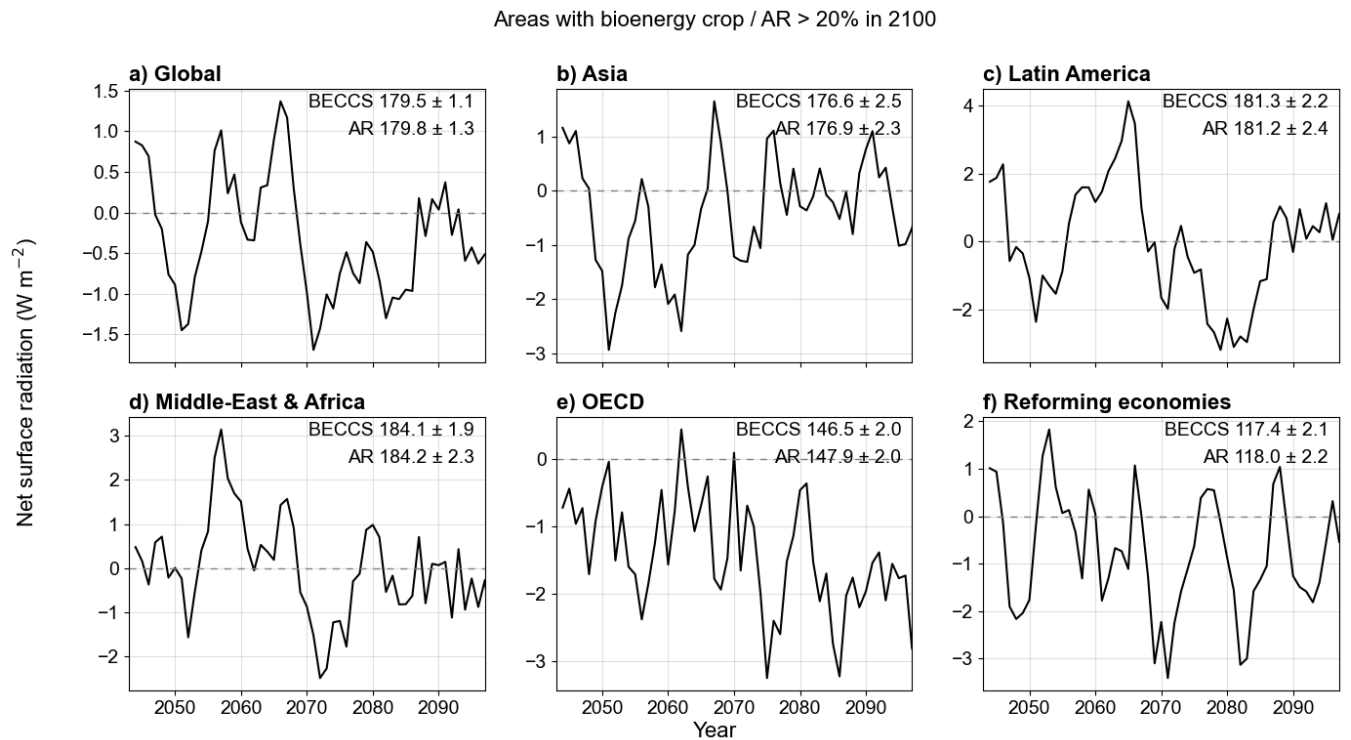


Figure S4. (a) Global and (b-f) subregional differences in land evapotranspiration (mm year^{-1}) between BECCS and AR experiments over gridboxes with over 20% of 2G bioenergy crops in 2100 by simulated by IPSL-CM6A-LR given as 5-year moving averages. Positive values indicate larger values in the BECCS than in the AR experiment. Each panel shows 2040–2100 mean $\pm$ interannual variation via one standard deviation in BECCS and AR experiments.

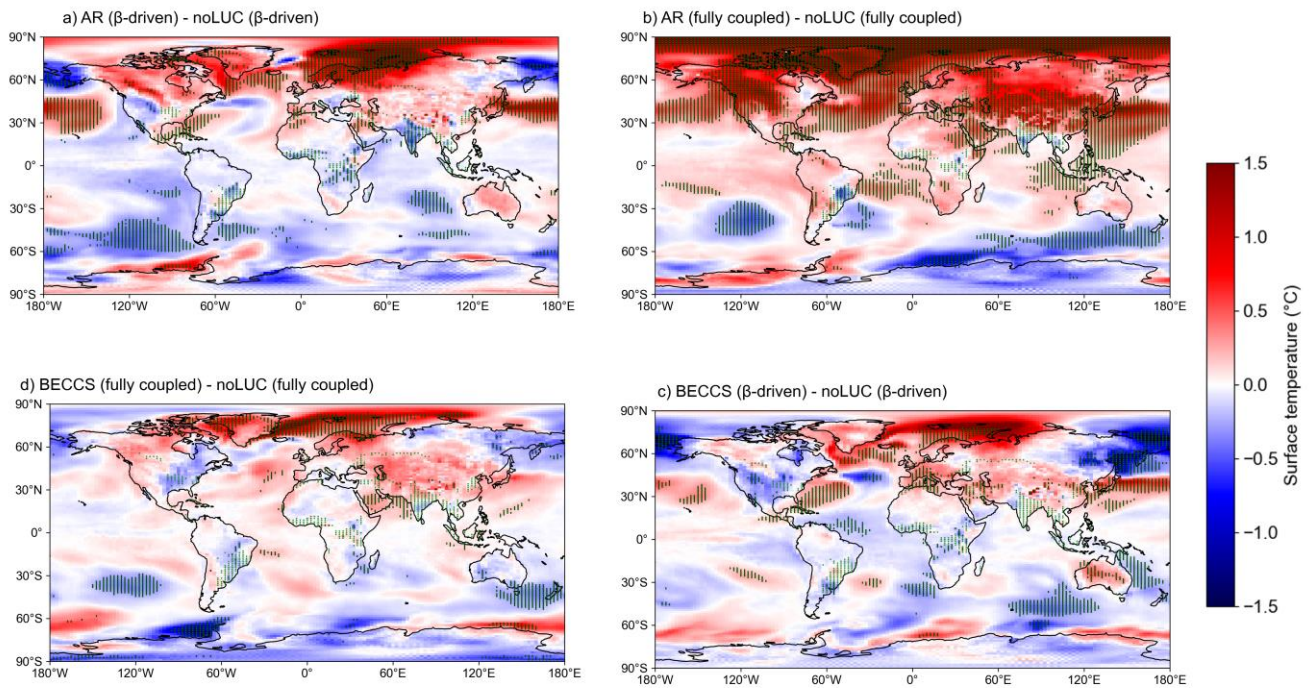
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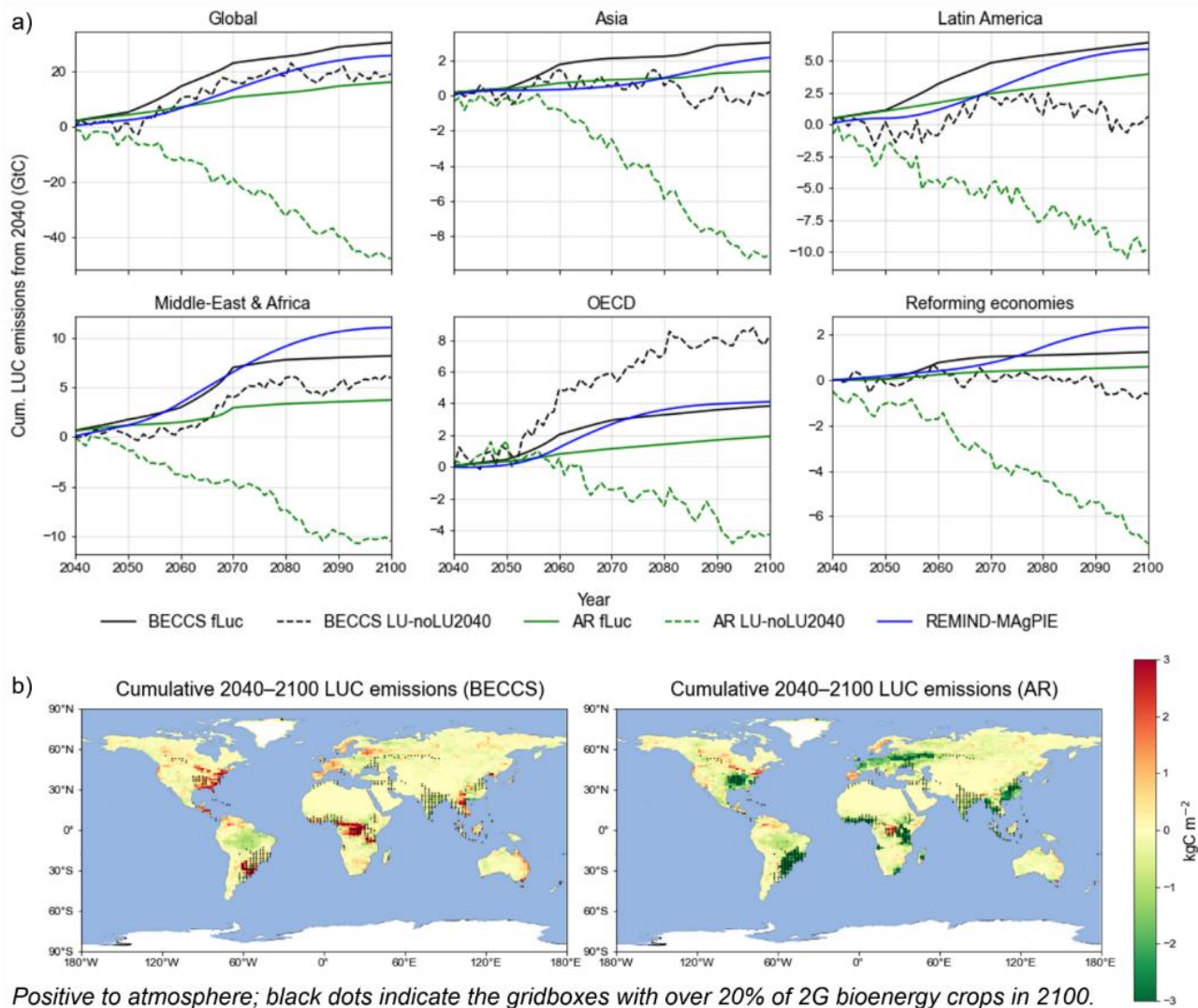
70 Figure S5. (a) Global and (b-f) subregional differences in land net surface solar radiation (W m^{-2}) between
71 BECCS and AR experiments over gridboxes with over 20% of 2G bioenergy crops in 2100 by simulated by IPSL-
72 CM6A-LR given as 5-year moving averages. Positive values indicate larger values in the BECCS than in the AR
73 experiment. Each panel shows 2040–2100 mean $\pm$ interannual variation via one standard deviation in BECCS and
74 AR experiments.

