Supplementary Information

Peatland protection and restoration are key for climate change mitigation

Florian Humpenöder, Kristine Karstens, Hermann Lotze-Campen, Jens Leifeld, Lorenzo Menichetti, Alexandra Barthelmes, Alexander Popp

Overview of study setup

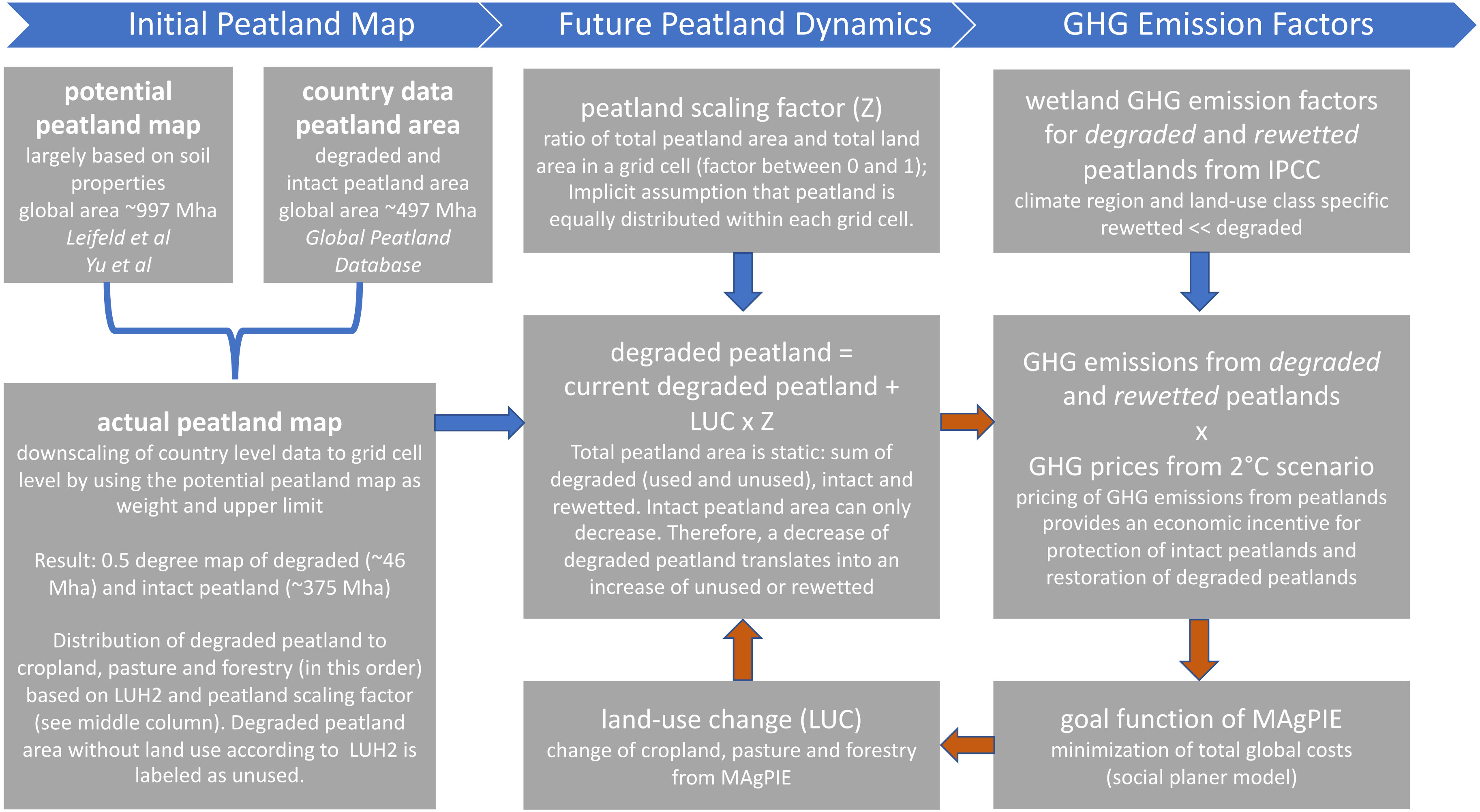

Figure S1: Overview of study setup. Blue arrows indicate inputs to the model. Red arrows indicate dynamics inside the model.

MAgPIE framework

The *Model of Agricultural Production and its Impact on the Environment* (MAgPIE) is developed and used to assess the competition for land and water, and the associated consequences for sustainable development under future scenarios of rising food, energy and material demand, climate change impacts, and land-related greenhouse gas mitigation policies (Dietrich *et al* 2019). MAgPIE is a global partial equilibrium model of the land-use sector that operates in a recursive dynamic mode and incorporates spatially explicit information on biophysical constraints into an economic decision making process (Lotze-Campen *et al* 2008). It takes regional economic conditions such as elastic demand for agricultural commodities, technological development and production costs as well as spatially explicit data on biophysical constraints into account. Geographically explicit data on biophysical conditions are provided by the Lund-Potsdam-Jena managed land model (LPJmL) (Bondeau *et al* 2007, Müller and Robertson 2014) on a 0.5 degree resolution and include e.g. carbon densities of different vegetation types, agricultural productivity such as crop yields and water availability for irrigation. Due to computational constraints, all model inputs in 0.5 degree resolution are aggregated to simulation units for the optimization process based on a clustering algorithm (Dietrich *et al* 2013). Available land types in MAgPIE are cropland, pasture area, forest, other land (including non-forest natural vegetation, abandoned agricultural land and deserts) and settlements. Cropland (rainfed and irrigated), pasture, forest and other land are endogenously determined, while settlement areas are assumed to be constant over time. The cropland covers cultivation of different crop types (e.g. temperate and tropical cereals, maize, rice, oilseeds, roots), both rainfed and irrigated systems, and two 2nd generation bioenergy crop types (grassy and woody). Considering international trade based on historical trade patterns and economic competitiveness, global production has to meet demand for food, feed, seed, processing and bioenergy. Food demand is derived based on population growth and dietary transitions, accounting for changes in intake and food waste, the shift in the share of animal calories, processed products, fruits and vegetables as well as staples. MAgPIE estimates flows of different greenhouse gases (GHGs) from land use and land-use change. CO_2 emissions are calculated based on changes in carbon stocks of vegetation, which are subject to land-use change dynamics such as conversion of forest into agricultural land (Popp *et al* 2014). In case of afforestation or when agricultural land is set aside from production, regrowth of natural vegetation absorbs carbon from the atmosphere (negative CO_2 emissions). Nitrogen emissions are estimated based on nitrogen budgets for croplands, pastures and the livestock sector (Bodirsky *et al* 2014). CH_4 emissions are based on livestock feed and rice cultivation areas (Popp *et al* 2010). In mitigation pathways, GHG emissions are subject to pricing, which affects the decision-making regarding land use and land expansion.

