

Supplementary Information

Total emissions and averaged bioenergy production for all scenarios

For reasons of clarity, in the main text total LUC emissions and averaged annual bioenergy are only shown for a selection of scenarios. Here we give an overview showing all scenarios.

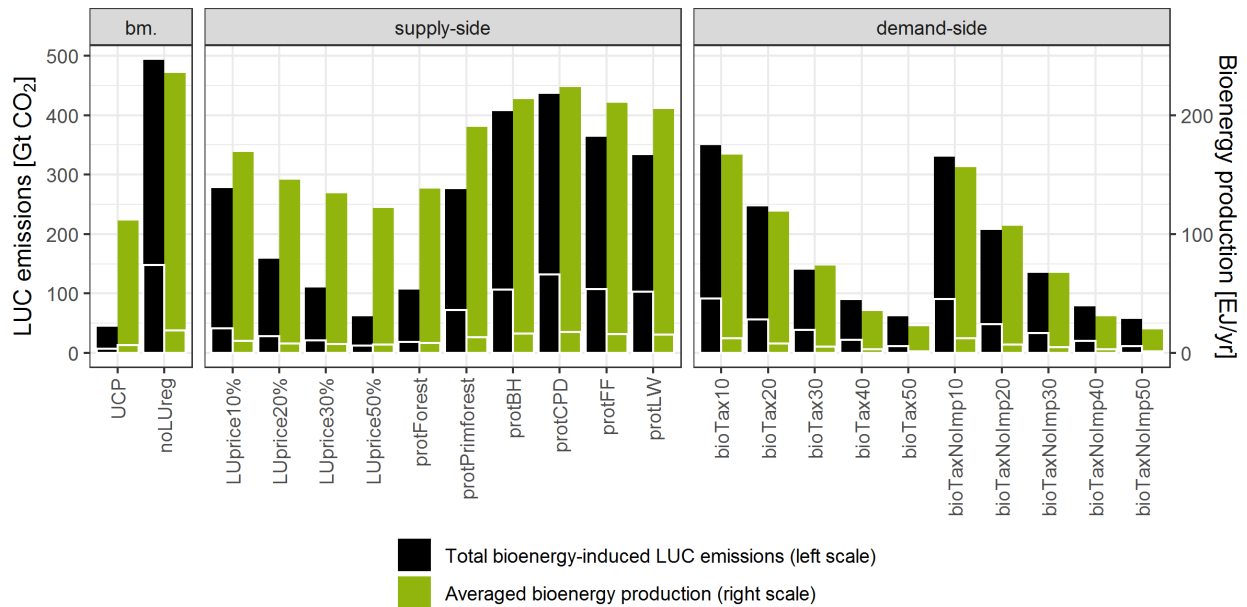


Fig. S1| Bioenergy-induced LUC emissions, bioenergy production and emission factors for all scenarios. Emissions, given as the total global LUC emissions and bioenergy, given as the averaged annual global production, are both evaluated for period from 2020 to 2100 and shown for different policy settings. Besides the two benchmark scenarios (“bm.”), policies are grouped into “supply-side” and “demand-side” policies. White bars indicate cumulative emissions in 2050 and the averaged annual bioenergy production until 2050, respectively.

Composition emissions for all scenarios

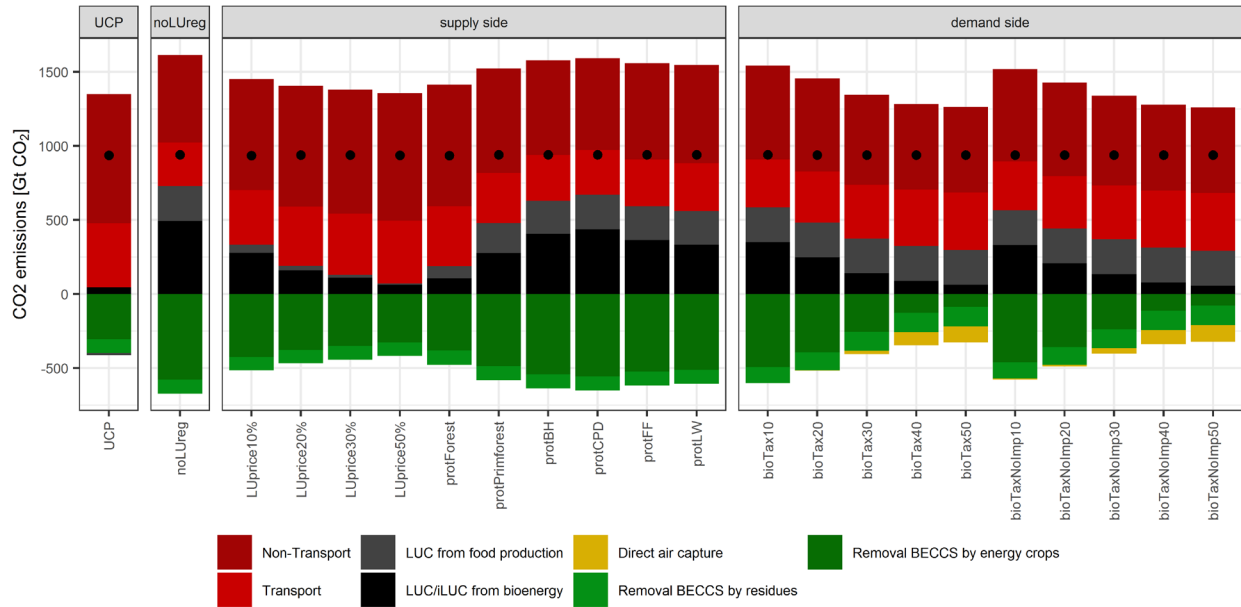


Fig. S2] Composition emissions for all scenarios. Composition of total anthropogenic CO₂ emissions, given for different policy assumptions cumulated from 2020 until 2100. Black dots refer to the net totals. LUC emissions not related to bioenergy production comprise CO₂ LUC emission from all other agricultural activities. Bioenergy from residues is assumed to be carbon neutral. For the calculation of the shares please refer to the methods section.

Emission factors from 2020-2050

If the evaluation period is only 30 years (2020 to 2050) EFs are substantially higher since a considerable fraction of LUC is actually happening before 2050, while only the smaller part of bioenergy has been produced by then.

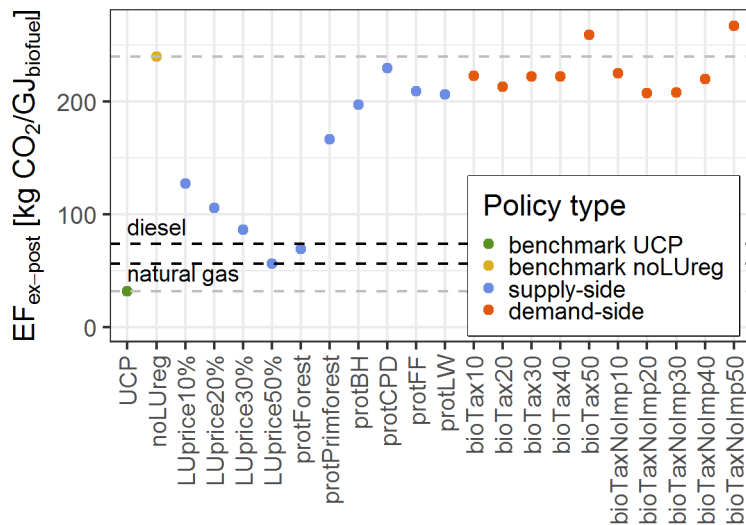


Fig. S3] Bioenergy emission factors in 2050. EFs in Fig. 1a are evaluated for the time horizon until 2100. Here we show the ex-post EFs for the much shorter 30-year time horizon from 2020 to 2050 for different policy assumptions.

