Appendix

Drivers and patterns of land biosphere carbon balance reversal

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The appendix includes extra figures and tables referenced in the main text. They are shown in the order of reference.
Table S1: GCM patterns (IPCC-DDC: AR4 GCM data: SRES scenarios, available at http://www.ipcc-data.org/sim/gcm_monthly/SRES_AR4/index.html) used in downscaling GMT change to local changes in temperature and precipitation, as described in Stehfest et al. (2014).

| Climate model name | Scenario used |
|--------------------|---------------|
| cccma CGCM3 1 t47  | a1b           |
| CNRM CM3           | a1b           |
| CSIRO mk3_0        | a1b           |
| ECHO G_            | a1b           |
| FGOALS g1.0        | b1            |
| GFDL CM2_0         | a1b           |
| GFDL CM2_1         | a1b           |
| GISS model_e_h     | a1b           |
| GISS model_e_r     | b1            |
| INM CM3.0          | a1b           |
| IPSL CM4           | a1b           |
| MICORC3.2 medres   | a1b           |
| MPI ECHAM5         | a2            |
| ncar ccsm3_0       | a1b           |
| ncar PCM1          | a1b           |
| UKMO HadCM3        | a2            |
Table S 2: Data exchange between IMAGE and LPJmL in coupled mode, exchange is annually, but climate data is resolved monthly.

| Data sent from IMAGE to LPJmL | Description                                                                                                                                                                                                 | Resolution               |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|
| Climate data: precipitation [mm], mean temperature [°C], number of wet days [-], cloudiness [%]                                          | Climate data, 30 year averages, as provided by CRU, and as calculated based on MAGICC 6.0 within the IMAGE framework                                      | 0.5° gridded, monthly    |
| Atmospheric CO₂ concentration [ppm] |                                                                                           | CO₂ concentration, affecting plant growth                                                                                                           | Global, annually         |
| Land clearance type [-]       | Indicator for land-use change. Either biomass is burnt or stored as wood                                                               | 0.5° gridded, annually   |
| Crop fraction [%]             | Fraction of agricultural grid cells that should be covered by the crop type as distinguished in IMAGE (1-19)                                                      | 0.5° gridded, annually   |
| Timber harvest [-]            | Fraction of grid cells that are harvested for timber and traditional biofuels.                                                            | 0.5° gridded, annually   |
| Timber use fraction [-]       | Fractions of timber being used in products with slow turnover time, with fast turnover time, or as traditional bio-energy.                                                                     | 0.5° gridded, annually   |

| Data sent from LPJmL to IMAGE | Purpose                                                                                                                                                                                                 | Resolution               |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|
| Potential vegetation [-]      | Potential natural vegetation type (biomes)                                                                                                                                             | 0.5° gridded, annually   |
| Biomass [gC m-2 yr-1]         | Carbon content in 9 carbon pools for land-use change module                                                                                                                             | 0.5° gridded, annually   |
| Net primary production (NPP, [gC m⁻² yr⁻¹]) | Net primary production (diagnostic output)                                                                                          | 0.5° gridded, annually   |
| Net ecosystem productivity (NEP, [gC m⁻² yr⁻¹]) | Net ecosystem production (calculated as NPP-Rh; contributes to C flux to atmosphere)                                                                 | 0.5° gridded, annually   |
| Heterotrophic respiration flux [Rₚ, gC m⁻² yr⁻¹] | Heterotrophic soil respiration (diagnostic output)                                                                                       | 0.5° gridded, annually   |
| Deforestation flux [gC m⁻² yr⁻¹] | CO₂ emissions from deforestation (contributes to C flux to atmosphere)                                                             | 0.5° gridded, annually   |
| Natural Fire emissions [gC m⁻² yr⁻¹] | CO₂ emissions from natural ecosystem fires (contributes to C flux to atmosphere)                                                      | 0.5° gridded, annually   |
| Agr. harvest flux [gC m⁻² yr⁻¹] | Harvest carbon flux from agricultural land (contributes to C flux to atmosphere)                                                 | 0.5° gridded, annually   |
| Biofuel harvest flux [gC m⁻² yr⁻¹] | Harvest carbon flux from biofuel plantations (contributes to C flux to atmosphere)                                                 | 0.5° gridded, annually   |
| Timber harvest flux [gC m⁻² yr⁻¹] | Harvest carbon flux from timber extraction (accumulates in product pools)                                                          | 0.5° gridded, annually   |
| Fast timber turnover [gC m⁻² yr⁻¹] | Emissions from fast decaying product pools (contributes to C flux to atmosphere)                                              | 0.5° gridded, annually   |
| Slow timber turnover [gC m⁻² yr⁻¹] | Emissions from slow decaying product pools (contributes to C flux to atmosphere)                                             | 0.5° gridded, annually   |
| Trad. biofuel flux [gC m⁻² yr⁻¹] | Emissions from traditional biofuels (contributes to C flux to atmosphere)                                                          | 0.5° gridded, annually   |
Table S 3: Mapping of IMAGE land-use systems to cropping systems and managed grassland in LPJmL. Crop functional types are typically parameterized as specific crops in LPJmL which are indicated in parenthesis.