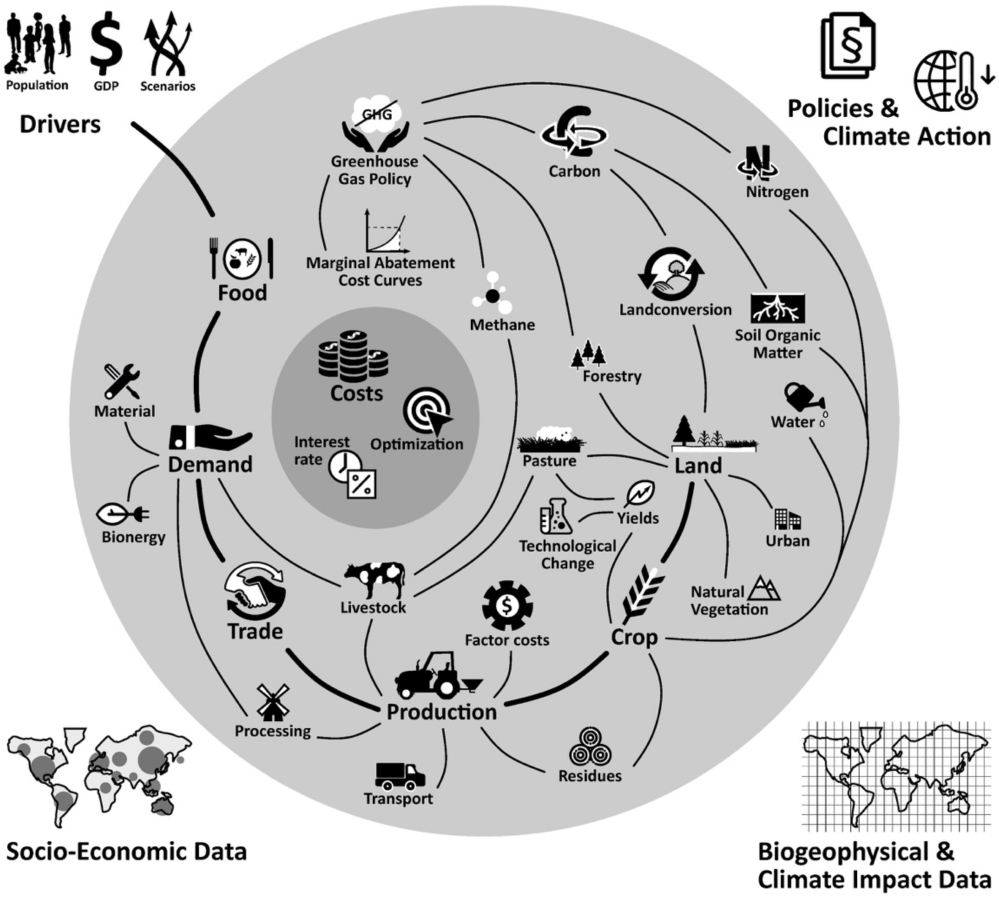

Figure S2: MAgPIE 4 framework with simplified modular structure and module interactions (reproduced from Dietrich et al *2019. CC BY 4.0).*

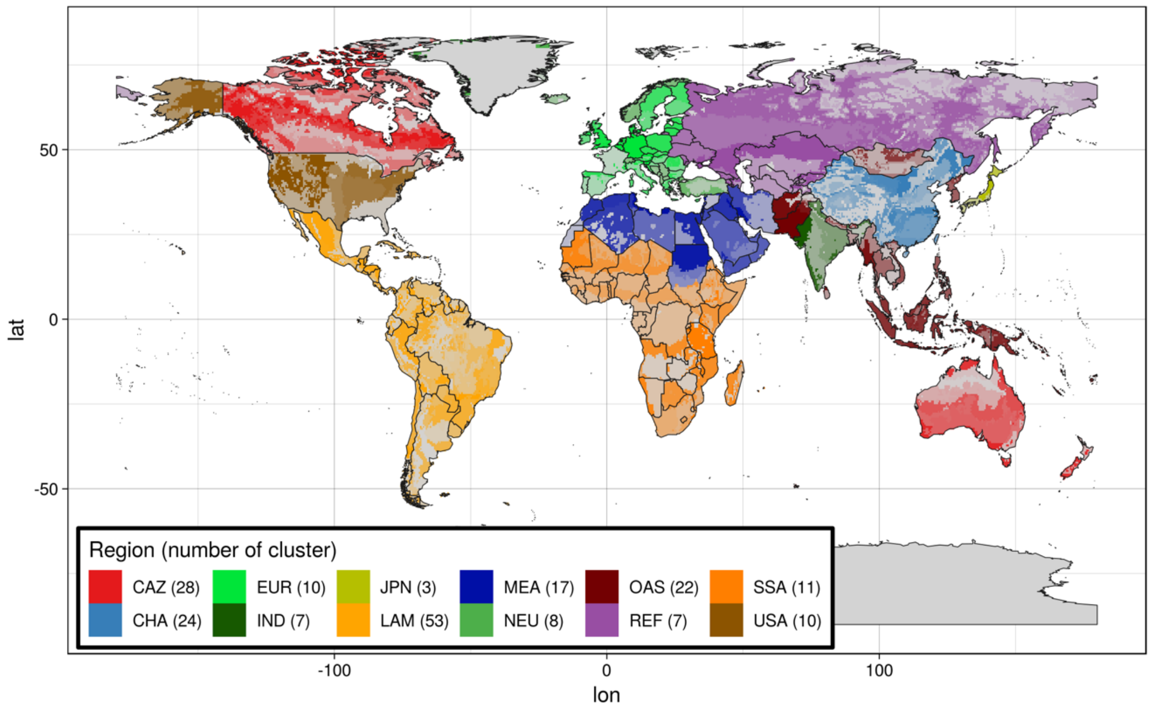

Figure S3: MAgPIE world regions (reproduced from Dietrich et al 2019. CC BY 4.0): Canada, Australia and New Zealand: CAZ; China: CHA; European Union: EUR; India: IND; Japan: JPN; Latin America: LAM; Middle East and north Africa: MEA; non-EU member states: NEU; other Asia: OAS; reforming countries: REF; Sub-Saharan Africa: SSA; United States: USA.

Peatland module

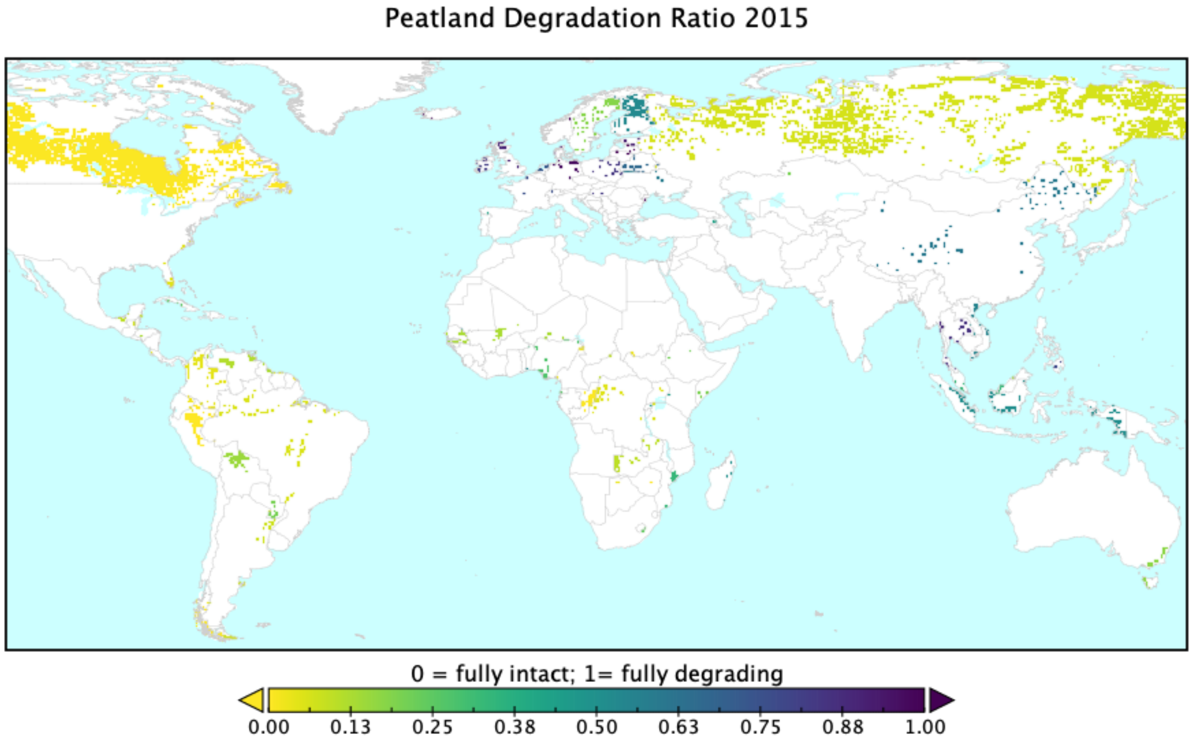

Figure S4: Map of present-day degraded and intact peatlands used to initialize the peatland module. The map shows the ratio of degraded peatlands and total peatland area (total = degraded + intact) in 2015 for each grid cell (i.e. a value of 0 corresponds to fully intact peatlands and a value of 1 corresponds to fully degrading peatlands). We generated this map by combining a map of potential peatland area provided by the authors of (Leifeld and Menichetti 2018, Yu et al 2010) with country level data on the status of peatlands for the year 2015 from the Global Peatland Database (Greifswald Mire Centre 2015) (see also Figure S1).