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 77 Figure S6. Spatial variations of (a, c) physiological and (b, d) total surface air temperature change (°C) in (a, b)
 78 AR and (c, d) experiments relative to constant land cover fixed in 2040 averaged over 2081–2100. Black vertical
 79 lines correspond to the gridboxes with a significant difference (p-value < 0.05) according to the Mann-Whitney U
 80 test, green dots indicate the gridboxes with over 20% of 2G bioenergy crops in 2100. Positive values indicate
 81 larger values in the BECCS/AR than in the noLUC2040 experiment.

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Positive to atmosphere; black dots indicate the gridboxes with over 20% of 2G bioenergy crops in 2100.

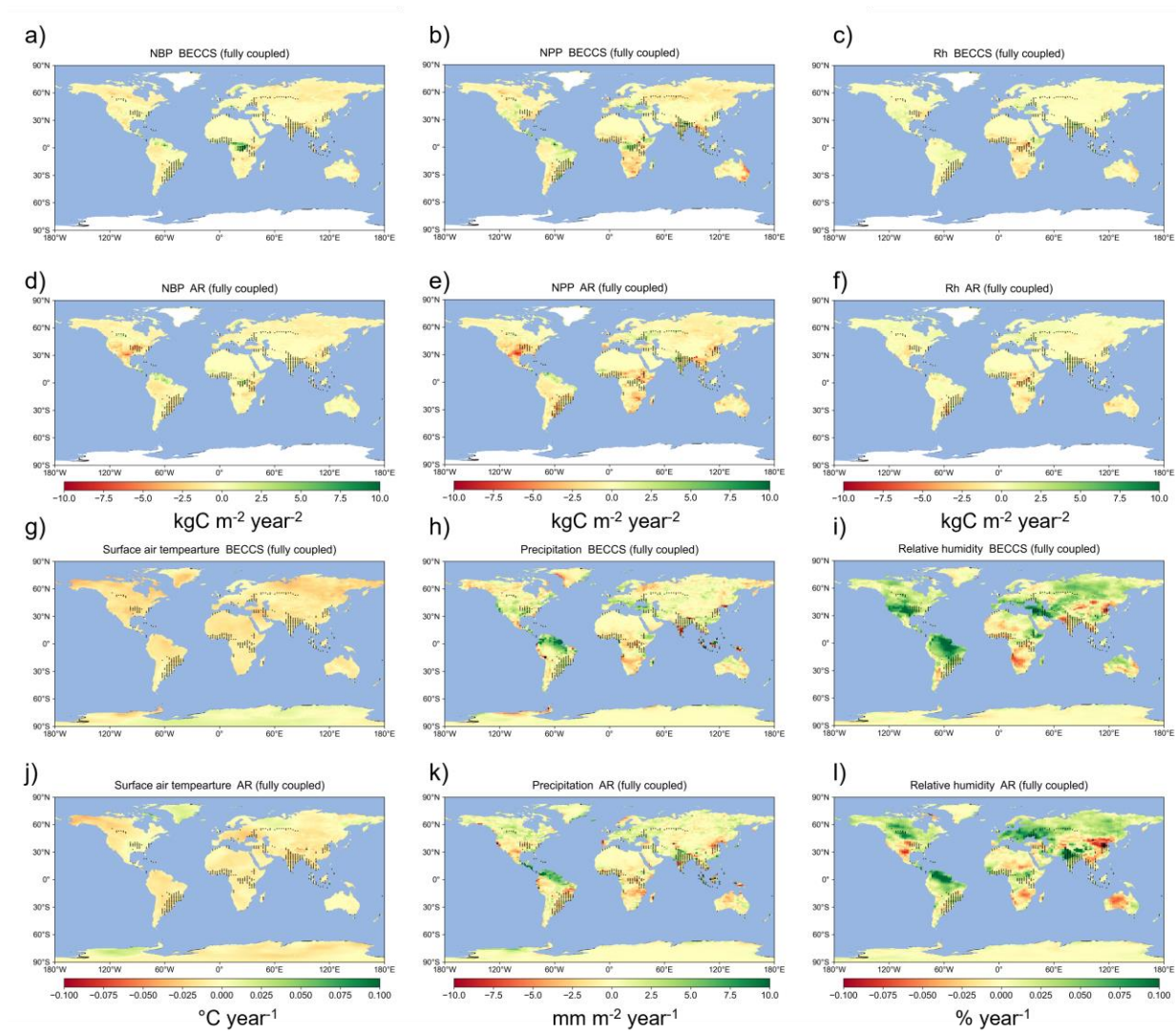


Figure S8. The slopes of linear regressions of (a–f) carbon fluxes and (g–l) surface climate variables in coupled BECCS and AR experiments over the 2061–2100 period.

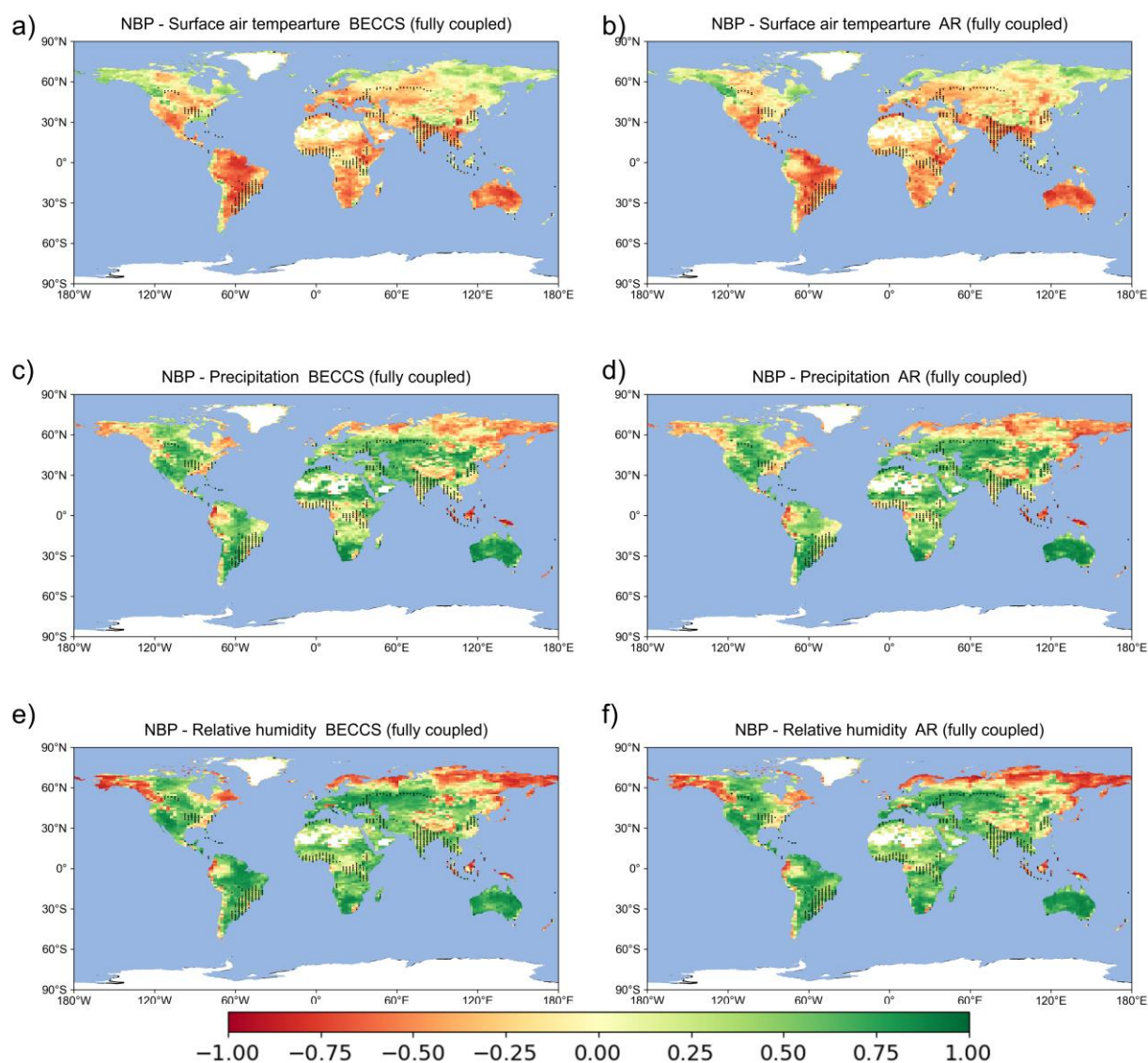


Figure S9. The correlation coefficients between NBP and climate surface climate variables in coupled (a, c, e) BECCS and (b, d, f) AR experiments over the 2061–2100 period.

