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Diverging land-use projections cause large variability in their impacts on ecosystems and related indicators for ecosystem services

Anita D. Bayer et al.

Correspondence to: Anita D. Bayer (anita.bayer@kit.edu)

Supplementary Information

Table S1. Overview of LPJ-GUESS simulation set-up. The simulation protocol using IMAGE and MAgPIE scenarios differed slightly from the other simulations.

	CLUMondo, LUH1, LUH2	**IMAGE, MAgPIE**
Simulation reference	This study	Krause et al. (2017)
Model period	1850-2099 (only until 2040 for CLUMondo)	1901-2099
Model spin-up	500 years (longer spin-up for soil C stocks, see Smith et al., 2014), using land-use fractions and CO_2 mixing ratio as in 1850 and repeated 1850-1870 climate	500 years (longer spin-up for soil C stocks, see Smith et al., 2014), using land-use fractions and CO_2 mixing ratio as in 1901 and repeated 1901-1930 climate
Atmospheric CO_2 mixing ratio	Ice core and later atmospheric measurements after Tans and Keeling (2015), with constant value of 286 ppmv before 1860 and following RCP 2.6 for the future period, with 440 ppmv in 2040	
Climate 1950-2099	Monthly climate data from IPSL-CM5A-LR model from ISI-MIP project (Warszawski et al., 2014), following RCP 2.6 for future period, bias-corrected after Hempel et al. (2013)	
Climate before 1950	De-trended climate data from 1950-1979 used repeatedly to generate data for 1850-1949	Random chose of years from 1950–1959 to generate data for 1901–1949
N deposition	Lamarque et al. (2011, 2010), with future values following RCP 2.6	
Representation of natural vegetation and vegetation dynamics	Ten woody and C3 and C4 grass plant functional types, as in Smith et al. (2014), 10 replicate patches to capture stochastic processes of vegetation dynamics in LPJ-GUESS (establishment, mortality)	
Crop functional types (CFT)	3: C3 crops, C4 crops and rice	4: C3 winter cereals, other C3 crops, C4 crops, rice
Crop fractions	MIRCA2000 after Portmann et al. (2010) with time-variant CFTs and fractions of rain-fed vs. irrigated management for 1950-2005 Fader et al. (2010). 13 Fader CFTs were summarized by their photosynthetic pathways (C3 or C4) and their physiological characteristics to three CFTs (see above, each rain-fed and irrigated). Crop distributions were assumed to stay constant after 2006.	From IMAGE and MAgPIE models aggregated to LPJ-GUESS CFTs (see Krause et al., 2017)
N fertilization	Zaehle et al. (2011), with future values following RCP 8.5	From IMAGE and MAgPIE models
Representation of bioenergy area and crops in scenarios including BECCS	None. Bioenergy land fractions of LUH1_26Be and LUH2_SSP1-26 were aggregated to cropland	C4 crops

Table S2. Translation of LUM land use information to three LPJ-GUESS land use types.

LPJ-GUESS landcover / ▼LUM landcover	Cropland	Pasture	Natural
CLU-Mondo	regionally varying composition of each CLUMondo land use system in natural, pasture and cropland area following Eitelberg et al. (2016)		
IMAGE	cropland (irrigated, non-irrigated)	pasture, degraded forests	forest, urban, other natural
MAgPIE	cropland (irrigated, non-irrigated)	pasture	forest, urban, other natural
LUH1	cropland (inclusing bioenergy cropland for 26BE scenario)	pasture	primary vegetation, secondary vegetation, urban
LUH2	C3/C4 annuals, C3/C4 perennial, C3 nitrogen fixing	managed pasture, rangeland	primary land, secondary land, urban

Tab S3. Global totals and change in ES indicators from 2000-2004 to 2036-2040 simulated with LPJ-GUESS for 16 land-use scenarios. The first line give the ES indicator level averaged globally for 2000-2004, second row is 2036-2040 and third and fourth rows give the change from 2000-2004 until 2036-2040 in absolute terms and in % relative to the level in 2000-2004. Blue color indicates positive and red color negative change. Total C stock is the sum of vegetation, soil and litter and product C (wood removed from deforestation but not oxidized immediately) and C stored via CCS for BECCS scenarios. Minor deviations in numbers may occur due to rounding.