	Land use	Drained					Rewetted					
	Category	CO_2	DOC	CH_4	N_2O	GWP	CO_2	DOC	CH_4	N_2O	GWP	ER
Boreal	Cropland	28.97	0.44	1.98	6.09	37.48	-2.02	0.29	6.21	0	4.48	33.00
	Pasture	20.90	0.44	2.03	4.45	27.82	-2.02	0.29	6.21	0	4.48	23.34
	Forestry	0.92	0.44	0.42	0.10	1.88	-1.25	0.29	1.86	0	0.90	0.98
Temperate	Cropland	28.97	1.14	1.98	6.09	38.18	1.83	0.88	9.79	0	12.5	25.68
	Pasture	13.20	1.14	2.16	0.75	17.25	1.83	0.88	9.79	0	12.5	4.75
	Forestry	9.53	1.14	0.27	1.31	12.25	1.83	0.88	9.79	0	12.5	-0.25
Tropical	Cropland	51.33	3.01	1.77	2.34	58.45	0	2.09	1.86	0	3.95	54.50
	Pasture	35.20	3.01	1.77	2.34	42.32	0	2.09	1.86	0	3.95	38.37
	Forestry	55.00	3.01	1.58	0.56	60.15	0	2.09	1.86	0	3.95	56.20

Table S1: GHG emission factors (tCO_{2eq} ha^{-1} yr^{-1}) for drained and rewetted peatlands (adapted with permission from Wilson et al 2016. Table 5). In line with the IPCC Tier 1 approach we use nutrient poor emission factors for boreal and nutrient rich emission factors for temperate regions. Emission factors for tropical grassland have been added based on the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Hiraishi et al 2014).

Af	tropical	Tropical rainforest climate
Am	tropical	Tropical monsoon climate
As	tropical	Tropical dry savanna climate
Aw	tropical	Tropical savanna, wet
BSh	tropical	Hot semi-arid (steppe) climate
BSk	tropical	Cold semi-arid (steppe) climate
BWh	tropical	Hot deserts climate
BWk	tropical	Cold desert climate
Cfa	tropical	Humid subtropical climate
Cfb	temperate	Temperate oceanic climate
Cfc	boreal	Subpolar oceanic climate
Csa	temperate	Hot-summer Mediterranean climate
Csb	temperate	Warm-summer Mediterranean climate
Csc	temperate	Cool-summer Mediterranean climate
Cwa	tropical	Monsoon-influenced humid subtropical climate
Cwb	tropical	Dry-winter subtropical highland climate
Cwc	boreal	Dry-winter subpolar oceanic climate
Dfa	temperate	Hot-summer humid continental climate
Dfb	boreal	Warm-summer humid continental climate
Dfc	boreal	Subarctic climate
Dfd	boreal	Extremely cold subarctic climate
Dsa	temperate	Hot, dry-summer continental climate
Dsb	boreal	Warm, dry-summer continental climate
Dsc	boreal	Dry-summer subarctic climate
Dsd	boreal	snow summer dry extremely continental
Dwa	temperate	Monsoon-influenced hot-summer humid continental climate
Dwb	boreal	Monsoon-influenced warm-summer humid continental climate
Dwc	boreal	Monsoon-influenced subarctic climate
Dwd	boreal	Monsoon-influenced extremely cold subarctic climate
EF	boreal	Ice cap climate
ET	boreal	Tundra

Table S2: Mapping between Koeppen-Geiger climate classification (1st column) and aggregate climate regions (2nd column) used in this study. The 3rd column provides definitions of the Koeppen-Geiger climate classification shown in column 1.

Scenario assumptions

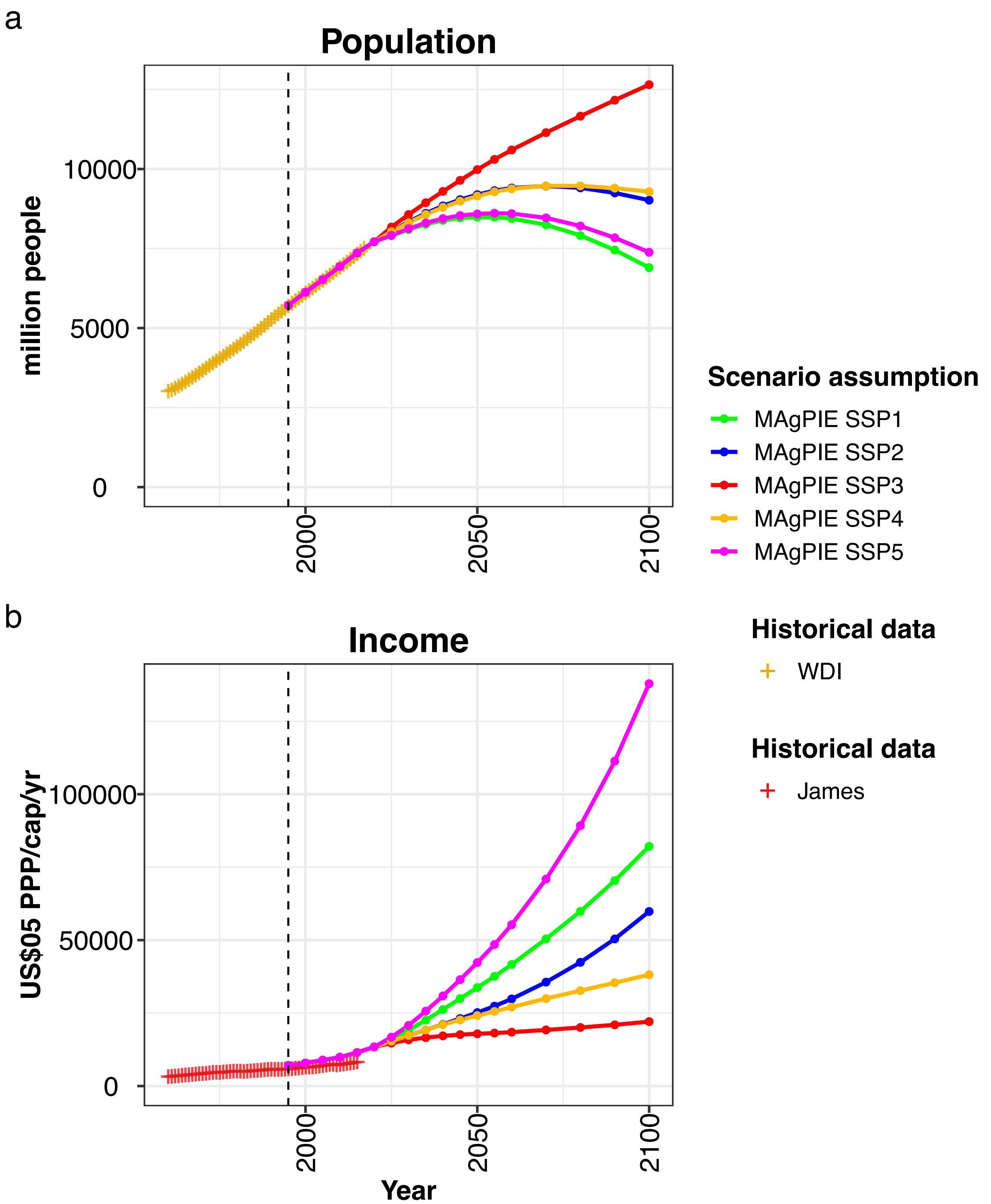

Figure S5: Global population (a) and income (b) trajectories for SSP1-5 used in this study, based on the SSP Database (IIASA 2018). Historical data is from Worldbank (WDI) and James et al (2012).