Comparison to N₂O emissions

The emission factor of bioenergy-induced N₂O emissions is barely effected by any policy and stays at low levels between 4.6 and 7.2 kg CO₂-eq/GJ_{biofuel}. While the N₂O EF can be neglected relative to the CO₂ EF in scenarios where LU policies are missing, for the UCP scenario N₂O emissions are roughly 40% of the CO₂ emissions, since the EF for CO₂ is relatively small.

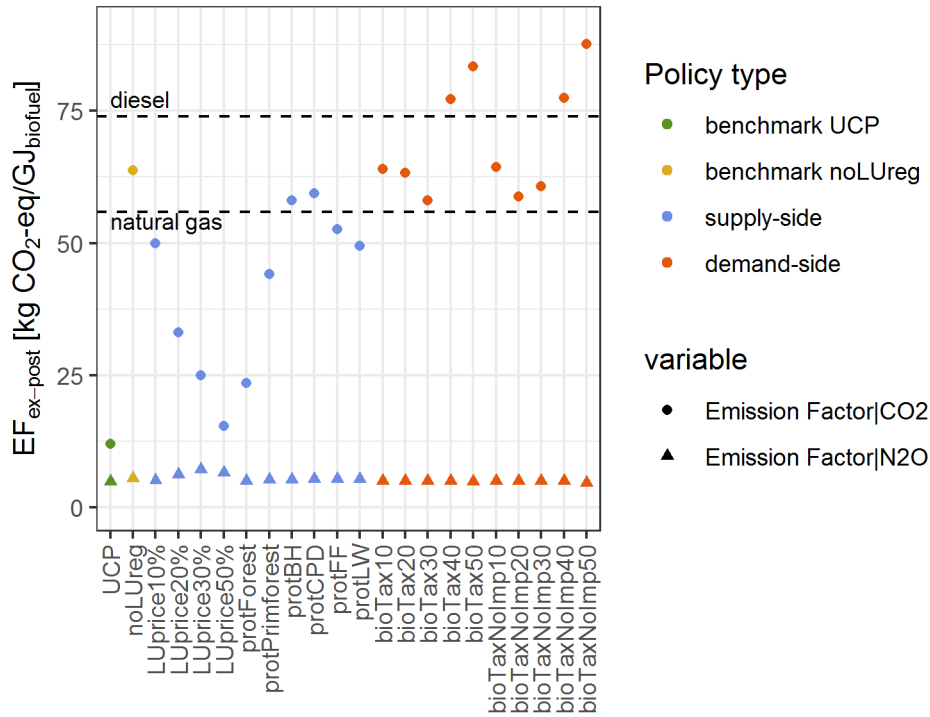


Fig. S4 | N₂O and CO₂ emission factors. Shown are bioenergy induced CO₂ and N₂O emission factors on a global average, for the evaluation period between 2020 and 2100 and for different policy assumptions. EFs for N₂O are converted to CO₂-eq using a global warming potential of 265⁵⁷ and are calculated equivalently to the EFs for CO₂.

Allocation of emissions and bioenergy production by local land-use characteristic for all scenarios

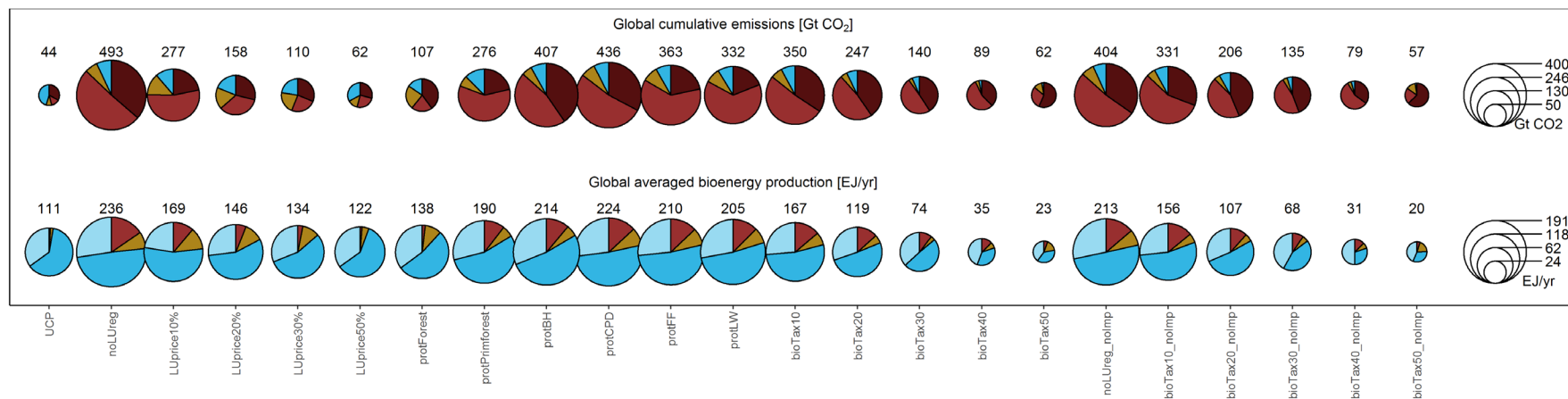


Fig. S5 | Allocation of LUC CO₂ emissions and bioenergy production by land-use characteristic. In Fig. 2 only a selection of scenarios was presented. Here we show the allocation of emissions and bioenergy production for all policy assumptions. For a description please refer to Fig. 2 in the main text.

BECCS efficiency factors until 2050

Evaluated for the 30-year time period between 2020 and 2050 bioenergy-induced LUC emissions exceed CDR savings by BECCS by far in all scenarios expect for UCP, where emissions are savings just equal out.

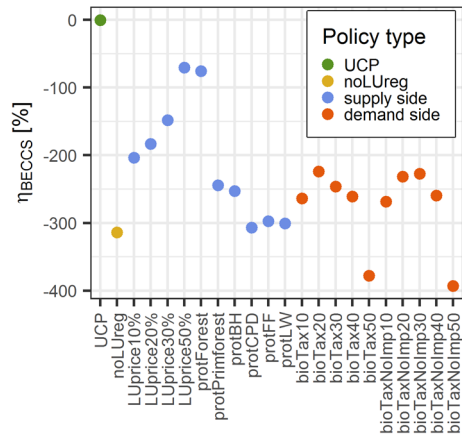


Fig. S6| The BECCS efficiency factor in 2050. η_{BECCS} is an indicator of how much of the sequestered carbon is effectively removed from the atmosphere if bioenergy-induced LUC emissions are subtracted. A negative efficiency indicates that bioenergy-induced LUC emissions exceed CDR savings by BECCS in the year 2050. For instance, $\eta_{BECCS} = -200\%$ implies that emissions are 200% higher than savings, i.e. three times as high. For the UCP policy setting, emissions and savings are just equal in 2050.