| IMAGE land-use system         | Implementation in LPJmL                                                                 |
|-------------------------------|----------------------------------------------------------------------------------------|
| Temperate cereals [irrigated/rainfed] | Temperate cereals (wheat) [irrigated/rainfed]                                          |
| Rice [irrigated/rainfed]      | Rice [irrigated/rainfed]                                                               |
| Maize [irrigated/rainfed]     | Maize [irrigated/rainfed]                                                              |
| Maize bioenergy [rainfed]     | Maize [rainfed]                                                                        |
| Non-woody bioenergy [rainfed] | Biomass grass [rainfed]                                                                |
| Sugar cane [rainfed]          | Sugar cane [rainfed]                                                                   |
| Tropical cereals [irrigated/rainfed] | Tropical cereals (millet) [irrigated/rainfed]                                      |
| Pulses [irrigated/rainfed]    | Pulses (field peas) [irrigated/rainfed]                                               |
| Roots and tubers [irrigated/rainfed] | Tropical roots and tubers (cassava) in the tropics (between 30°N and 30°S), temperate roots and tubers (sugar beet) otherwise [irrigated/rainfed] |
| Oil crops [irrigated/rainfed]  | 50% soybean and 50% groundnut in the tropics (between 30°N and 30°S), 50% rapeseed and 50% sunflower otherwise [irrigated/rainfed] |
| Pasture [rainfed]             | Managed grassland [rainfed]                                                            |
Figure S1: Computation of climate change patterns in IMAGE. NEP and LUC emission fields are computed internally by LPJmL, which is the biosphere module in IMAGE 3.0. Monthly fields of temperature, precipitation, cloudiness, and wet days are computed by the atmosphere module in IMAGE and supplied to the biosphere module (LPJmL), where these are interpolated to daily values. Data exchange between the atmosphere and biosphere module occurs at annual time steps. In the experiments here, we use 16 different geographic scaling patterns that are derived from GCM simulations to account for the uncertainty in the spatial patterns of climate change. Geographic scaling patterns describe local changes in temperatures, precipitation and cloudiness as a function of GMT change and these factors are specific to GCM, location (grid cell) and month. Reproduced (with permission) from Stehfest et al. (2014).
Figure S 2: As figure 2 in main text but with the alternative definition of carbon balance reversal that also includes cases with a significant negative trend over at least the last 20 years that leads to a reversal if extrapolated for another 20 years to the year 2120.
Figure S 3: Cumulative carbon balance over the 21st century. On average, cases that lead to a reversal of the land biosphere's carbon balance emit the carbon that was accumulated in the beginning but can also lead to strong emissions of carbon to the atmosphere.
Figure S 4: Oceanic carbon uptake rates over the 21st century.
Figure S 5: As figure 3 in main text but with the alternative definition of carbon balance reversal that also includes cases with a significant negative trend over at least the last 20 years that leads to a reversal if extrapolated for another 20 years to the year 2120.
Figure S 6: Temporal development of the rate of global warming [°C/year]. Groups of lines distinguish the different equilibrium climate sensitivities as well as the socio-economic settings.
Figure S 7: The maximum rate of global warming [°C/decade] is closely related to the maximum global mean temperature (GMT) increase in the 2091-2100 decade compared to pre-industrial [°C] at the low temperature range, but is more variable at higher temperatures.
Figure S 8: There is large agreement on tree cover decline across all cases (dark areas, top panel) in boreal and tropical regions. Tree cover decline in the tropics is mainly driven by land-use change. In the boreal zones the tree cover decline is mainly a response to heat and drought stress. Cases with carbon balance reversal typically see tree cover decline in larger areas in the boreal zone (orange, top) and the decline is more pronounced (bottom panel). The bottom panels depicts the difference in tree cover change [%] between the average of all cases that lead to a carbon balance reversal and that of all cases that do not lead to a carbon balance reversal. The increase in tree cover in the far north compared to cases without carbon balance reversal is driven by a more intensive boreal greening (blue, top).
Figure S 9: There is great agreement on reductions in soil carbon (dark areas in top panel), but for cases with carbon balance reversal, this loss of soil carbon typically extends further into the tropics and temperate zones (orange). Also, the loss of soil carbon is typically more pronounced in cases with carbon balance reversal than in cases without (red/yellow areas in bottom panel). The bottom panel depicts the difference in soil carbon content [kgC m$^{-2}$] between the average soil carbon content of all cases that lead to a carbon balance reversal and that of all cases that do not lead to a carbon balance reversal. The loss of soil carbon is generally stronger in cases with carbon balance reversal, but most pronouncedly in the areas north 60°N. There are areas that see increasing soil carbon stock only for the cases with carbon balance reversal (blue in top and bottom panel; e.g. parts of Canada and Russia). This is, because reductions in tree cover lead to greater soil carbon stocks due to higher litter fall.
Figure S 10: Rising probability of carbon reversal with equilibrium climate sensitivity.

Stehfest E, Vuuren D v, Kram T, Bouwman L, Alkemade R, Bakkenes M, Biemans H, Bouwman A, Elzen M d, Janse J, et al. 2014 Integrated Assessment of Global Environmental Change with IMAGE 3.0 - Model description and policy applications: PBL Netherlands Environmental Assessment Agency)