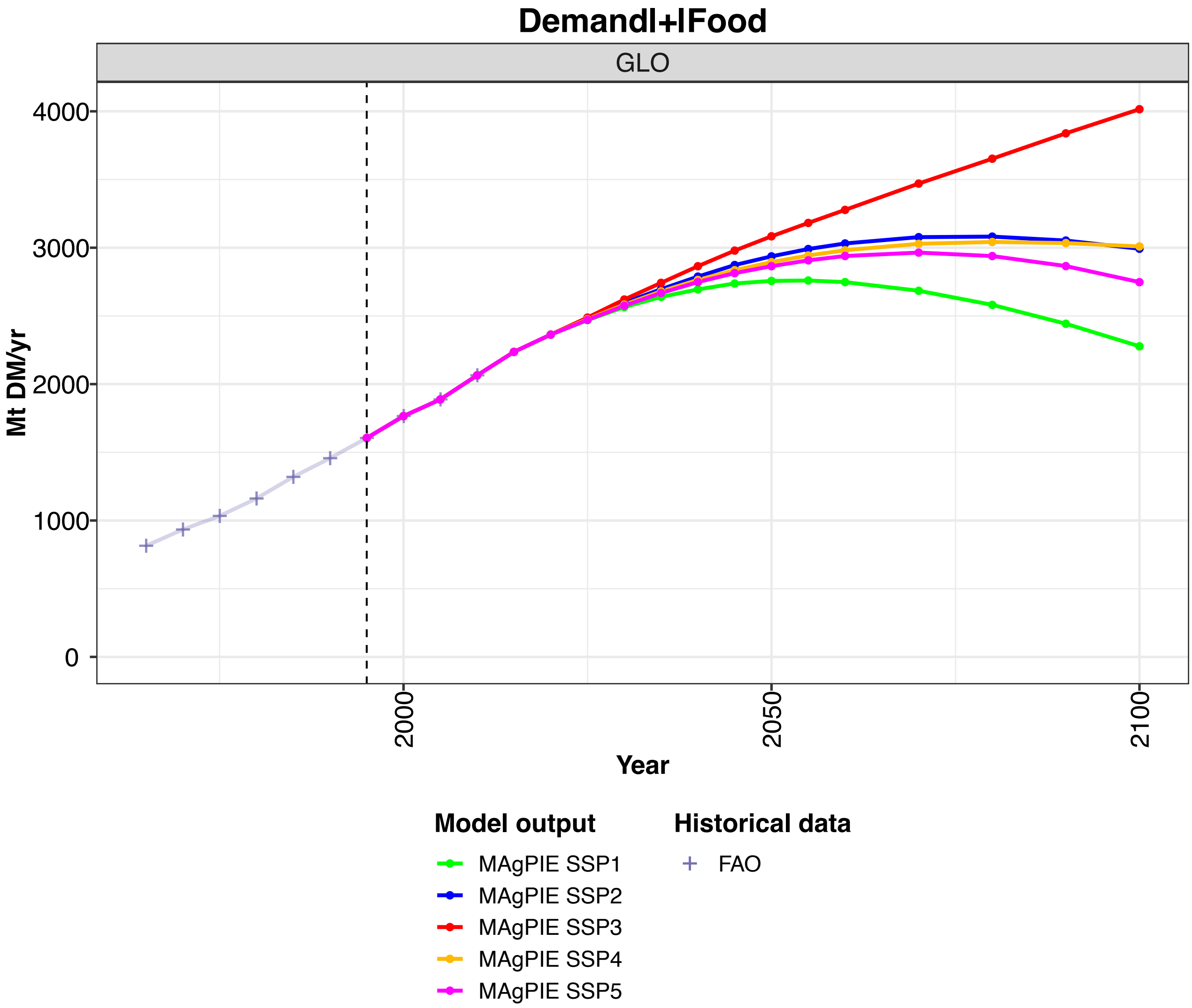

Figure S6: Demand for food in SSP1-5 assumed in this study. Historical data from FAOSTAT (2015).

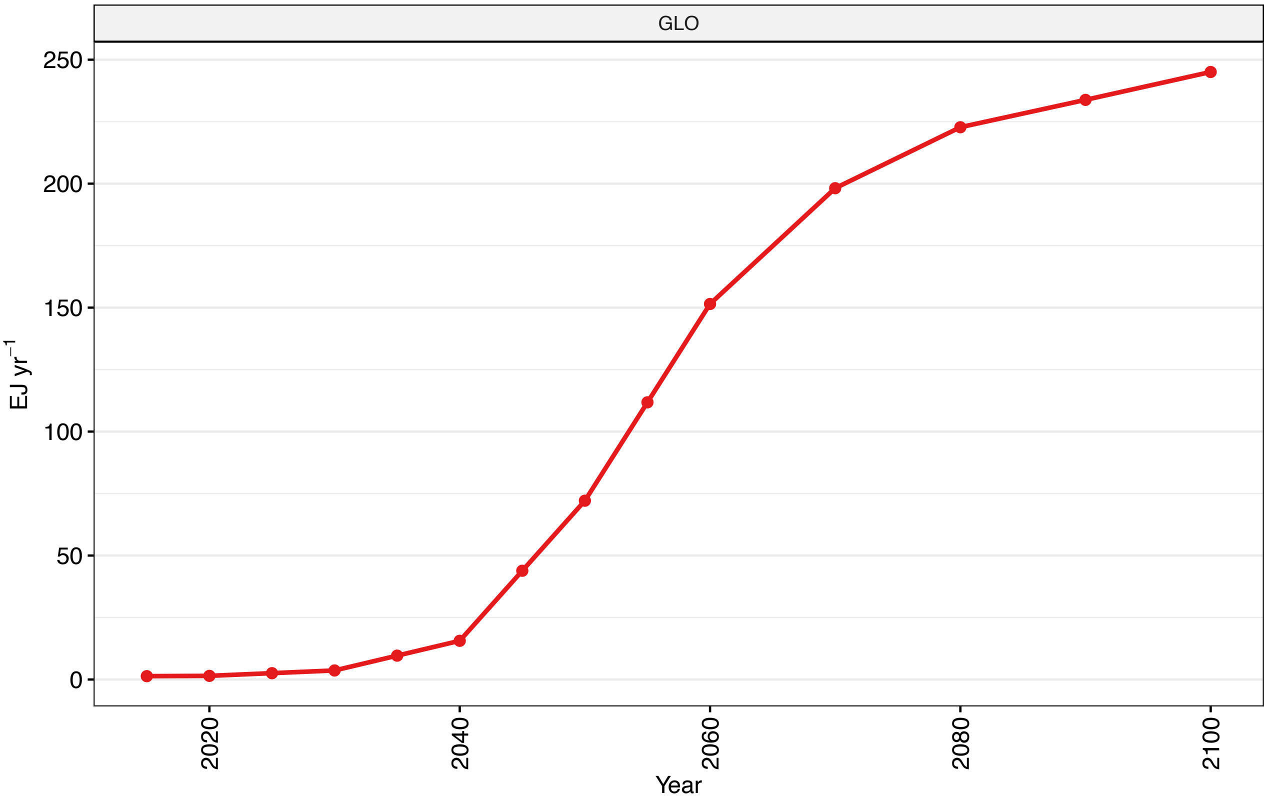

Figure S7: 2nd generation bioenergy demand used in this study. Based on the scenario "REMIND-MAGPIE - SSP2-26" in the SSP Database (IIASA 2018) (Variable "Agricultural Demand|Crops|Energy").