Liquids by primary energy carrier

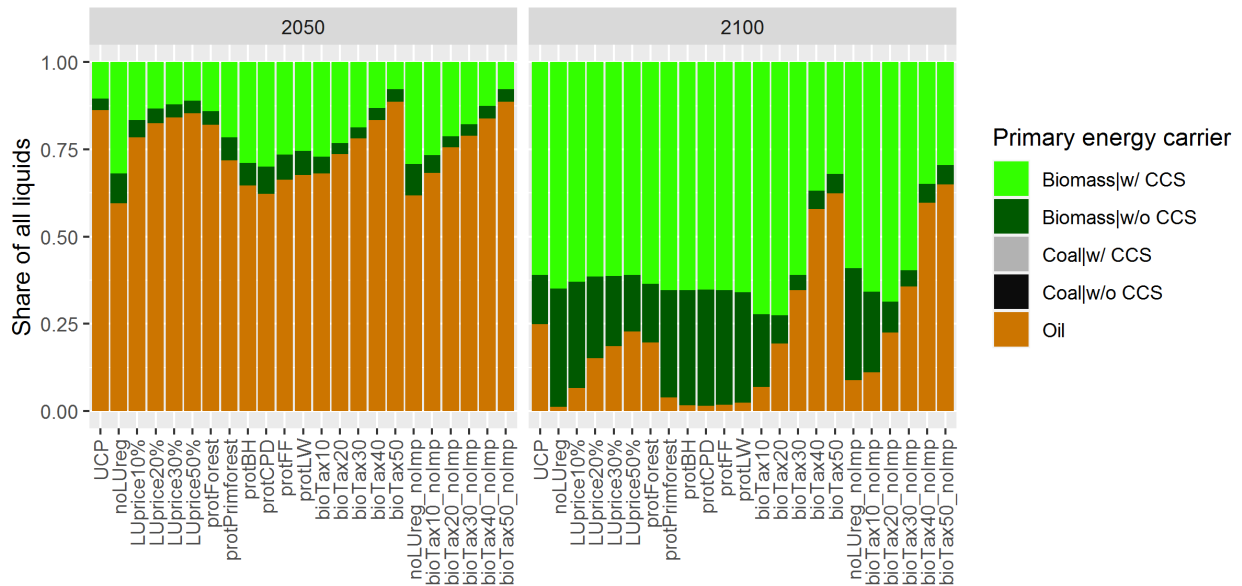


Fig. S7| Liquids by primary energy carrier. Biomass, coal and oil can be converted to liquid fuels, biomass and coal have an option to add CCS. Shown are shares of all liquids that are produced from these primary energy carriers, either with or without CCS included. Shares are given in the year 2050 and 2100 for different policy settings.

Final energy mix

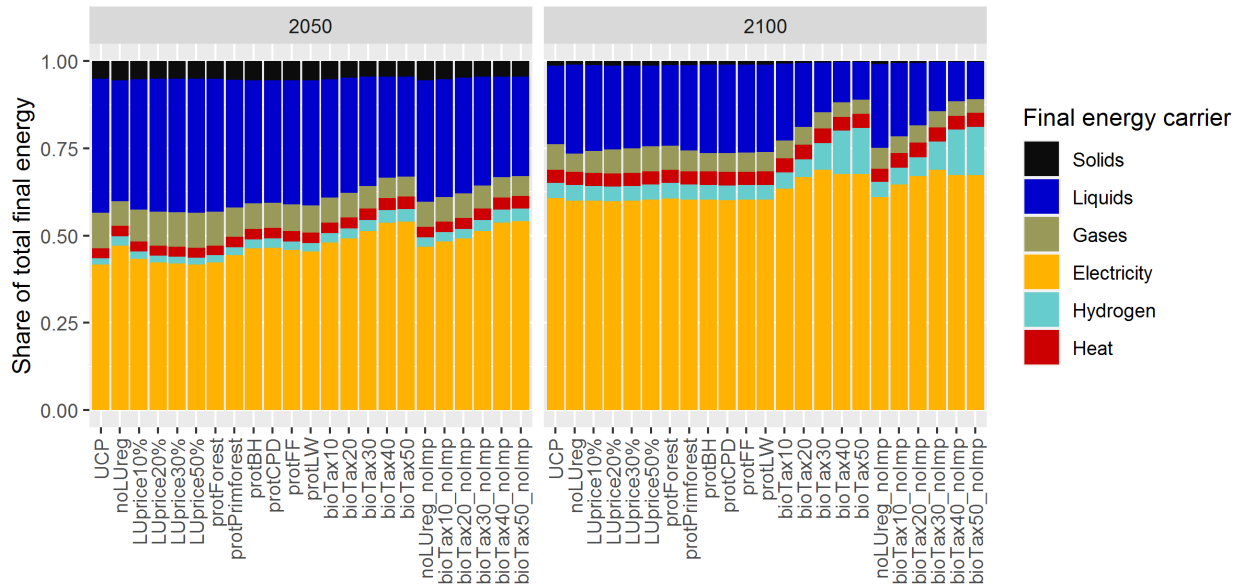


Fig. S8] Final energy mix. Total final energy is compound of different energy carriers. The shares are shown for different policy settings in the years 2050 and 2100.

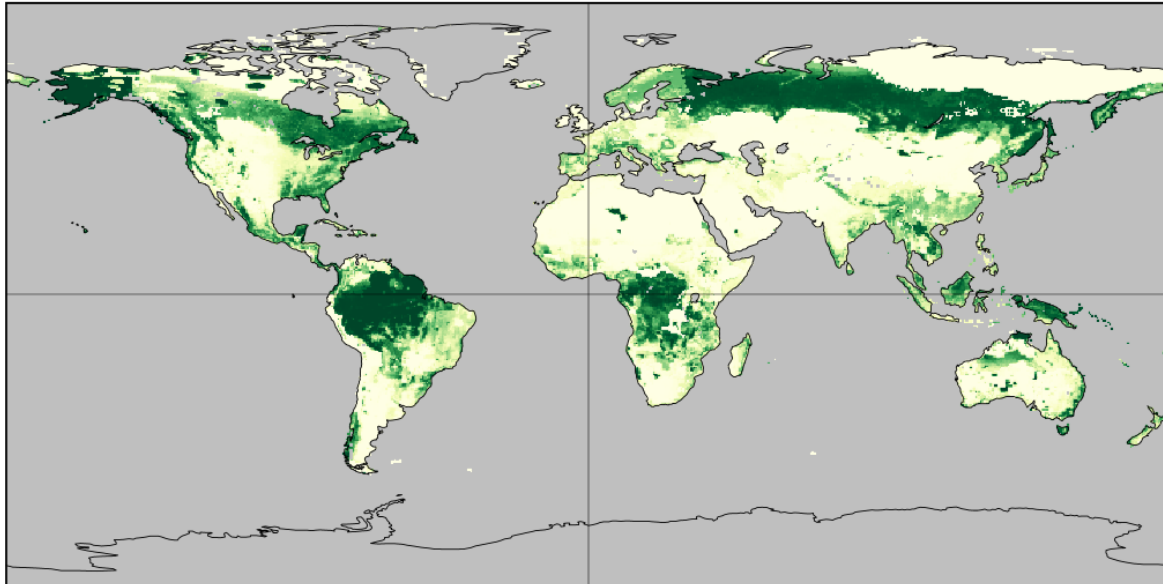
Protected areas

The policy settings *protForest*, *protPrimforest*, *protBH*, *protCPD*, *protFF*, *protLW* are directly protecting distinct areas that are thereby excluded from the land-pool available for agricultural activities, as explained in the methods section. Here we display the protected areas. Shown are grid cells with a resolution of $0.5^\circ \times 0.5^\circ$. The color code indicates the share of available land that is protected within the respective grid cell. Dark green implies that all of the available land is protected, bright beige means all land is at disposal for agricultural activities.