	CLUMondo FAOref	CLUMondo Cstor	CLUMondo Bdiv	IMAGE Base	IMAGE ADAFF	IMAGE BECCS	MAgPIE Base	MAgPIE ADAFF	MAgPIE BECCS	LUH1 26Be	LUH1 45Aff	LUH1 60Stab	LUH1 85Pop	LUH2 SSP1-26	LUH2 SSP3-70	LUH2 SSP5-85	Average and uncertainty across 16 LU scenarios
NPP [PgC/yr]	58.9	58.8	58.8	59.6	59.6	59.6	61.2	61.2	61.2	59.4	59.4	59.4	59.4	55.5	55.5	55.5	58.9 ± 1.9
	65.5	65.5	65.5	64.8	64.5	64.9	66.5	66.5	67.0	65.4	67.2	65.8	66.2	61.5	61.5	61.1	65.0 ± 1.9
	+6.7	+6.7	+6.7	+5.1	+4.8	+5.2	+5.3	+5.3	+5.8	+6.0	+7.8	+6.5	+6.8	+6.0	+5.9	+5.6	+6.0 ± 0.8
	+11.3%	+11.4	+11.3%	+8.6%	+8.1%	+8.8%	+8.7%	+8.7%	+9.4%	+10.2%	+13.2%	+10.9%	+1.5	+10.8%	+10.7%	+10.0%	+10.2% ± 1.4%
Vegetation C stocks [PgC]	426	426	426	378	378	378	390	390	390	423	423	423	423	392	392	392	403 ± 19.8
	474	477	473	387	408	377	428	428	419	460	494	494	467	441	421	424	441 ± 3528
	+48.1	+51.5	+47.7	+9.2	+29.6	-1.1	+32.1	+38.0	+29.0	+37.6	+70.8	+57.1	+44.3	+48.9	+28.9	+32.5	+37.8 ± 17.6
	+11.3%	+12.1%	+11.2%	+2.4%	+7.8%	-0.3%	+8.2%	+9.8%	+7.4%	+8.9%	+16.7	+13.5	+10.5%	+12.5%	+7.4%	+8.3%	+9.2% ± 4.1%
Soil and litter C stocks [PgC]	1626	1626	1626	1576	1576	1576	1584	1586	1586	1633	1633	1633	1633	1513	1513	1513	1590 ± 45
	1622	1624	1623	1560	1562	1558	1569	1571	1568	1624	1635	1627	1628	1513	1509	1509	1581 ± 46
	-3.3	-2.6	-3.0	-15.5	-14.0	-18.0	-16.4	-14.9	-17.4	-9.0	+2.4	-5.0	-4.9	-0.2	-3.8	-4.4	-8.1 ± 6.8
	-0.2%	-0.2%	-0.2%	-1.0%	-0.9%	-1.1%	-1.0%	-0.9%	-1.1%	-0.6%	+0.2%	-0.3%	-0.3%	-0.0%	-0.3%	-0.3%	-0.5% ± 0.4%
Total C stocks [PgC]	2056	2056	2056	1960	1960	1960[2]	1980	1980	1981[2]	2059	2059	2059	2059	1908	1908	1908	1997 ± 60