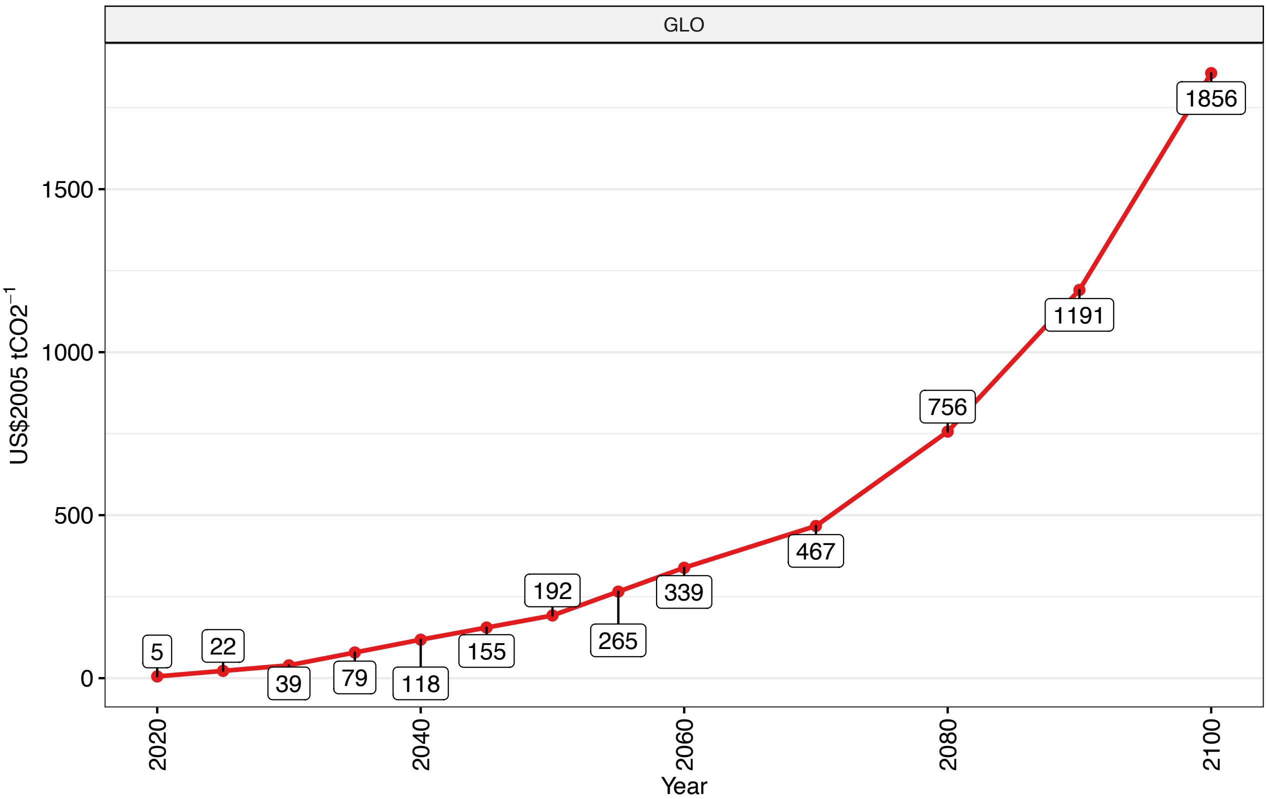

Figure S8: CO_2 price path used in this study. Based on the scenario "REMIND-MAGPIE - SSP2-26" in the SSP Database (IIASA 2018) (Variable "Price|Carbon"). Note that before 2040 the CO_2 price is not globally uniform but differs across regions. For the aggregation to global level population has been used as weight.

Additional model outputs

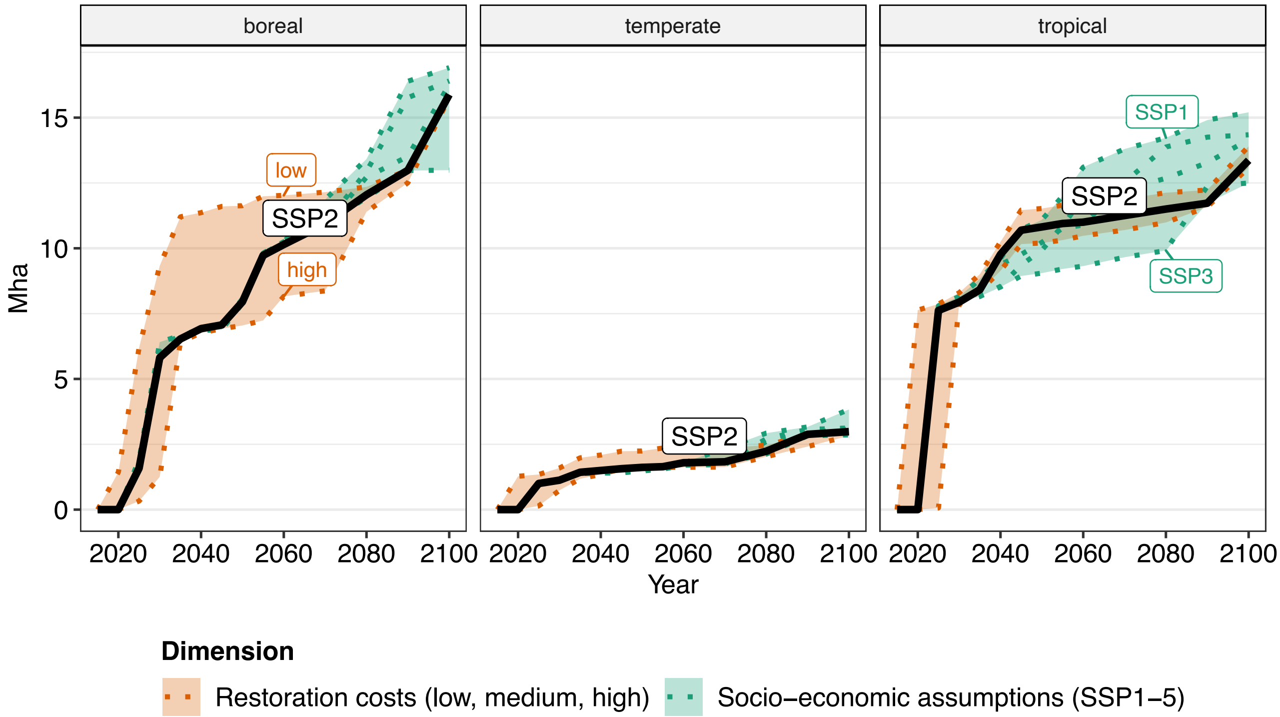

Figure S9: Sensitivity analysis of peatland restoration (scenario: RCP2.6+PeatRestor, variable: rewetted peatland with respect to restoration costs (low, medium and high) and socio-economic assumptions (SSP1-5). One-time (USD ha^{-1}) and recurring costs (USD ha^{-1} yr^{-1}) for restoration: low=875/25, medium=7000/200, high=14000/400. Results for the variation of restoration costs (low, medium, high) are all based on SSP2, while the results for the variation of socio-economic assumptions (SSP1-5) are all based on medium restoration costs. The thick black line indicates the RCP2.6+PeatRestor scenario, which is based on SSP2 and medium restoration costs.

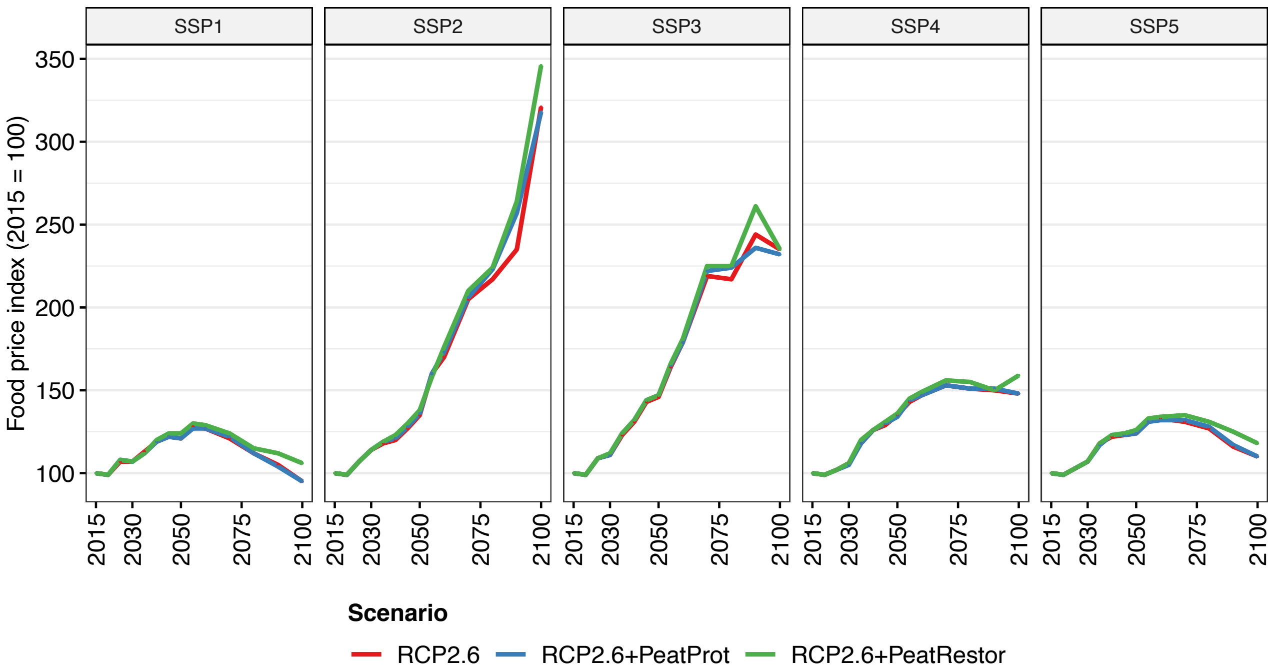

Figure S10: Global food price index across scenarios. The food price index weights current prices based on current food baskets (Paasche price index). The food prices used for calculating the food price index are shadow prices, taken from the regional food *demand constraint in the model. For more details regarding the calculation of the food price index we refer to Humpenöder et al and Stevanović et al* (2018, 2017).