Please note that in *all* scenarios – not only in those with explicit protection schemes – areas from the World Database on Protected Areas (WDPa) are removed from the available land-pool.

Primary and secondary forests + WDPA

Resolution: 0.5°x0.5°

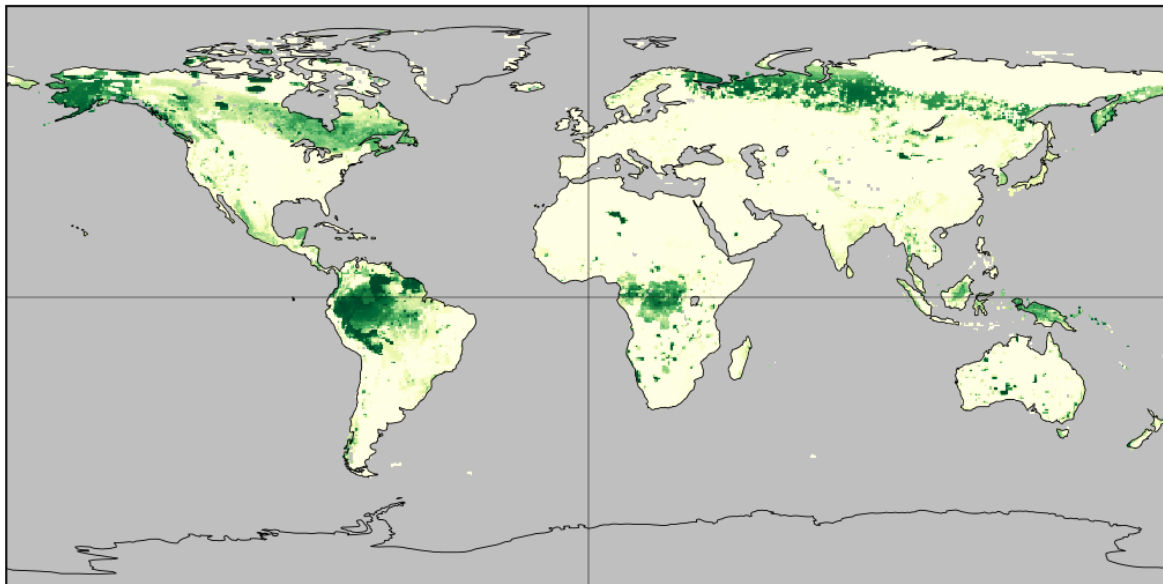


Data Min = 0.0, Max = 1.0, Mean = 0.3

Fig. S9| Protected areas – primary and secondary forests. This protection scheme was applied in the scenario “protForest”.

Primary forests + WDPA

Resolution: 0.5°x0.5°

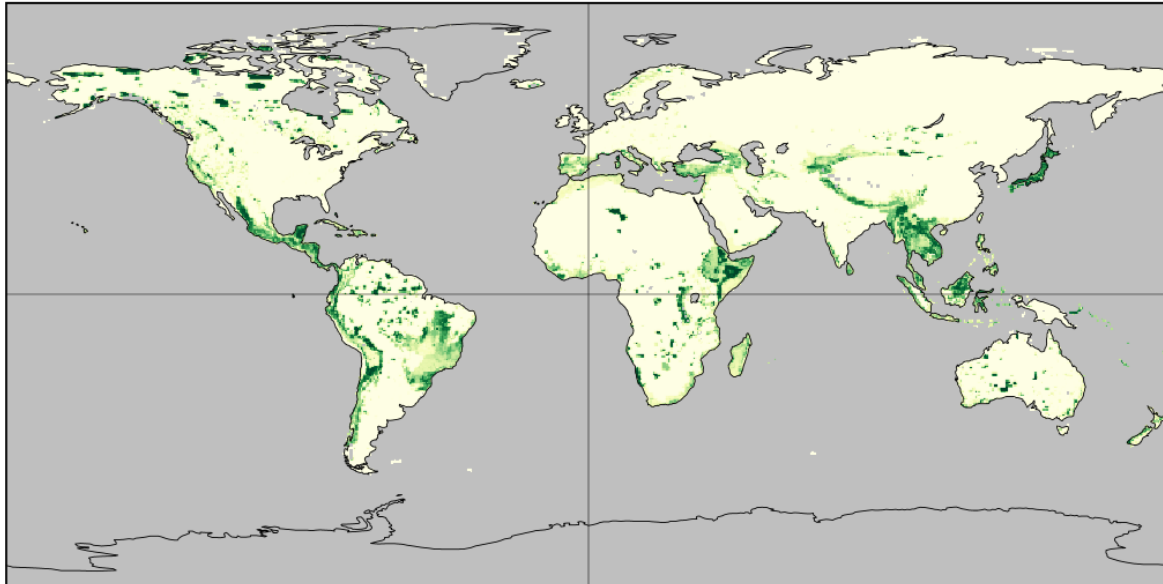


Data Min = 0.0, Max = 1.0, Mean = 0.1

Fig. S10| Protected areas – primary forests. This protection scheme was applied in the scenario “protPrimforest”.

Biodiversity Hotspots (BH) + WDPA

Resolution: 0.5°x0.5°

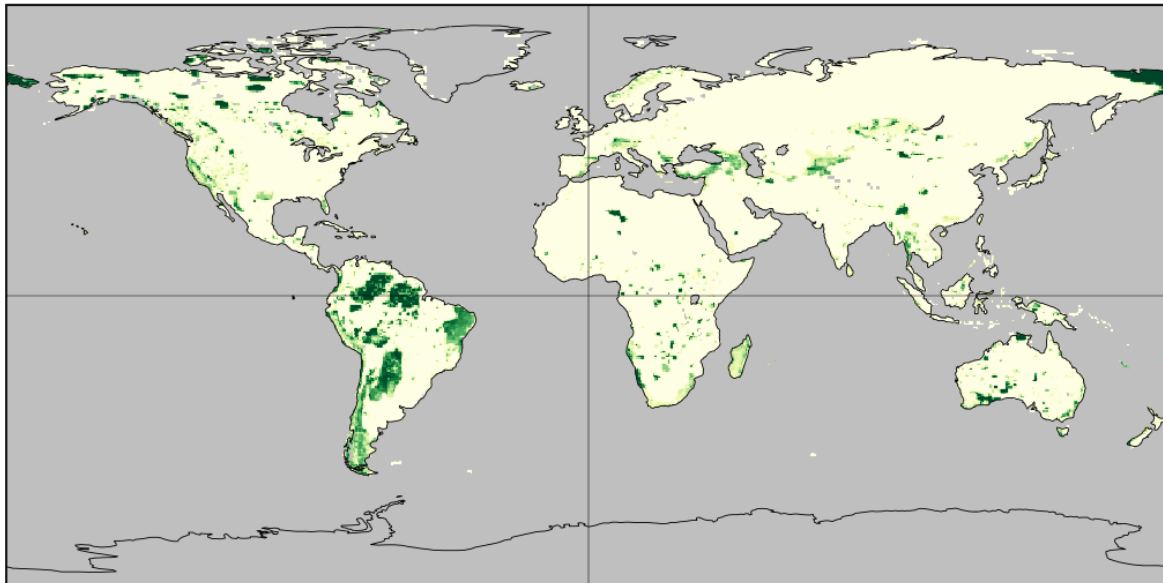


Data Min = 0.0, Max = 1.0, Mean = 0.1

Fig. S11| Protected areas – biodiversity hotspots. This protection scheme was applied in the scenario “protBH”.