	2099	2103	2099	1953	1972	1949[2]	1993	2000	1997[2]	2087	2130	2110	2098	1955	1934	1936	2026 ± 74
	+43.3	+47.2	+43.5	-6.9	+12.4	-10.7	+13.2	+20.2	+16.0	+28.0	+70.5	+50.2	+38.1	+47.2	+25.9	+28.3	+29.2 ± 21.6
	+2.1%	+2.3%	+2.1%	-0.4%	+0.6%	-0.6%	+0.7%	+1.0%	+0.8%	+1.4%	+3.4%	+2.4%	+1.9%	+2.5%	+1.4%	+1.5%	+1.5% ± 1.1%
Crop production [Ecal]	23.7	23.7	23.7	22.9[1]	22.0[1]	22.0[1]	20.8[1]	20.8[1]	20.8[1]	23.2[3]	23.2	23.2	23.2	20.8[3]	22.8	22.8	22.6 ±1.0
	32.1	31.4	31.6	27.6[1]	25.7[1]	25.8[1]	29.0[1]	27.7[1]	28.4[1]	33.8[3]	23.8	28.8	29.8	32.7[3]	32.8	33.0	29.6 ± 3.0
	+8.4	+7.7	+7.9	+4.7	+3.7	+3.8	+8.2	+6.9	+7.6	+10.6	+0.6	+5.6	+6.6	+9.9	+10.0	+10.2	+7.0 ± 2.8
	+35.2%	+32.5%	+33.3%	+20.7%	+16.8%	+17.1%	+39.5%	+33.4%	+36.8%	+45.7%	+2.6%	+24.1%	+28.4%	+43.5%	+44.0%	+45.0%	+31.2% ± 12.2%
Annual water runoff [1000 km³/yr]	50.0	50.0	50.0	50.5	50.5	50.5	50.2	50.2	50.2	50.1	50.1	50.1	50.1	47.7	47.7	47.7	49.7 ± 1.0
	54.0	+54.0	54.0	56.5	56.1	56.6	55.7	55.7	55.7	54.2	53.7	53.8	54.2	51.7	52.0	51.8	54.3 ± 1.6
	+4.0	+4.0	+4.0	+6.0	+5.6	+6.1	+5.5	+5.4	+5.5	+4.2	+3.7	+3.7	+4.1	+4.0	+4.3	+4.1	+4.6 ± 0.9
	+8.0%	+7.9%	+8.0%	+11.8%	+11.1%	+12.1%	+11.0%	+10.8%	+10.9%	+8.3%	+7.3%	+7.4%	+8.2%	+8.3%	+8.9%	+8.6%	+9.3% ± 1.7%
Evapotranspiration [1000 km³/yr]	58.5	58.5	58.5	58.4	58.4	58.4	58.7	58.7	58.7	58.4	58.4	58.4	58.4	55.9	55.9	55.9	58.0 ± 1.0
	60.0	60.0	60.0	57.7	58.1	57.6	58.6	58.6	58.6	59.8	60.3	60.2	59.8	57.3	57.1	57.2	58.8 ± 1.2
	+1.5	+1.6	+1.5	-0.7	-0.4	-0.9	-0.2	-0.1	-0.1	+1.4	+1.9	+1.8	+1.4	+1.4	+1.2	+1.3	+0.8 ± 1.0
	+2.6%	+2.7%	+2.6%	-1.2%	-0.6%	-1.5%	-0.3%	-0.2%	-0.3%	+2.4%	+3.2%	+3.1%	+2.4%	+2.5%	+2.1%	+2.3%	+1.4% ± 1.7%