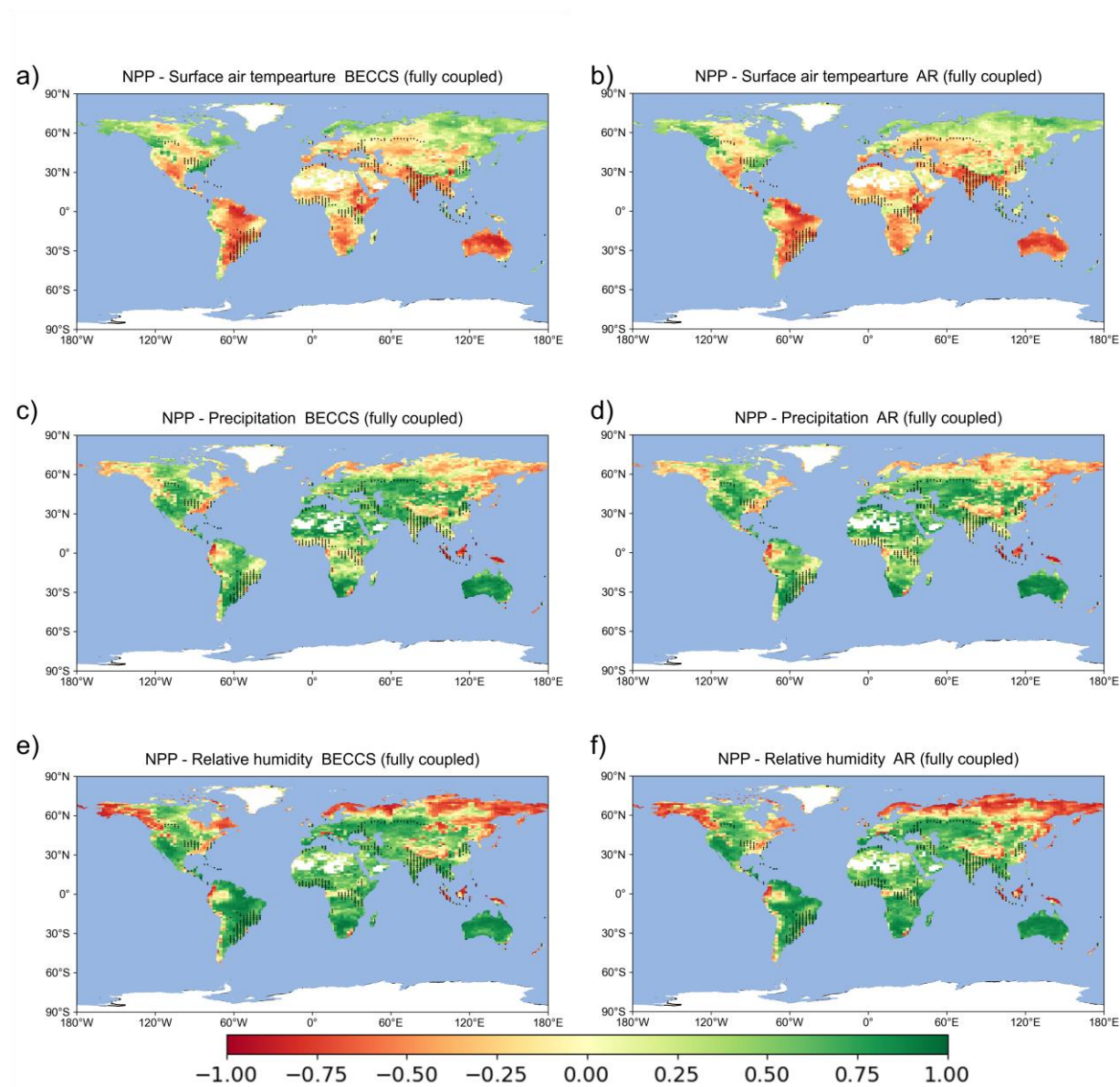


Figure S10. The correlation coefficients between NPP and climate surface climate variables in coupled (a, c, e) BECCS and (b, d, f) AR experiments over the 2061–2100 period.

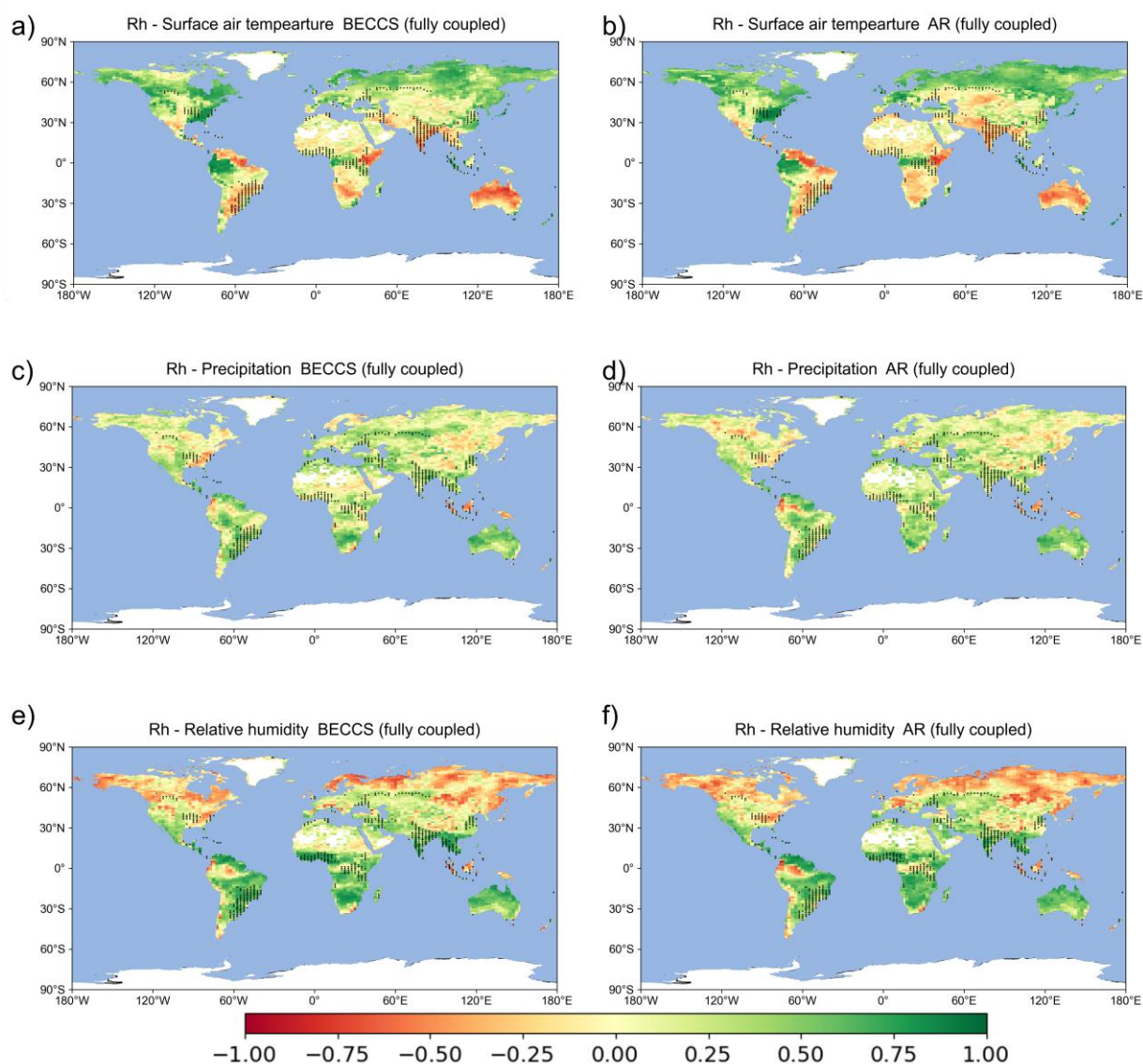


Figure S11. The correlation coefficients between Rh and climate surface climate variables in coupled (a, c, e) BECCS and (b, d, f) AR experiments over the 2061–2100 period.