Centers of Plant Diversity (CPD) + WDPA

Resolution: 0.5°x0.5°

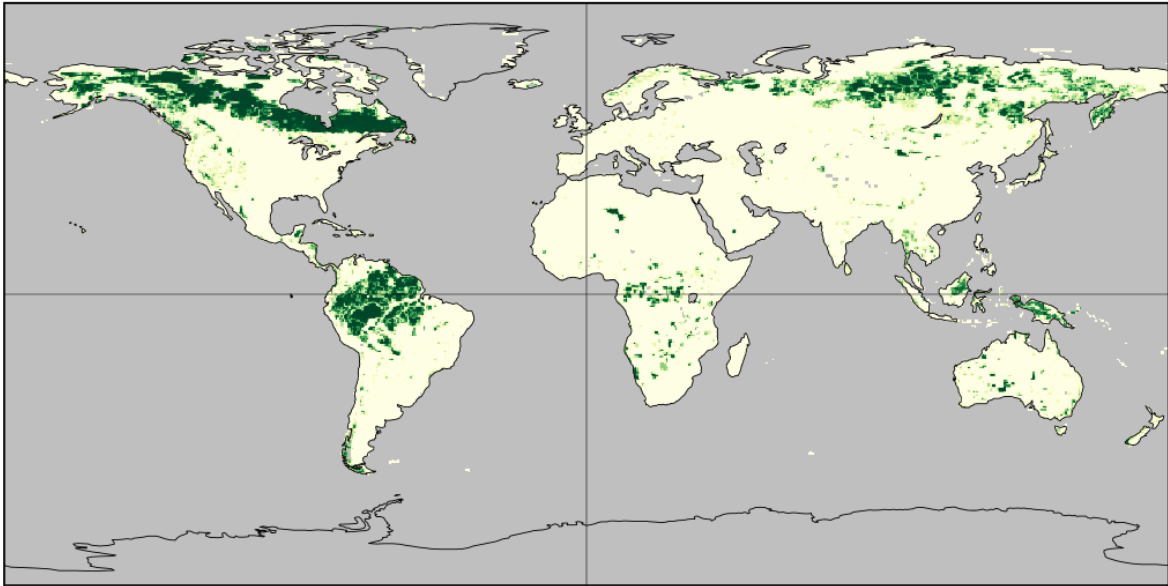


Data Min = 0.0, Max = 1.0, Mean = 0.1

Fig. S12| Protected areas – centers of plant diversity. This protection scheme was applied in the scenario “protCPD”.

Frontier Forests (FF) + WDPA

Resolution: 0.5°x0.5°

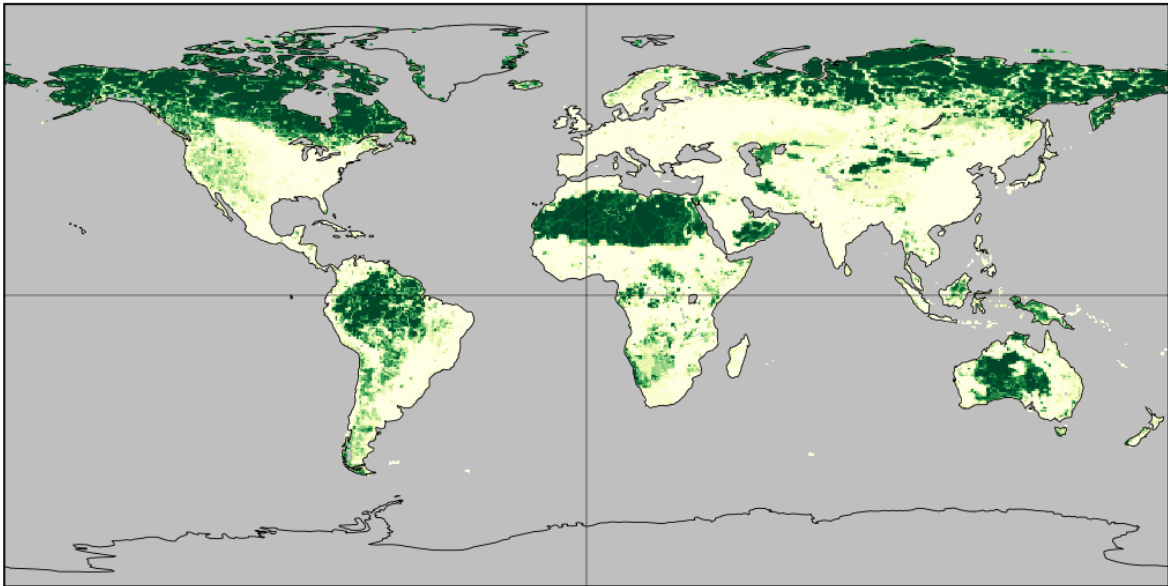


Data Min = 0.0, Max = 1.0, Mean = 0.1

Fig. S13| Protected areas – frontier forests. This protection scheme was applied in the scenario “protFF”.

Last Wild areas (LW) + WDPA

Resolution: 0.5°x0.5°



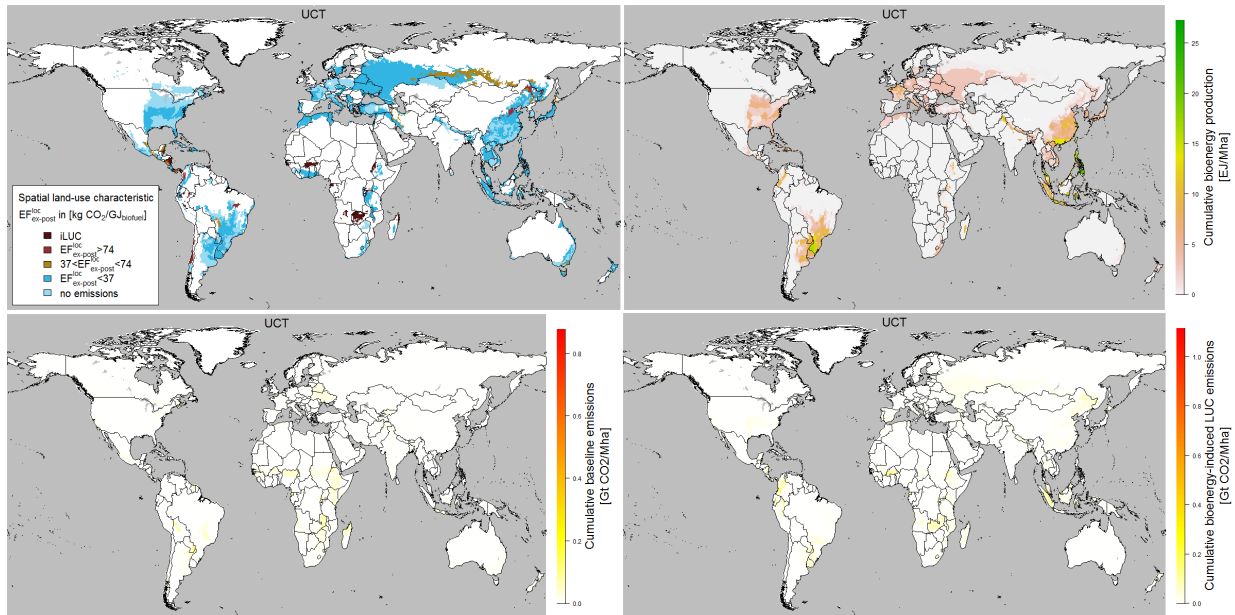
Data Min = 0.0, Max = 1.0, Mean = 0.3

Fig. S14| Protected areas – last wild areas. This protection scheme was applied in the scenario “protLW”.