[1]IMAGE and MAgPIE models follow different crop type and management (fertilization) pathways than the other scenarios. [2]Total C stocks are already higher for 2000-2004 for MAgPIE_BECCS because CCS in MAgPIE model starts in 1995 (see Krause et al., 2017). [3]For LUH1 and LUH2, bioenergy area was merged to cropland, respectively in LUH2 it was not extracted from cropland area. Therefore, crop yield production includes crops planted on bioenergy areas. Contribution from those areas is estimated to be on average about 1.6 Ecal per year (average for 2000-2040) assuming similar bioenergy areas and productivity as croplands as in IMAGE_BECCS and MAgPIE_BECCS scenarios.

Table S4. Land use changes and change rates in historical reconstructions and other available databases.

	Ramankutty (Ramankutty et al., 2008)	**HYDE 3.1** (Klein Goldewijk et al., 2010, 2011)	**HYDE 3.2** (Klein Goldewijk, 2016)	**LUH1** (Hurtt et al., 2011)	**HILDA+ (net changes)** (Winkler et al., in prep.)	**ESA CCI Land Cover** (Liu et al., 2018)
Time period (T), number of classes (C) and spatial resolution (S)	T: 1960-2000 C: 3 S: 0.5° x 0.5°				T: 1960-2015 C: 6 S: 1 km.	T: 1992-2015 C: 8 S: 300m/0.5° x 0.5°
Total area under change between 2000 and 2040 [10^6 km^2]	16.98 12.84%	16.08 12.11%	10.86 7.53%	12.95 9.80%	18.20 13.8%	5.99 3.4%

Table S5. Total area of cropland, pasture and natural land and change therein from 2000-2004 to 2036-2040 averaged across 16 land-use scenarios and split across seven biomes (see Fig. S4 for biome classification). The first line gives the global total area for 2000-2004, second row is 2036-2040 and third and fourth rows give the change from 2000-2004 until 2036-2040 in absolute terms and in % relative to the level in 2000-2004. Blue color indicates positive and red color negative change. Total area under change from 2000 to 2040 is given in absolute terms and as % of the biome/global land area (see methods of main text). Minor deviations in numbers may occur due to rounding.

	Tropical forest	**Temperate forest**	**Boreal forest**	**Tropical savanna**	**Temperate shrubland and grassland**	**Tundra**	**Desert**	**Global average and uncertainty across 16 LU scenarios**
Cropland [10^6 km^2]	2.6 3.4 +0.8 +30.5%	3.4 3.6 +0.2 +6.9%	2.1 2.0 -0.0 -1.7%	4.4 4.9 +0.5 +10.3%	2.6 3.0 +0.3 +12.2%	0.0 0.0 +0.0 +3.6%	0.2 0.2 +0.0 +12.7%	15.4 ± 0.3 17.2 ± 1.8 +1.8 ± 1.6 +11.7% ± 10.5%
Pasture [10^6 km^2]	4.4 4.4 +0.1 +1.2%	2.7 2.4 -0.3 -10.9%	3.8 3.7 -0.2 -3.8%	5.6 5.4 -0.2 -4.3%	13.6 13.2 -0.4 -3.1%	0.01 0.01 0.00 +7.7%	2.4 2.3 -0.0 -1.7%	32.6 ± 2.8 31.5 ± 4.1 -1.0 ± 2.6 -3.5% ± 7.6 %
Natural [10^6 km^2]	17.5 16.7 -0.9 -4.9%	6.6 6.6 +0.1 +0.9%	20.2 20.4 +0.2 +0.9%	7.1 6.9 -0.2 -3.0%	14.8 14.9 +0.1 +0.6%	4.8 4.8 -0.00 -0.02%	12.5 12.6 +0.0 +0.1%	83.4 ± 3.4 82.7 ± 5.0 -0.7 ± 3.3 -0.9% ± 4.0%
Total area under change between 2000 and 2040 [10^6 km^2]	2.5 10.2%	1.5 11.8%	1.0 3.7%	2.3 13.1%	2.3 7.3%	0.0 0.1%	0.2 1.3%	9.7 ± 2.9 7.4% ± 2.2%

Table S6. Uncertainty in ES indicators due to climatic pathways from IPSL-CM5A-LR, GFDL-ESM2M, HadGEM2-ES, MIROC-ESM-CHEM and NorESM1-M models (RCP 2.6 for all climate models) investigated for the four diverse LUH1 scenarios. First row gives average ES indicator level for 2000-2004 averaged across the five GCMs and the standard deviation across GCMs in % and second row is for 2036-2040.