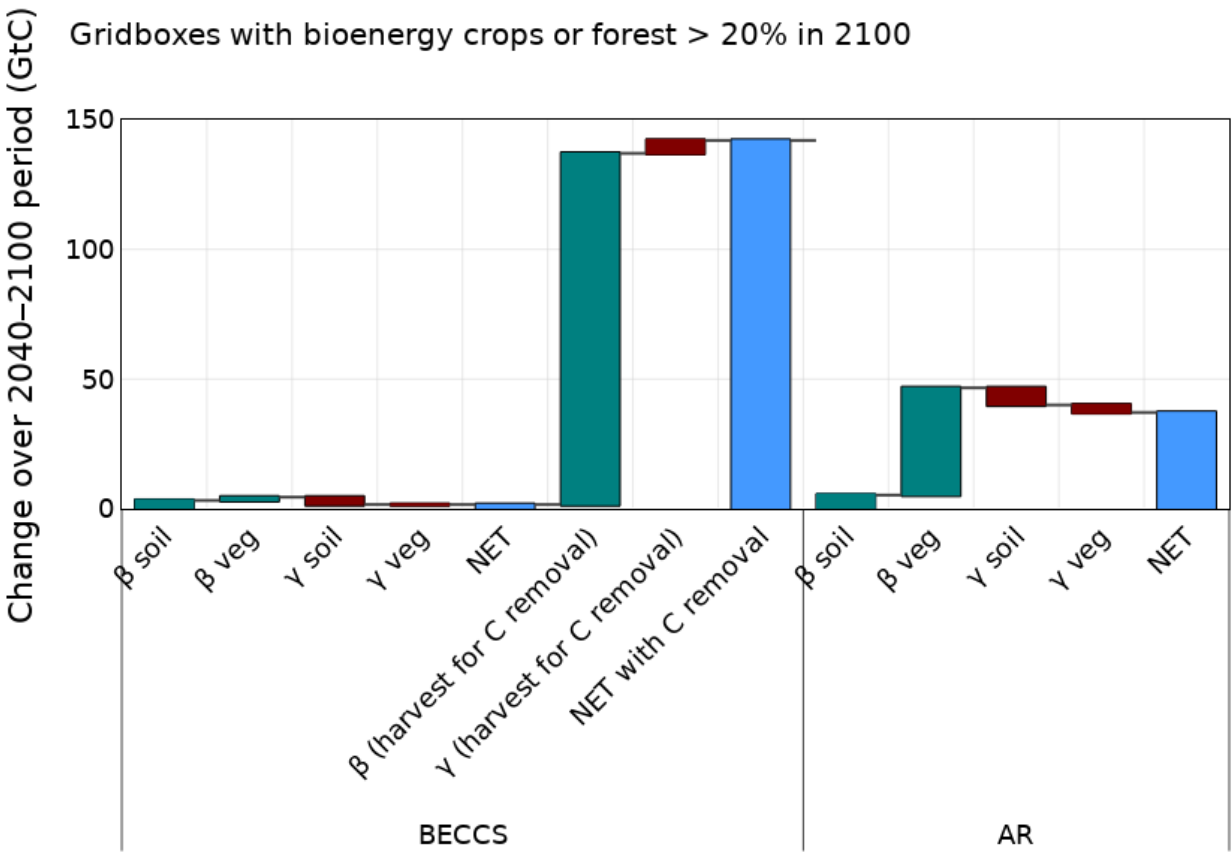


Figure S12. Changes in the β - and γ -driven contributions to the land carbon budget, including biomass harvest for BECCS CDR, in the BECCS and AR SSP5-3.4-OS experiments over the 2040–2100 period globally in the gridboxes with over 20% of 2G bioenergy crops in 2100. The β -driven contribution is estimated from the BGC experiment, and the γ -driven contribution is estimated from the difference between COU and BGC experiments. LUC emissions are included in the β - and γ -driven contributions. Harvest for carbon removal stands for harvested biomass for BECCS (prior to multiplying by a permanently captured fraction).

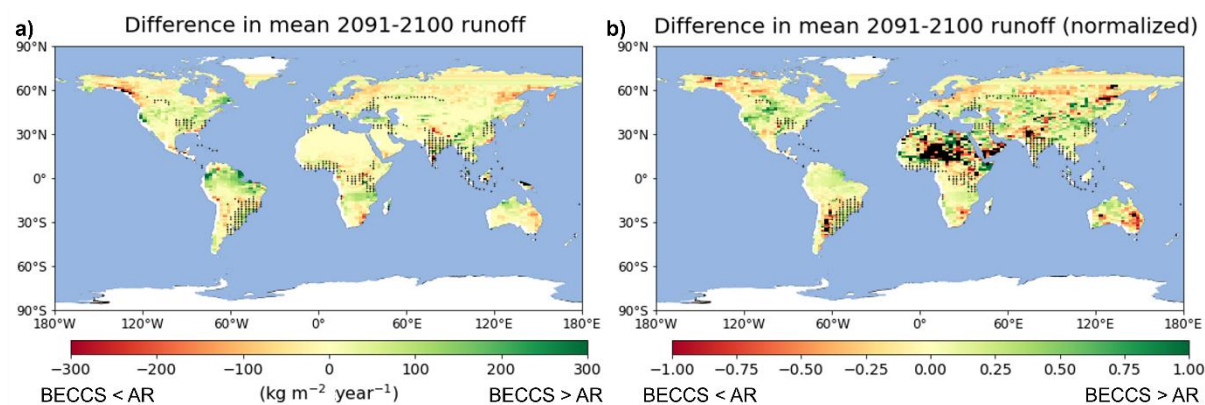


Figure S13. Differences in 2091–2100 mean total (a) runoff and (b) runoff normalized by long-term piControl mean of BECCS and AR experiments. Black dots indicate the gridboxes with over 20% of bioenergy crops in 2100.

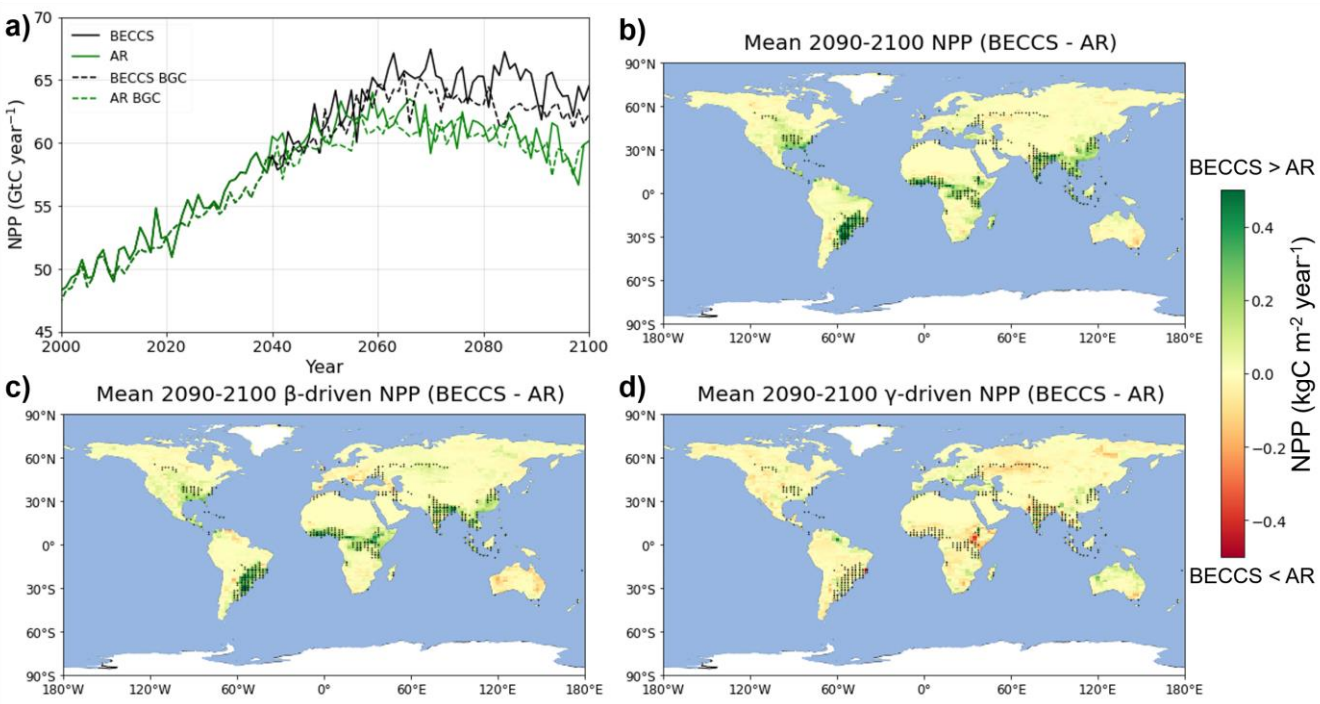


Figure S14. (a) Time series of global NPP in COU (solid lines) and BGC (dashed lines) AR and BECCS experiments. Distribution of mean 2090–2100 NPP in (b) COU and (c) BGC, and (d) COU – BGC (difference) runs between the BECCS and AR experiments. Positive values indicate larger values in the BECCS than in the AR experiment. The black dots indicate the gridboxes with over 20% of 2G bioenergy crops in 2100.