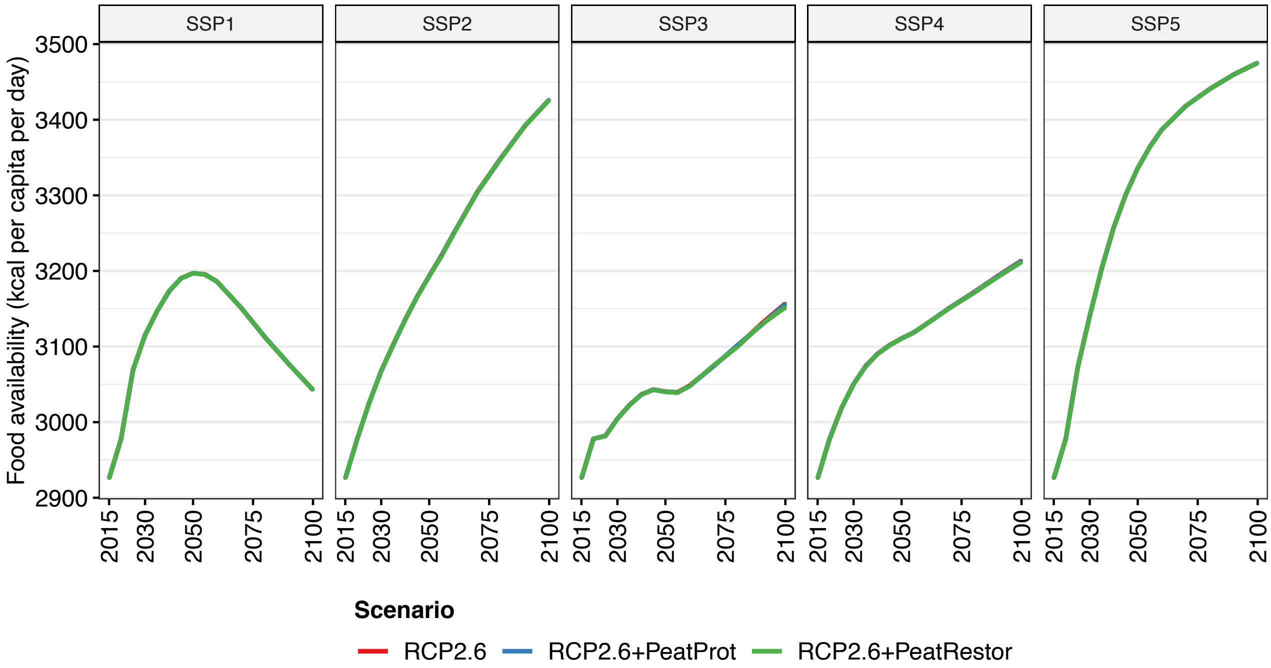

Figure S11: Global food availability across scenarios. The food demand in MAgPIE is price-elastic. However, in our scenarios there is no demand reaction to changing food prices, which indicates that the additional pressure due to peatland protection and restoration on top of climate policy is very small.

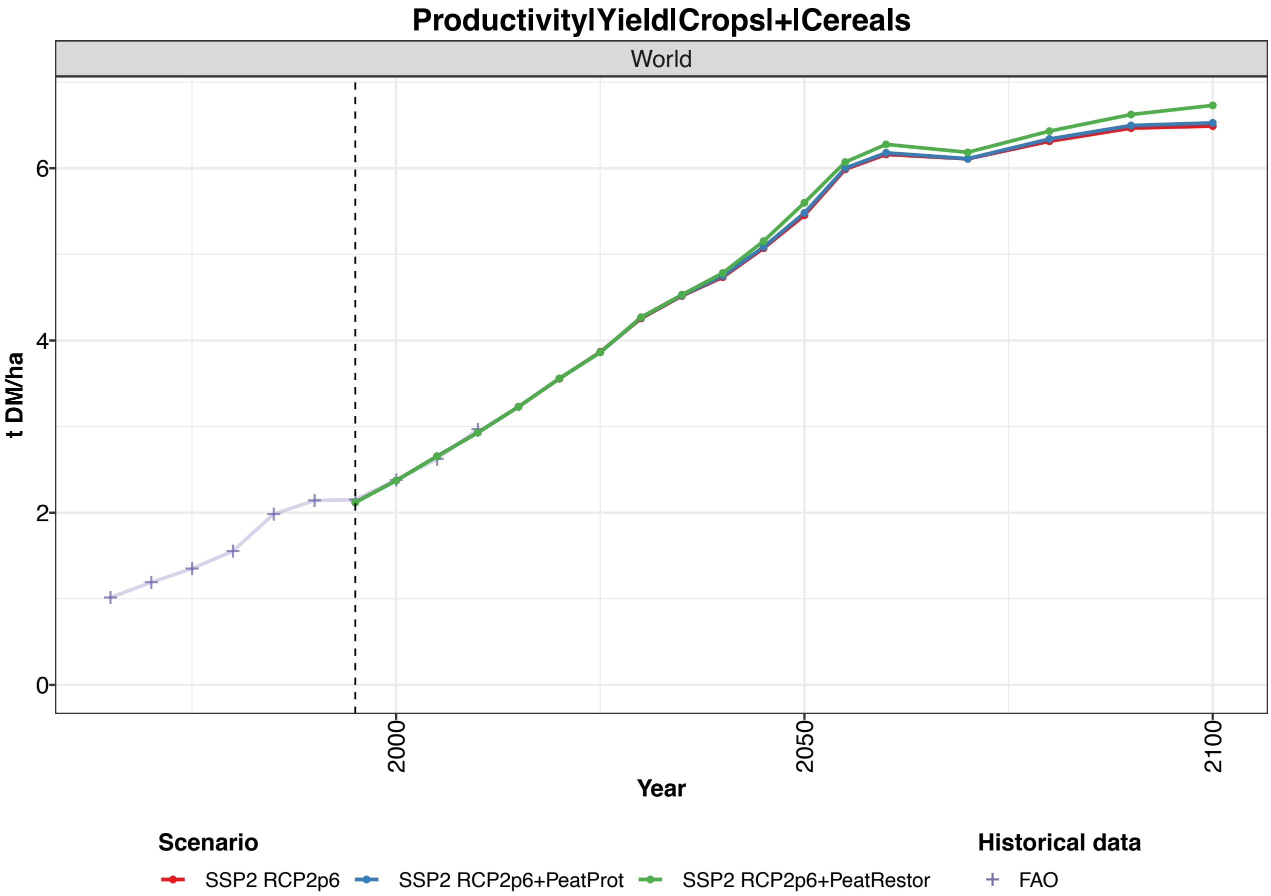

Figure S12: Global cereal crop yields across scenarios. Historical data from FAOSTAT (2015).