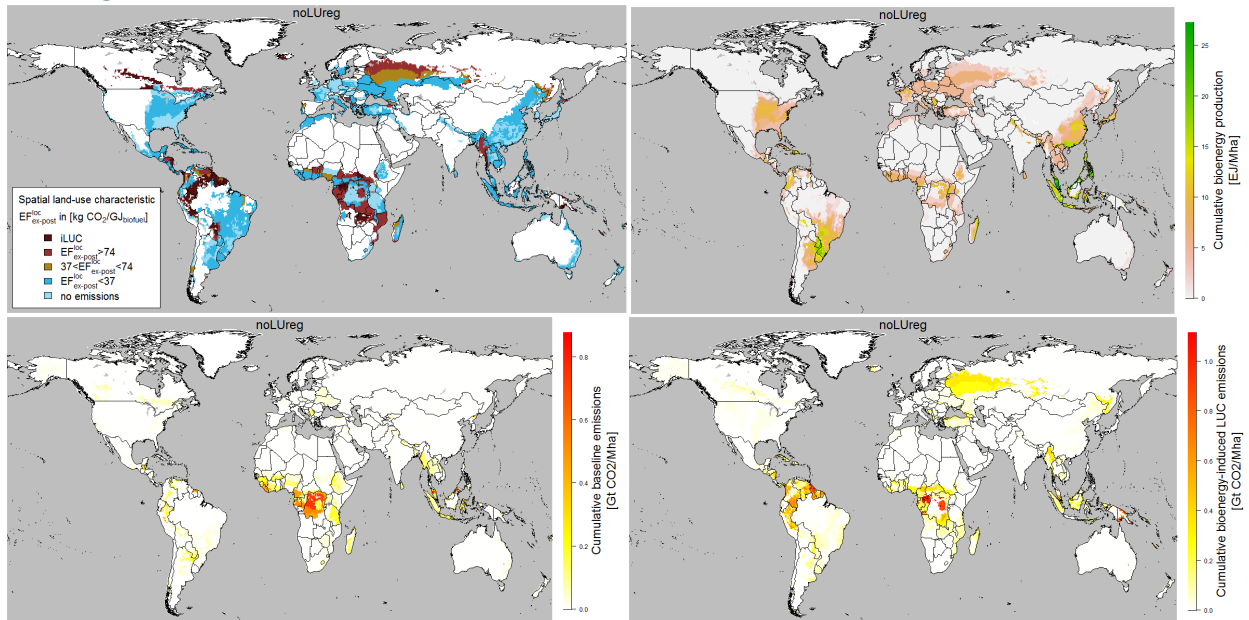
Spatial land-use characteristics

In the following the spatial allocation of **EFs** (top left), **bioenergy production** (top right), **baseline/counterfactual LUC emissions** (bottom left) and **bioenergy-induced LUC emissions** (bottom right) are shown for different scenarios.