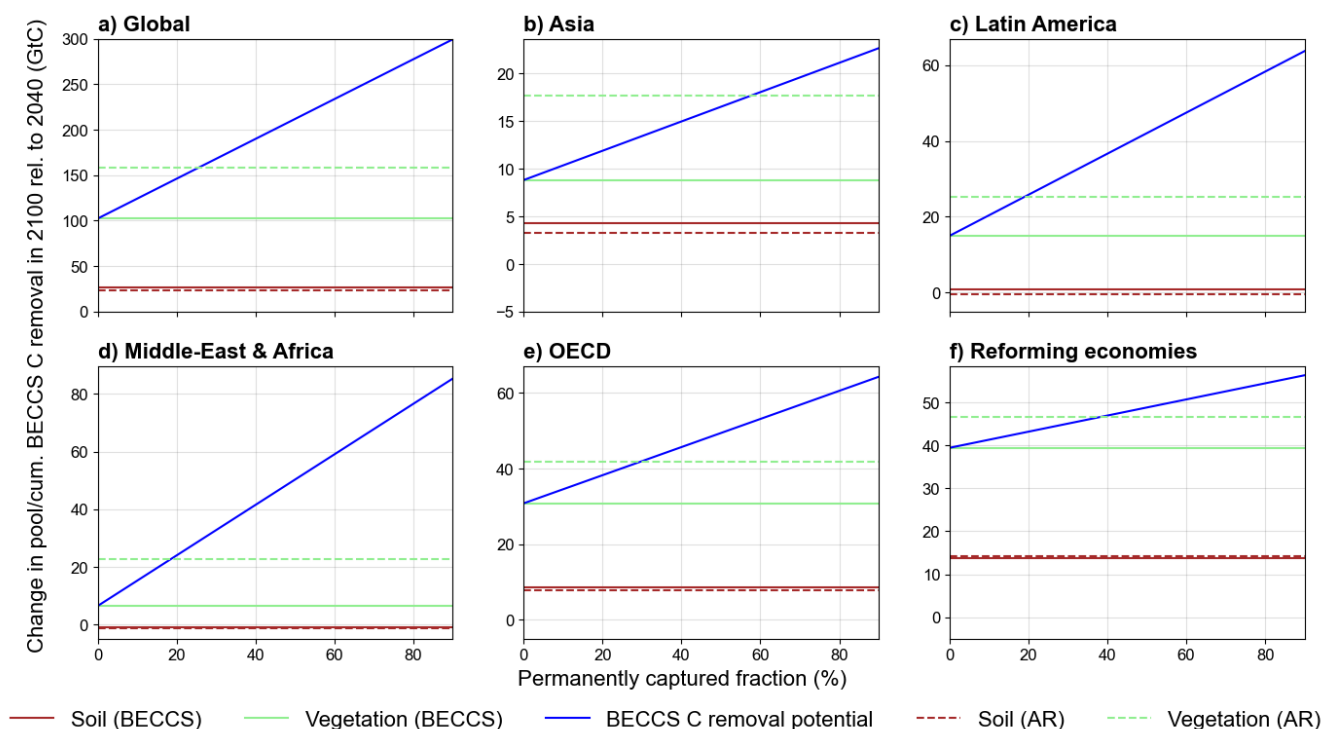


Figure S15. Variation of stacked changes in the contributors to land carbon budget, including CDR of BECCS (assuming permanently captured fraction from 50 to 90%) in 2100 in BECCS and AR SSP5-3.4-OS experiments from the COU and BGC simulations plotted against permanently captured fraction. Regional allocation of CDR refers to the location of biomass extraction.

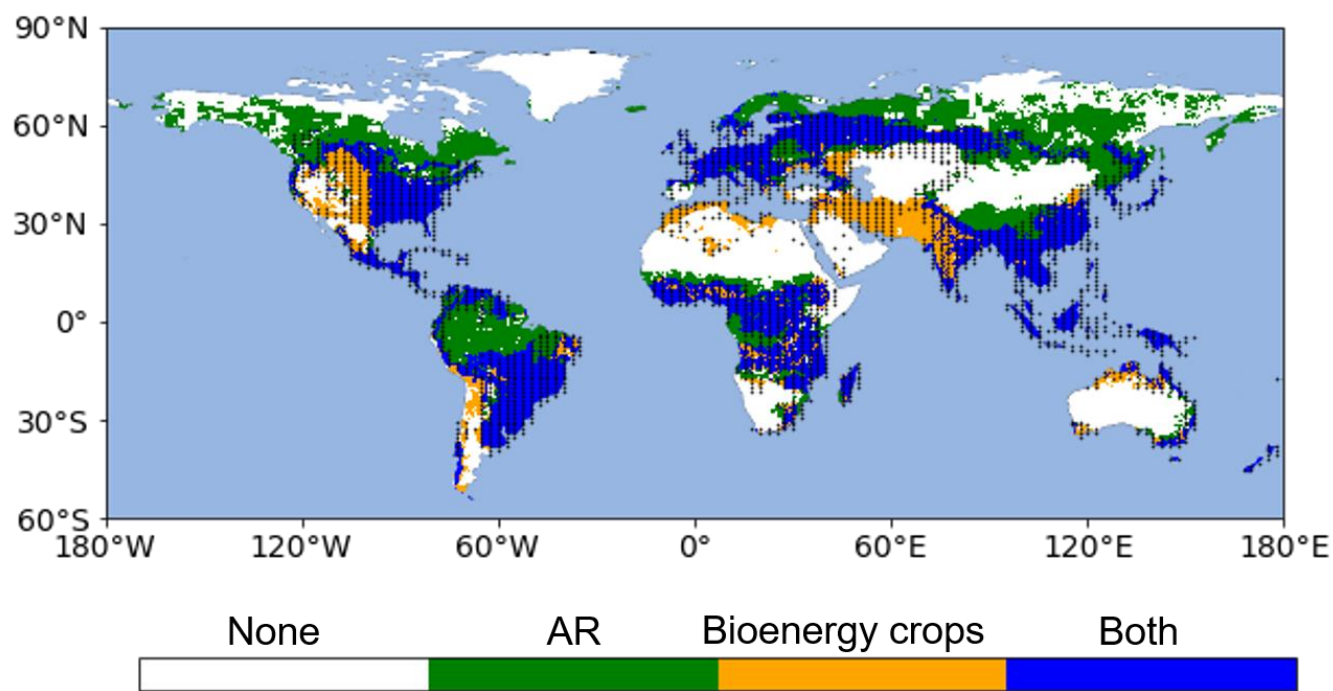


Figure S16. “BECCS-favored”, “AR-favored”, “AR-/BECCS-favored” and “noAR-/noBECCS-favored” areas defined from common areas of added grid area fraction of forest under SSP1-1.9 and SSP1-2.6 scenarios with allocated bioenergy crops under SSP5-3.4-OS scenario over 2015–2100 period by LUH2. Dotes indicate gridboxes with added crops/forest during the 2040–2100 period in the IPSL-CM6A-LR simulations.