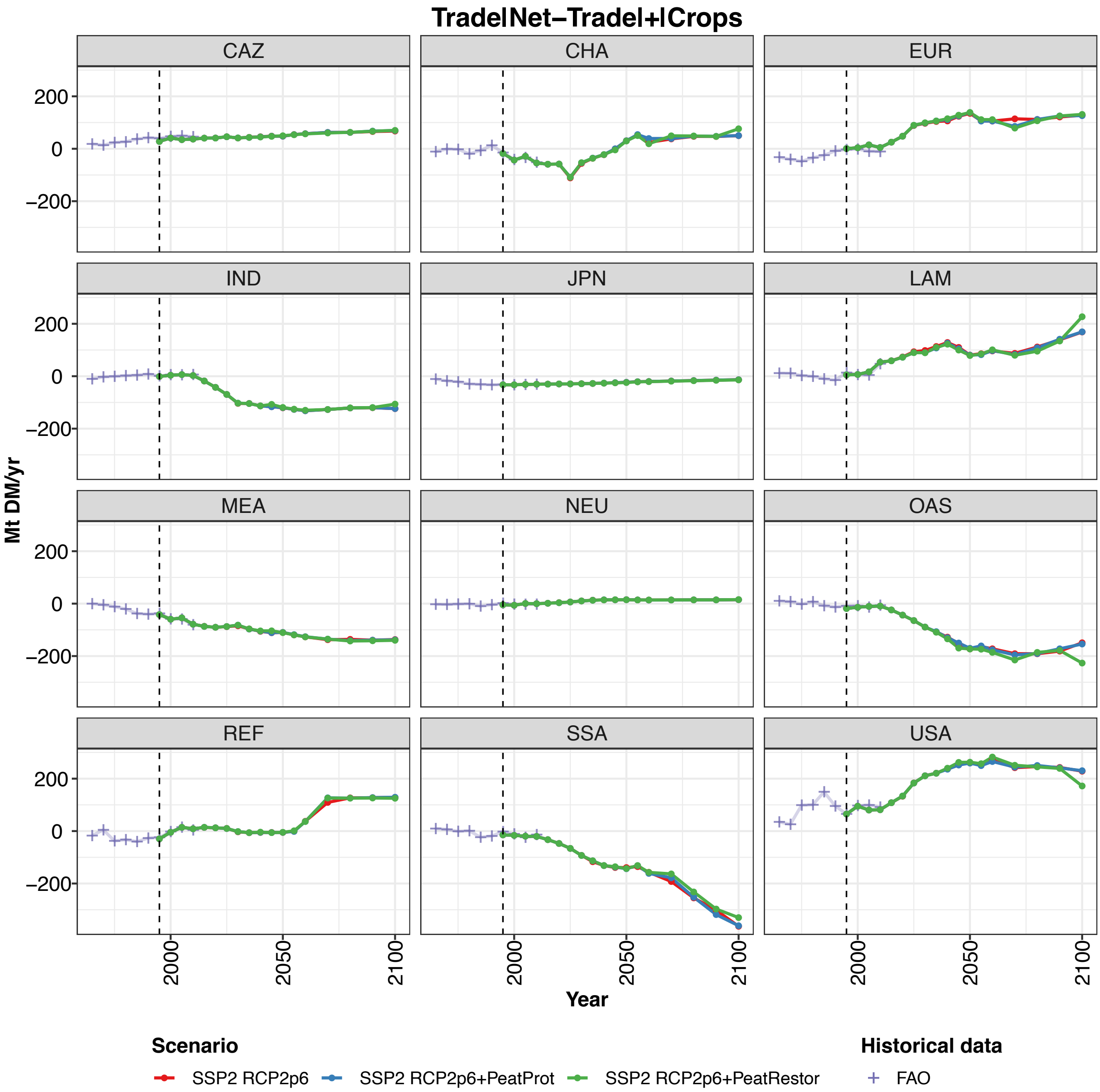

Figure S13: Regional net-trade of crops across scenarios. Historical data from FAOSTAT (2015).

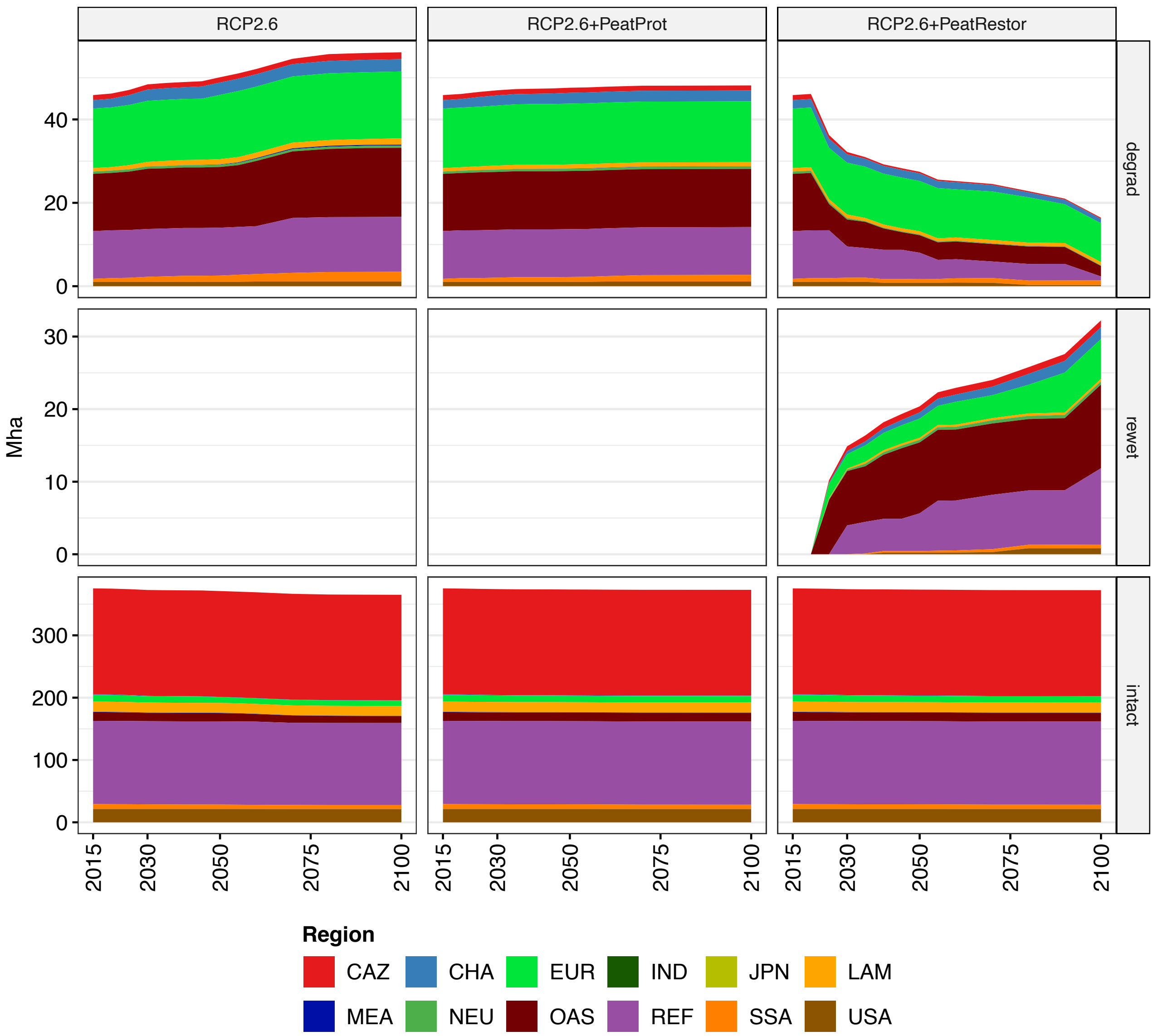

Figure 14: Regional distribution of intact, degraded and rewetted peatlands. See Figure S3 for the definition of regions.