	LUH1_26Be	LUH1_45Aff	LUH1_60Stab	LUH1_85Pop
NPP [PgC/yr]	61.20 ±4.0% 66.28 ± 3.8%	61.20 ± 4.0% 67.99 ± 3.7%	61.20 ± 4.0% 66.70 ± 3.8%	61.20 ± 4.0% 67.03 ± 3.7%
Vegetation C stocks [PgC]	438 ± 8.2% 472 ± 8.6%	438 ± 8.2% 507 ± 8.6%	438 ± 8.2% 493 ± 8.6%	438 ± 8.2% 479 ± 8.6%
Soil and litter C stocks [PgC]	1642 ± 1.9% 1634 ± 1.4%	1642 ± 1.9% 1646 ± 1.4%	1642 ± 1.9% 1638 ± 1.4%	1642 ± 1.9% 1638 ± 1.4%
Total C stocks [PgC]	2084 ± 3.2% 2109 ± 3.0%	2084 ± 3.2% 2154 ± 3.1%	2084 ± 3.2% 2133 ± 3.0%	2084 ± 3.2% 2120 ± 3.0%
Crop production [Ecal]	22.96 ± 0.1% 24.97 ± 0.2%	22.96 ± 0.1% 24.56 ± 0.2%	22.96 ± 0.1% 23.67 ± 0.2%	22.96 ± 0.1% 24.25 ± 0.2%
Annual water runoff [1000 km³/yr]	52.56 ± 2.7% 53.67 ± 4.2%	52.56 ± 2.7% 53.17 ±4.2%	52.56 ± 2.7% 53.22 ± 4.2%	52.56 ± 2.7% 53.62 ± 4.2%
Evapotranspiration [1000 km³/yr]	60.15 ± 3.5% 60.68 ± 4.5%	60.15 ± 3.5% 61.12 ± 4.5%	60.15 ± 3.5% 61.09 ± 4.5%	60.14 ± 3.6 60.76 ± 4.1 %

Tab S7. Biome and global totals and change in ES indicators from 2000-2004 to 2036-2040 simulated with LPJ-GUESS across 16 land-use scenarios (see Fig. S4 for biome classification). The first line gives the ES indicator level summed across each biome area for 2000-2004, second row is 2036-2040 and third and fourth row gives the change from 2000-2004 until 2036-2040 in absolute terms and in % relative to the level in 2000-2004. Blue color indicates positive and red color negative change. The fifth row gives the regional variability for each biome as the biome-wide average of the per-cell standard deviation in relative ES indicator changes across the 16 scenarios (same methodology as in main text Fig. 4). Here, cells where the base value in 2000-2004 was below 1% of the global average were not included in calculation of regional variability. Global totals (from Table S3) are shown for comparison in the last column. Total C stocks is the sum of vegetation, soil and litter and product C (wood removed from deforestation but not oxidized immediately) and C stored via CCS in BECCS scenarios. Minor deviations in numbers may occur due to rounding.