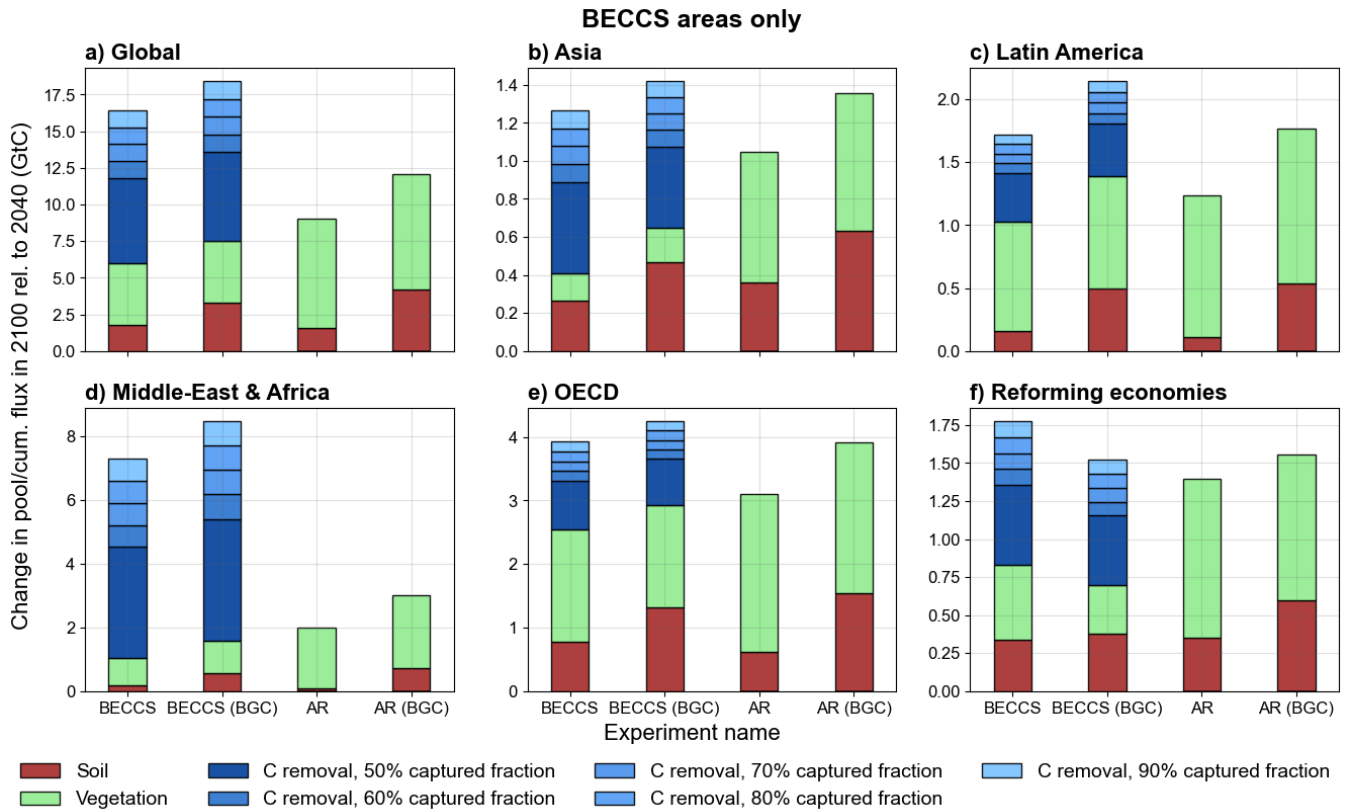


Figure S17. Changes in the land carbon budget, including BECCS carbon removal (assuming permanently captured carbon fraction from 50 to 90%) in the BECCS and AR SSP5-3.4-OS experiments from the fully coupled simulations and simulations that do not consider climate feedbacks over the 2040–2100 period globally (a) and regionally (b–f) in the BECCS-favored areas.

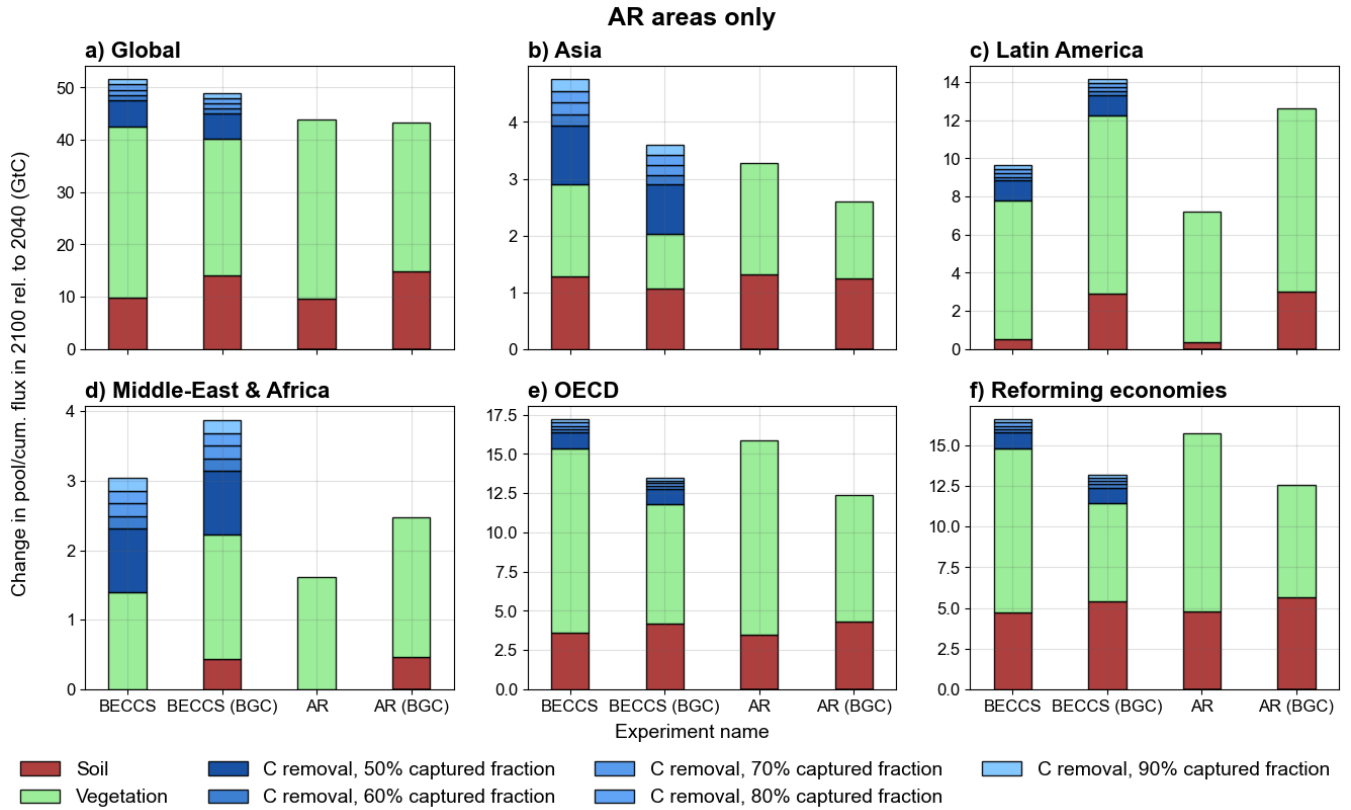


Figure S18. Changes in the land carbon budget, including BECCS carbon removal (assuming permanently captured carbon fraction from 50 to 90%) in the BECCS and AR SSP5-3.4-OS experiments from the fully coupled simulations and simulations that do not consider climate feedbacks over the 2040–2100 period globally (a) and regionally (b–f) in the AR-favored areas.

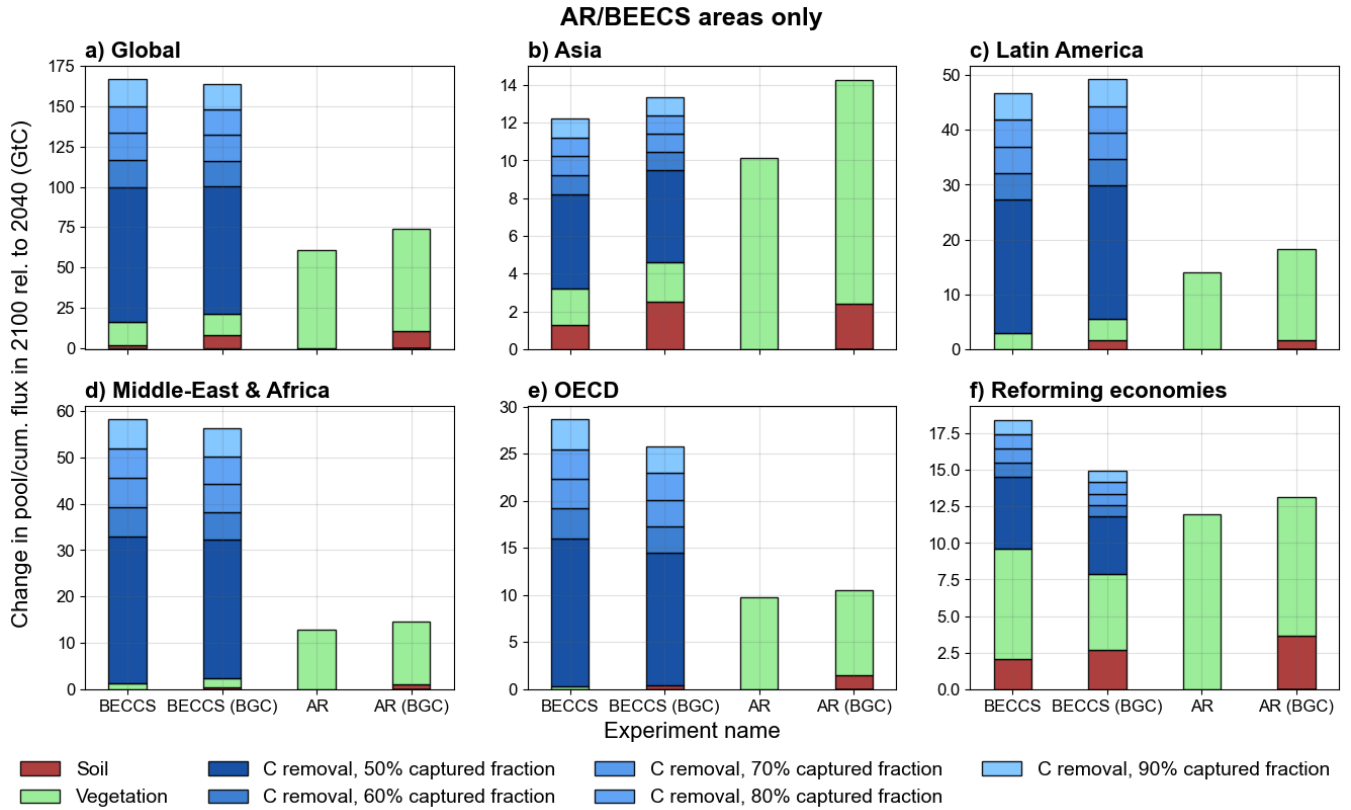


Figure S19. Changes in the land carbon budget, including BECCS carbon removal (assuming permanently captured carbon fraction from 50 to 90%) in the BECCS and AR SSP5-3.4-OS experiments from the fully coupled simulations and simulations that do not consider climate feedbacks over the 2040–2100 period globally (a) and regionally (b–f) in the AR-/BECCS-favored areas.