IAMC 1.5°C scenario explorer

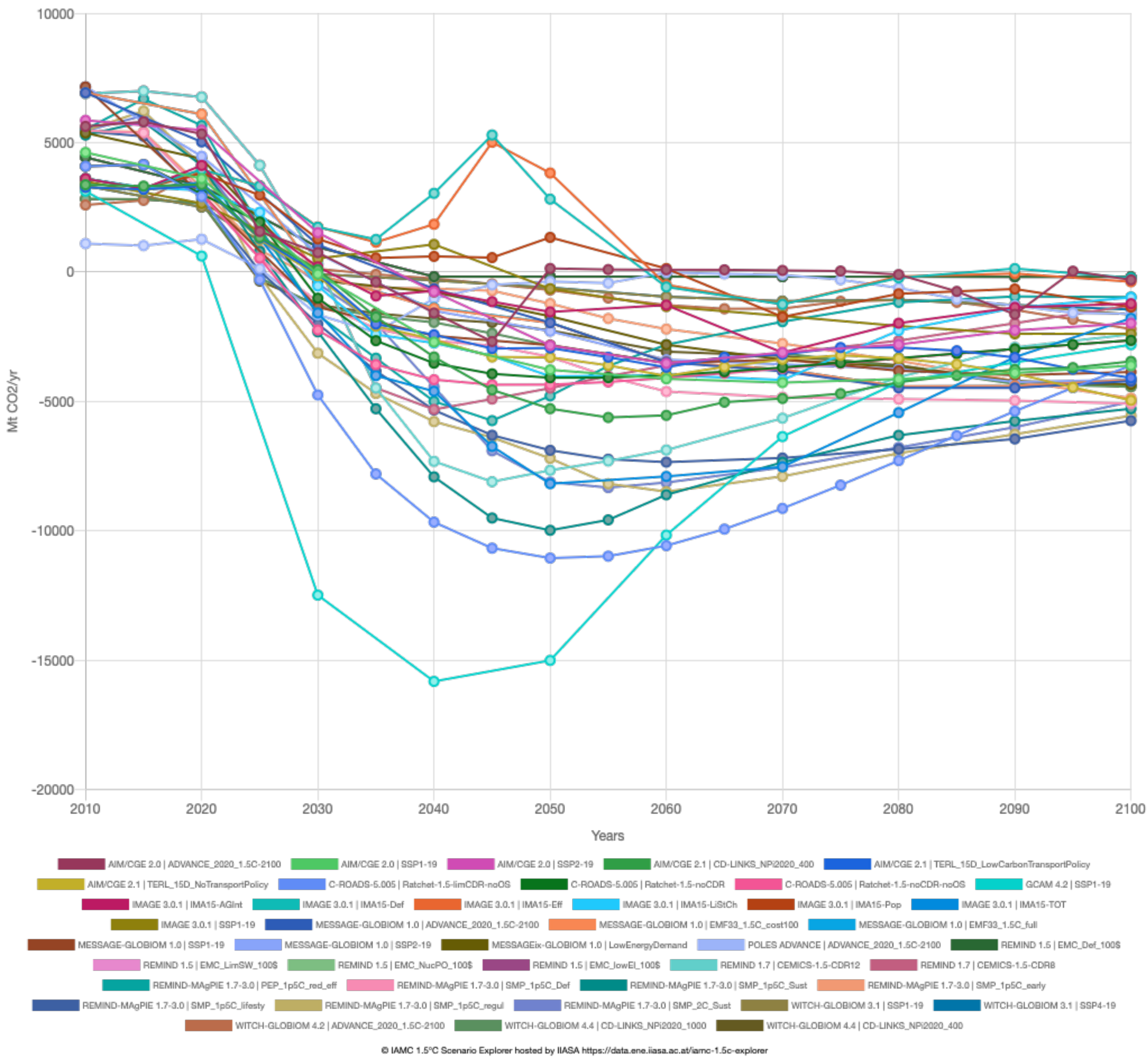

Figure 15: Emissions|CO2|AFOLU in 1.5°C pathways (reproduced from Huppmann et al 2018. © IIASA and IAMC 2018-2019. CC BY 4.0). This figure shows the development of global net CO2 emissions from the land system in all pathways limiting global warming to below 1.5°C at the end of the century.

References

Bodirsky B L, Popp A, Lotze-Campen H, Dietrich J P, Rolinski S, Weindl I, Schmitz C, Müller C, Bonsch M, Humpenöder F, Biewald A and Stevanovic M 2014 Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution *Nat. Commun.* **5** 3858

Bondeau A, Smith P C, Zaehle S, Schaphoff S, Lucht W, Cramer W, Gerten D, Lotze-Campen H, Müller C, Reichstein M and Smith B 2007 Modelling the role of agriculture for the 20th century global terrestrial carbon balance *Glob Change Biol* **13** 679–706

Dietrich J P, Bodirsky B L, Humpenöder F, Weindl I, Stevanović M, Karstens K, Kreidenweis U, Wang X, Mishra A, Klein D, Ambrósio G, Araujo E, Yalew A W, Baumstark L, Wirth S, Giannousakis A, Beier F, Chen D M-C, Lotze-Campen H and Popp A 2019 MAgPIE 4 – a modular open-source framework for modeling global land systems *Geosci. Model Dev.* **12** 1299–317

Dietrich J P, Popp A and Lotze-Campen H 2013 Reducing the loss of information and gaining accuracy with clustering methods in a global land-use model *Ecol. Model.* **263** 233–43

FAO 2015 *FAO statistical database* (Rome: Food and Agriculture Organization of the United Nations)

Greifswald Mire Centre 2015 *Global Peatland Database* (Greifswald, Germany: Greifswald Mire Centre) Online: https://greifswaldmoor.de/global-peatland-database-en.html

Hiraishi T, Krug T, Tanabe K, Srivastava N, Baasansuren J, Fukuda M and Troxler T G 2014 *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (Switzerland: IPCC) Online: http://www.ipcc-nggip.iges.or.jp/public/wetlands/

Humpenöder F, Popp A, Bodirsky B L, Weindl I, Biewald A, Hermann Lotze-Campen, Dietrich J P, Klein D, Kreidenweis U, Müller C, Susanne Rolinski and Stevanovic M 2018 Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environ. Res. Lett.* **13** 024011

Huppmann D, Kriegler E, Krey V, Riahi K, Rogelj J, Rose S K, Weyant J, Bauer N, Bertram C, Bosetti V, Calvin K, Doelman J, Drouet L, Emmerling J, Frank S, Fujimori S, Gernaat D, Grubler A, Guivarch C, Haigh M, Holz C, Iyer G, Kato E, Keramidas K, Kitous A, Leblanc F, Liu J-Y, Löffler K, Luderer G, Marcucci A, McCollum D, Mima S, Popp A, Sands R D, Sano F, Strefler J, Tsutsui J, Van Vuuren D, Vrontisi Z, Wise M and Zhang R 2018 *IAMC 1.5°C Scenario Explorer and Data hosted by IIASA (doi: 10.22022/SR15/08-2018.15429)* (Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis) Online: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer

IIASA 2018 *SSP Database (version 2.0)* (Laxenburg: International Institute for Applied Systems Analysis) Online: https://secure.iiasa.ac.at/web-apps/ene/SspDb

James S L, Gubbins P, Murray C J and Gakidou E 2012 Developing a comprehensive time series of GDP per capita for 210 countries from 1950 to 2015 *Popul. Health Metr.* **10** 12

Leifeld J and Menichetti L 2018 The underappreciated potential of peatlands in global climate change mitigation strategies *Nat. Commun.* **9** 1071

Lotze-Campen H, Müller C, Bondeau A, Rost S, Popp A and Lucht W 2008 Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach *Agric. Econ.* **39** 325–38

Müller C and Robertson R D 2014 Projecting future crop productivity for global economic modeling *Agric. Econ.* **45** 37–50

Popp A, Humpenöder F, Weindl I, Bodirsky B L, Bonsch M, Lotze-Campen H, Müller C, Biewald A, Rolinski S, Stevanovic M and Dietrich J P 2014 Land-use protection for climate change mitigation *Nat. Clim. Change* **4** 1095–8

Popp A, Lotze-Campen H and Bodirsky B 2010 Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production *Glob. Environ. Change* **20** 451–62

Stevanović M, Popp A, Bodirsky B L, Humpenöder F, Müller C, Weindl I, Dietrich J P, Lotze-Campen H, Kreidenweis U, Rolinski S, Biewald A and Wang X 2017 Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices *Environ. Sci. Technol.* **51** 365–74

Wilson D, Blain D and Couwenberg J 2016 Greenhouse gas emission factors associated with rewetting of organic soils *Mires Peat* **17** 4 28 pp

Yu Z, Loisel J, Brosseau D P, Beilman D W and Hunt S J 2010 Global peatland dynamics since the Last Glacial Maximum *Geophys. Res. Lett.* **37**