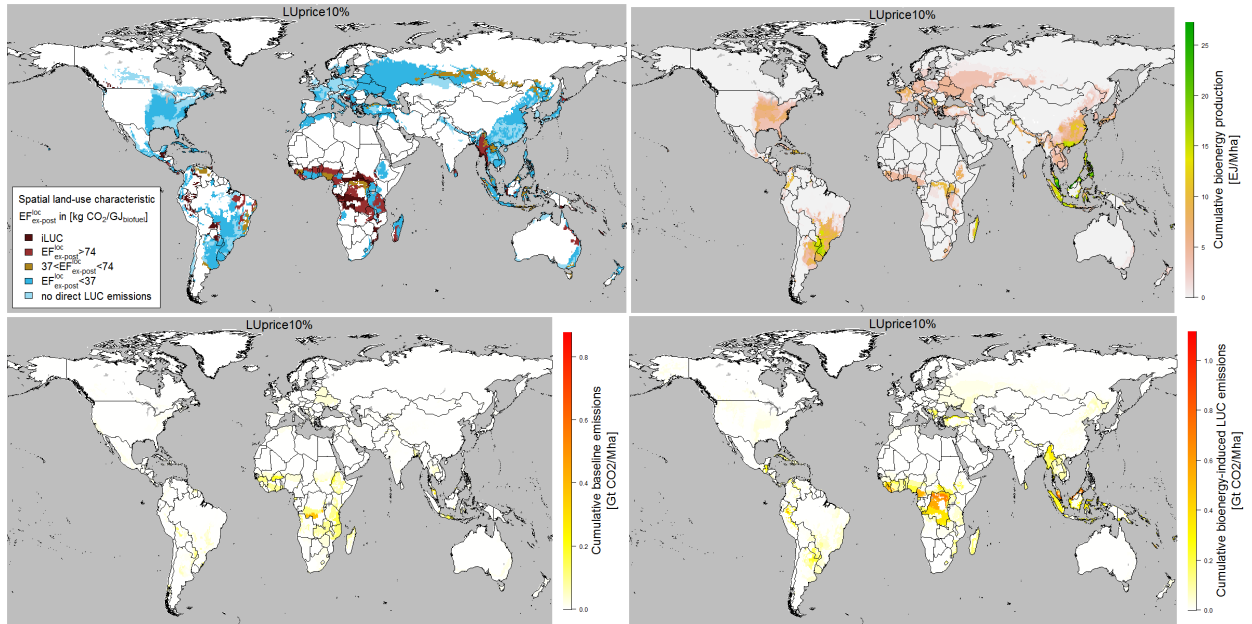
UCP



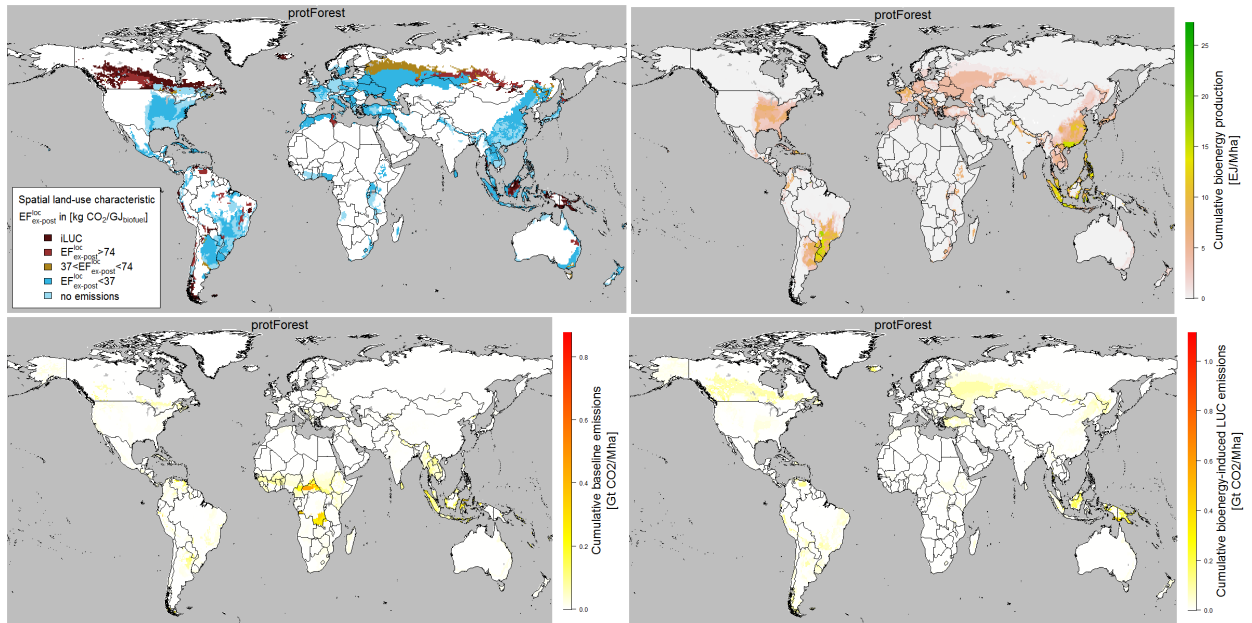
noLUreg



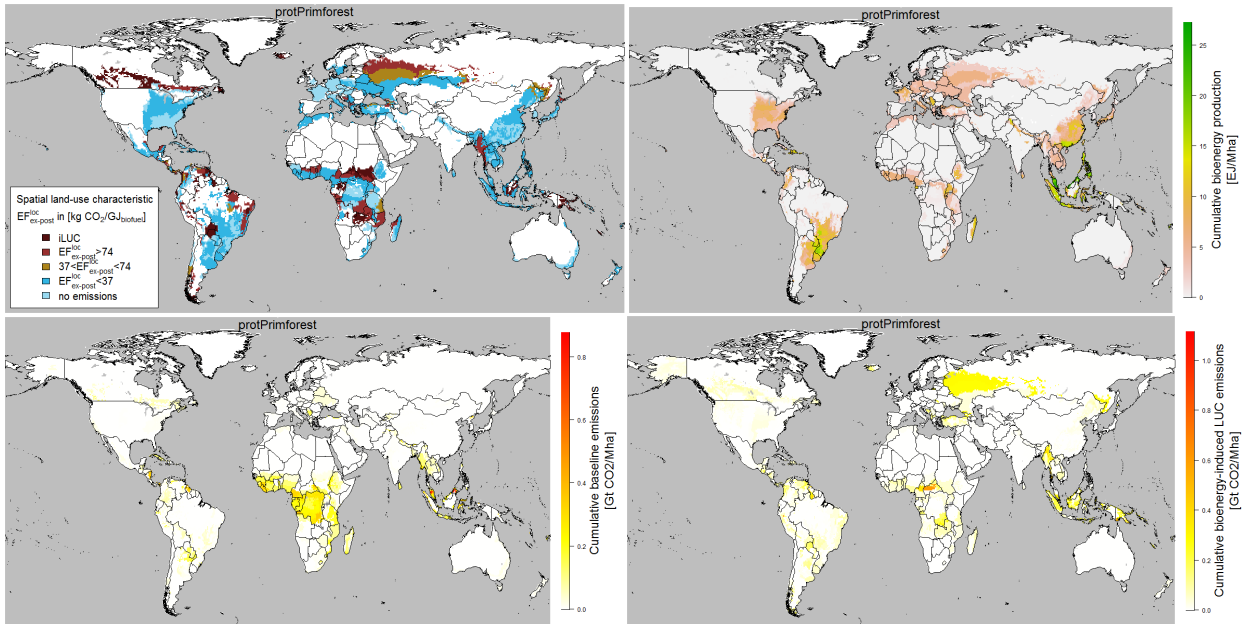
LUprice10%



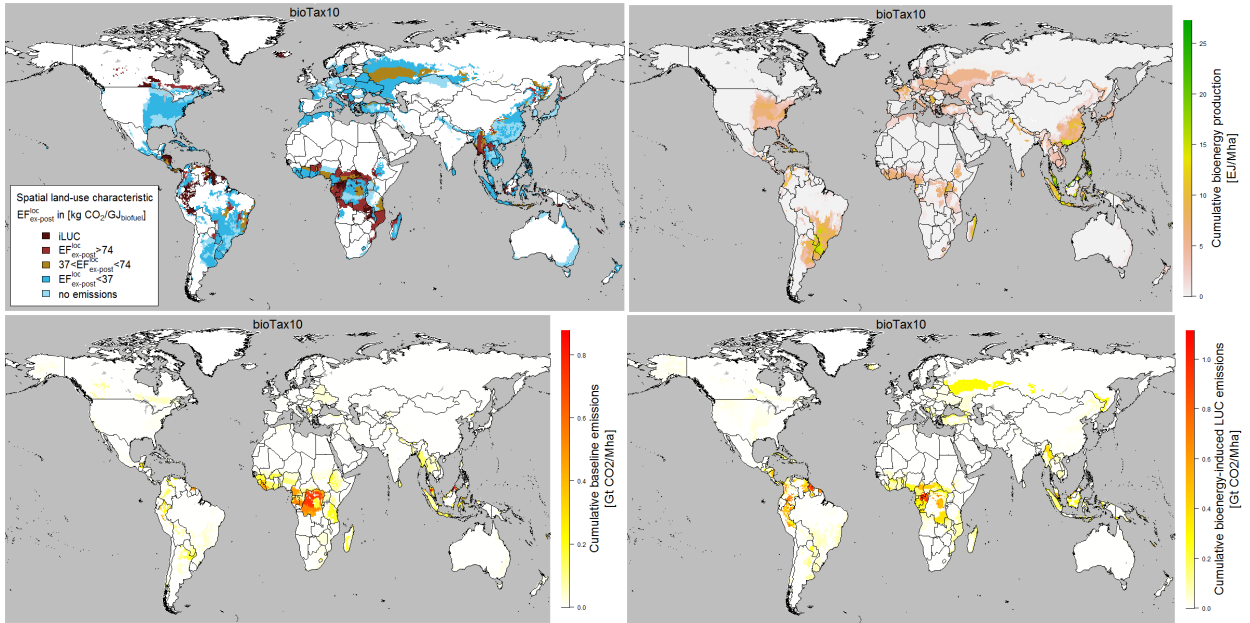
protForest



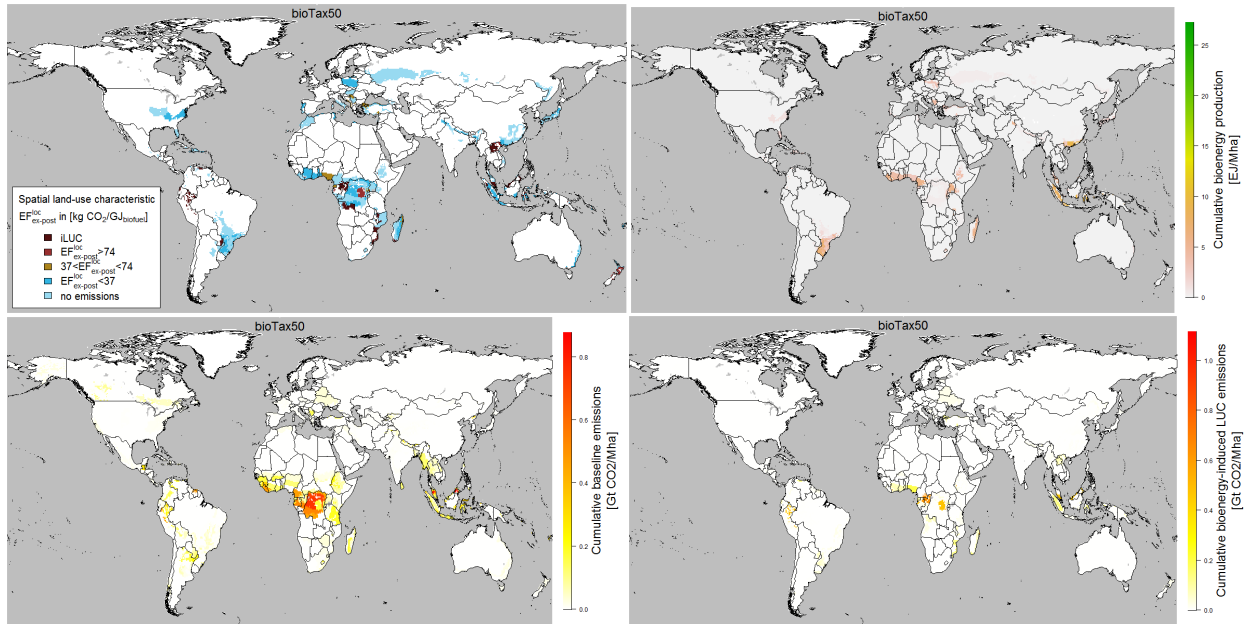
protPrimforest



bioTax10



bioTax50



MAGPIE Simulation units

- 1

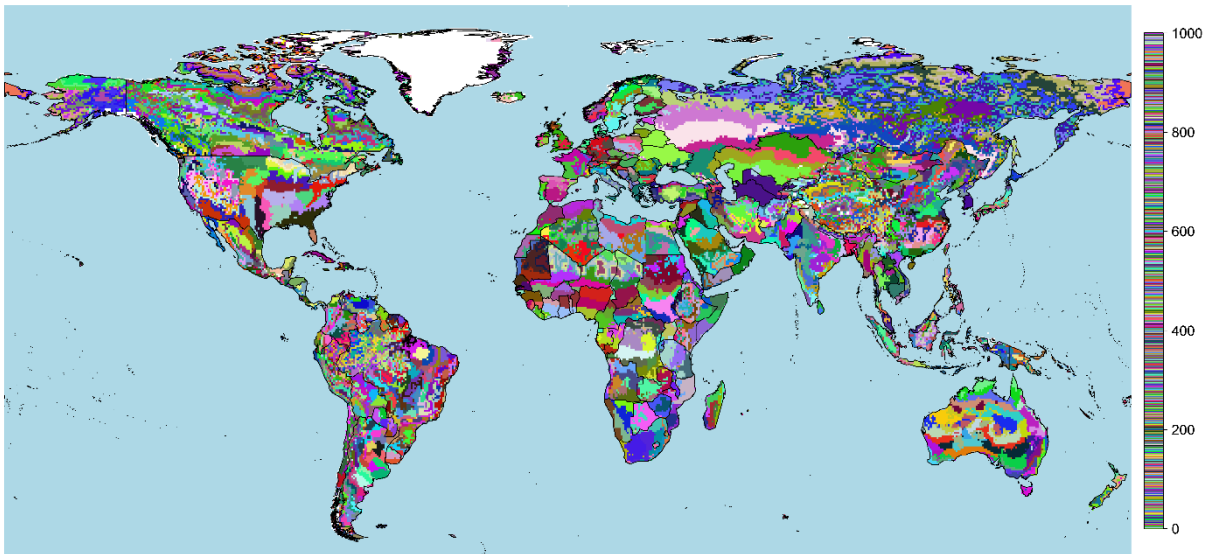


Fig. S15| The 1000 MAGPIE simulation units. As described in the methods section, each of these simulation units represents a cluster of aggregated 0.5-degree resolution grid cells with similar properties and reveals individual patterns of agricultural activities