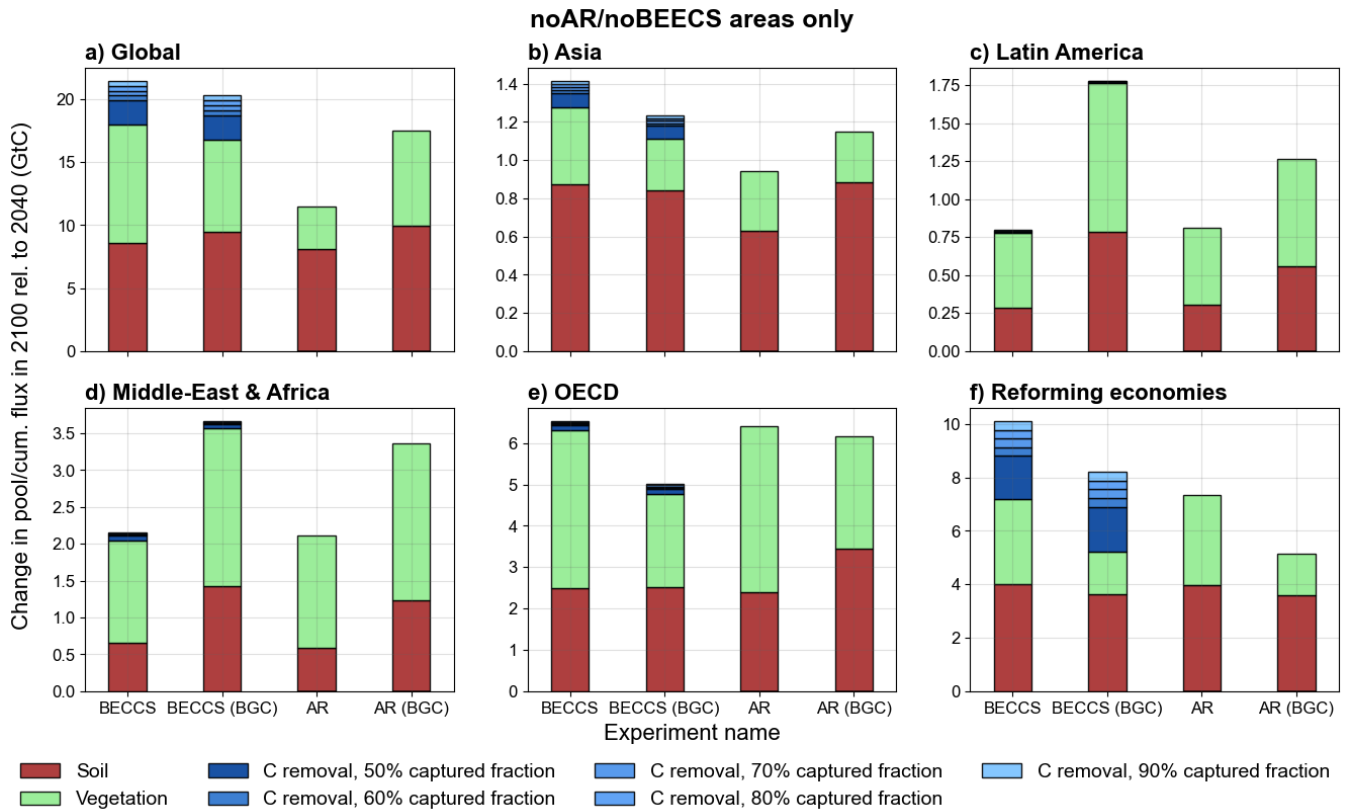


Figure S20. Changes in the land carbon budget, including BECCS carbon removal (assuming permanently captured carbon fraction from 50 to 90%) in the BECCS and AR SSP5-3.4-OS experiments from the fully coupled simulations and simulations that do not consider climate feedbacks over the 2040–2100 period globally (a) and regionally (b–f) in the noAR-/noBECCS-favored areas.

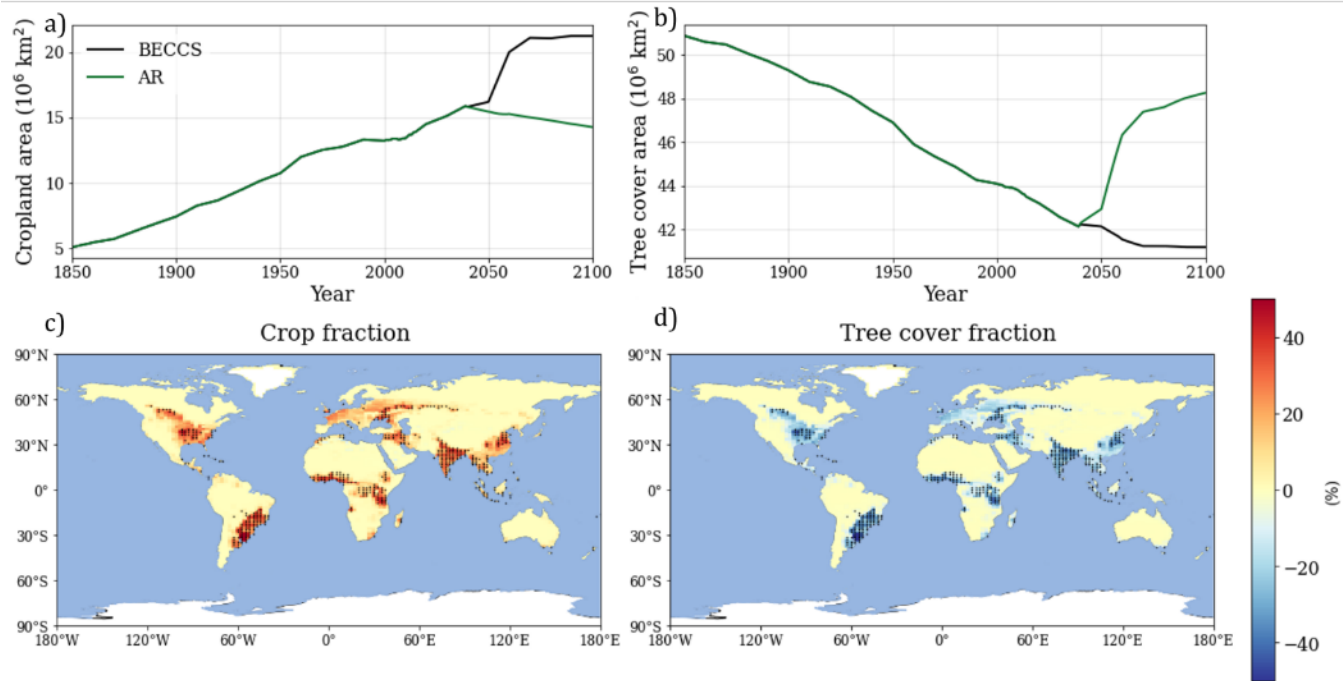


Figure S21. (a, b) Global cropland and tree cover areas (10^6 km^2) over the period 1850-2100. (c, d) Spatial distribution of the differences in the cropland and tree covers (%) in SSP5-3.4-OS with BECCS (standard) and AR experiments using IPSL-CM6A-LR in 2100. Positive values indicate a larger magnitude in BECCS than in the AR experiment. Black dots indicate the gridboxes with over 20% of bioenergy crops in 2100.

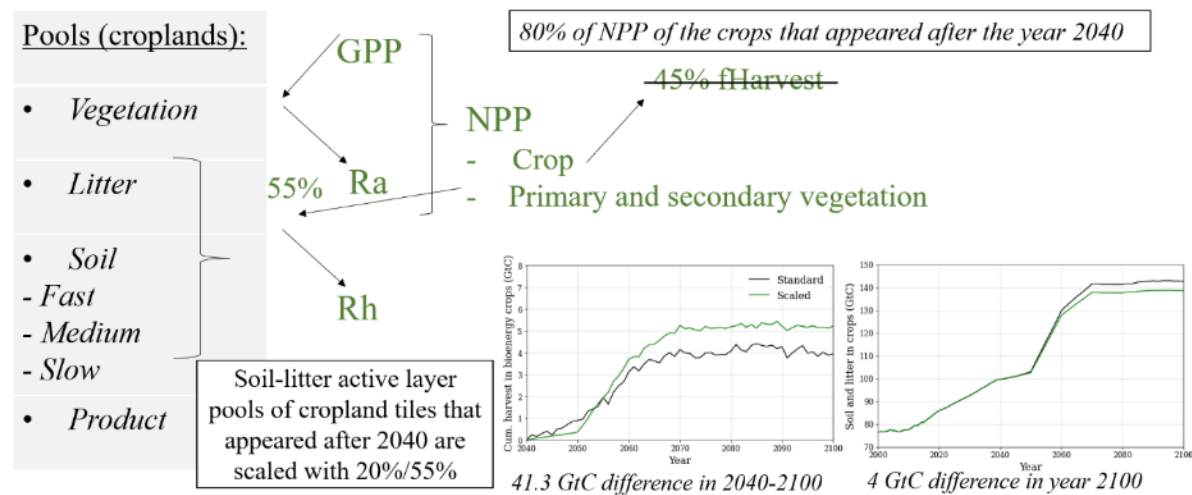


Figure S22. The schematic representation of the post-processing procedures that were applied to re-scale the harvest and soil carbon pool over the bioenergy croplands.

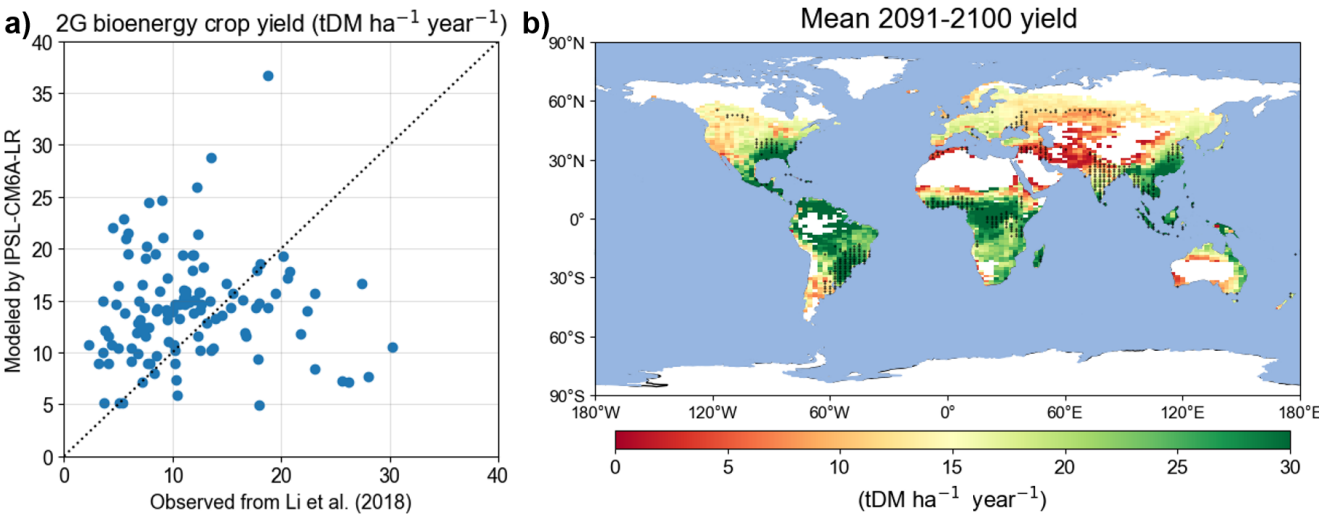


Figure S23. (a) Evaluation of modelled bioenergy yield by IPSL-CM6A-LR against point observations from the dataset of Li et al. (2018). (b) Spatial variation of mean modelled yield over the 2091–2100 period.

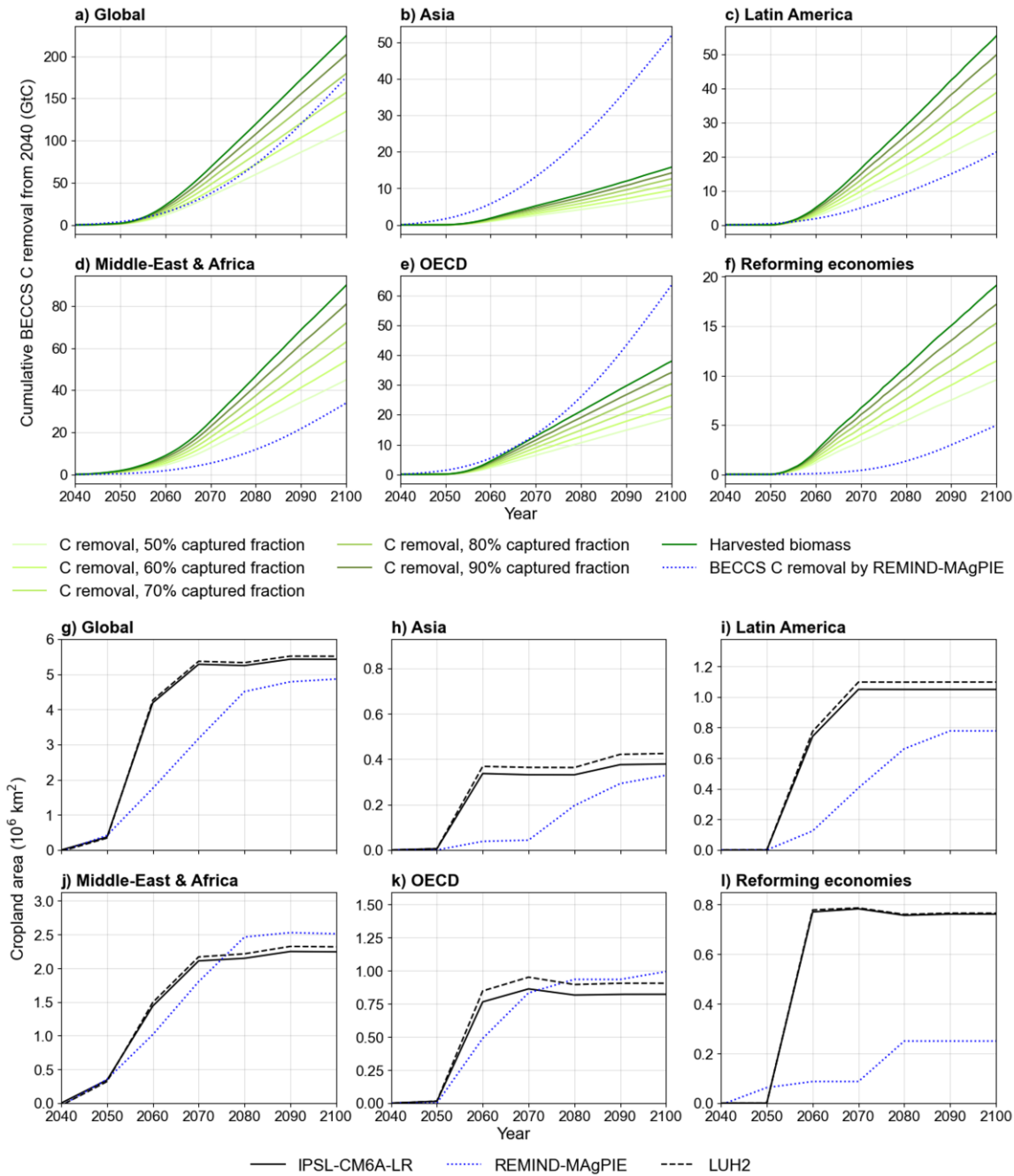


Figure S24. Global and regional (a-f) cumulative biomass harvest and carbon removal (GtC) in the bioenergy crops sequestered from 2040, estimated by REMIND-MAGPIE and IPSL-CM6A-LR with permanently captured fraction from 50 to 90%, (g-l) changes in the cropland area (10^6 km^2) relative to 2040 estimated by REMIND-MAGPIE, IPSL-CM6A-LR, and LUH2 under SSP5-3.4-OS.

187 Table S1. Comparison of global and regional CDR and effects of biogeochemical and biogeophysical feedbacks of BECCS and AR under SSP5-3.4-OS
188 pathway given at global and subregional (over the gridboxes with over 20% of 2G bioenergy crops in 2100) scales.

	Global	Asia	Latin America	Middle-East & Africa	OECD	Reforming economies
C removal	AR<< BECCS in the long-term, in the span of 20 to 30 years BECCS $\approx$ AR	BECCS < AR if permanently captured fraction of bioenergy crops < 60%	AR<< BECCS	AR<< BECCS	AR< BECCS	BECCS < AR if permanently captured fraction of bioenergy crops < 40%
Contributions of biogeochemical feedbacks	$\begin{cases} 0 < \beta_{BECCS} \ll \beta_{AR} \\ \gamma_{AR} < \gamma_{BECCS} < 0 \end{cases}$	$\begin{cases} 0 < \beta_{BECCS} \ll \beta_{AR} \\ \gamma_{AR} < \gamma_{BECCS} < 0 \end{cases}$	$\begin{cases} 0 < \beta_{BECCS} \ll \beta_{AR} \\ \gamma_{AR} <_{\epsilon} \gamma_{BECCS} < 0 \end{cases}$	$\begin{cases} 0 < \beta_{BECCS} \ll \beta_{AR} \\ \gamma_{AR} <_{\epsilon} \gamma_{BECCS} < 0 \end{cases}$	$\begin{cases} 0 < \beta_{BECCS} < \beta_{AR} \\ 0 < \gamma_{AR} \approx \gamma_{BECCS} \end{cases}$	$\begin{cases} 0 < \beta_{BECCS} < \beta_{AR} \\ 0 < \gamma_{AR} \approx \gamma_{BECCS} \end{cases}$
Biogeophysical effects	BECCS leads to cooling, AR to warming globally and in the northern latitudes, opposite in most of the subtropical regions	BECCS leads to higher max temperature and frequency of hot days in India	AR leads to non-radiative cooling, BECCS leads to higher max temperature and frequency of hot days	Spatially different temperature response, BECCS leads to lower surface humidity and a much higher frequency of hot days	BECCS leads to lower temperatures and surface humidity than AR	BECCS leads to lower temperatures and drier air, more frequent hot days than AR

189 $<_{\epsilon}$ is defined as “slightly less than”.