Climate response

Since scenarios without a price on GHGs involve different levels of CH₄ and N₂O emissions (as explained in the methods section), radiative forcing and global mean temperature response can differ between scenarios.

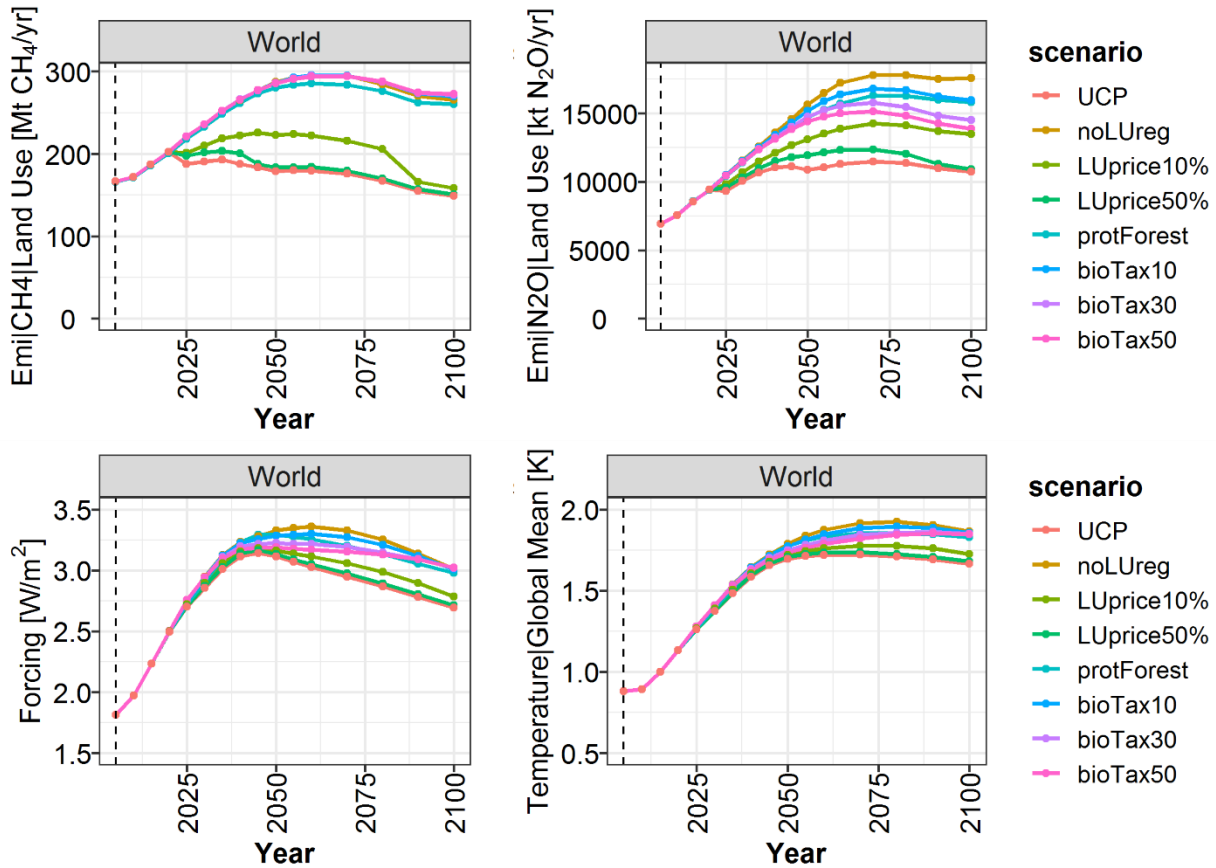


Fig. S16] Climate response. GHG trajectories of LU-based CH₄ (a) and N₂O (b) emissions for a selection of climate policy settings. Panel c shows trajectories of the resulting radiative forcing levels and panel d the corresponding increase in global mean temperature to the pre-industrial level. Radiative forcing and temperature response are derived with MAGICC 6⁵⁴.