	Tropical forest	Temperate forest	Boreal forest	Tropical savanna	Temperate shrubland and grassland	Tundra	Desert	Global average and uncertainty across 16 LU scenarios
NPP [PgC/yr]	21.4 22.2 +0.9 +4.1% ± 7.6%	7.0 7.7 +0.7 +10.4% ±7.4%	12.9 14.7 +1.8 +14.3% ± 5.3%	8.5 9.3 +0.9 +10.5% ±9.1%	7.4 8.5 +1.1 +14.5% ±20.2%	1.4 1.8 +0.4 +29.7% ±6.8%	0.5 0.7 +0.2 +43.4% ±36.5%	58.9 ± 1.9 65.0 ± 1.9 +6.0 ± 0.8 +10.2% ± 1.4% ± 11.5%
Vegetation C stocks [PgC]	212.1 214.3 +2.2 +1.1% ± 25.8%	44.3 48.2 +3.8 +8.7% ±27.4%	112.2 136.1 +23.9 +21.3% ±22.4%	18.3 21.2 +2.9 +16.0% ± 30.4%	13.1 14.6 +1.5 +11.7% ± 20.1%	2.2 4.7 +2.5 +118.4% ± 24.1%	0.9 1.6 +0.8 +84.7% ±38.9%	403 ± 19.8 441 ± 3528 +37.8 ± 17.6 +9.2% ± 4.1 ± 25.2%
Soil and litter C stocks [PgC]	261.7 258.4 -3.3 -1.3% ±7.1%	156.1 154.2 -2.0 -1.3% ±4.0%	728.5 722.7 -5.8 -0.8% ±1.8%	132.9 132.4 -0.5 -0.4% ±2.3%	173.9 174.8 +1.8 +1.0% ±1.9%	113.1 113.6 +0.5 +0.4% ±1.0%	24.3 25.5 +1.2 +4.8% ±5.4.0%	1590 ± 45 1581 ± 46 -8.1 ± 6.8 -0.5% ± 0.4% ± 3.1%
Total C stocks [PgC]	476.2 475.1 -1.1 -0.2% ±9.6%	201.2 203.0 +1.8 +0.9% ± 5.9%	841.1 859.0 +17.9 +2.1% ±1.9%	151.6 154.0 +2.4 +1.6% ±4.5%	186.3 189.5 +3.3 +1.8% ± 2.7%	115.2 118.3 +3.0 +2.6% ±1.1%	25.2 27.1 +1.9 +7.7% ±6.0%	1997 ± 60 2026 ± 74 +29.2 ± 21.6 +1.5% ± 1.1% ± 4.2%
Crop production [Ecal]	5.53 8.09 +2.56 +46.3% ±334.0%	5.8 7.1 +1.4 +23.5% ±131.0%	2.3 2.7 +0.04 +17.4% ±88.2%	5.5 7.2 +1.7 +31.3% ±180.4%	3.4 4.3 +1.0 +28.9% ± 139.1%	0.01 0.01 +0.0 +7.7% ± 29.0%	0.2 0.2 +0.0 +18.4% ± 57.8%	22.6 ±1.0 29.6 ± 3.0 +7.0 ± 2.8 +31.2% ± 12.2% ±169.8%
Annual water runoff [1000 km³/yr]	25.0 27.5 +2.5 +10.0% ±6.2%	7.2 7.1 -0.1 -1.6% ±4.4%	7.4 7.6 +0.2 +2.3% ± 7.2%	5.1 6.4 +1.3 +24.7% ± 14.5%	2.7 3.3 +0.6 +23.8% ± 30.7%	1.2 1.3 +0.1 +5.2% ± 3.3%	1.0 1.1 +0.1 +10.1% ± 9.9%	49.7 ± 1.0 54.3 ± 1.6 +4.6 ± 0.9 +9.3% ± 1.7% ± 11.5%
Evapotranspiration [1000 km³/yr]	22.3 21.9 -0.5 -2.2% ±4.7%	8.3 8.4 +0.0 +0.5% ±2.8%	8.9 9.5 +0.6 +6.5% ±2.9%	8.7 8.8 +0.2 +1.9% ±4.2%	8.2 8.4 +0.2 +2.1% ±5.6%	0.7 0.8 +0.1 +16.5% ±3.2%	0.9 1.1 +0.2 +22.7% ±10.6%	58.0 ± 1.0 58.8 ± 1.2 +0.8 ± 1.0 +1.4% ± 1.7% ± 4.7%

Table S8. Percent increase in ES indicators per percent change in natural, pasture and cropland fraction on average for each biome and across all scenarios. Figure S5 provides an example for scatter plots and regression analyses creating the relationships depicted in this table. For this analysis, values below the 0.001 and above the 0.999 percentiles were excluded as well as cells with no LULC change. In the table, relationships with R^2 below 0.1 are greyed out for clarity. Percent changes in ES indicators are relative to their level in 2000-2004 (e.g. increase in 10% compared to 2000-2004), while percent changes in land use fractions are absolute fractions of grid-cells (e.g. 10% of a grid-cell changed in land use).

	NPP	Vegetation C	Soil and litter C	Total C stock	Crop production	Annual water runoff	Evapotranspiration
	Change in natural fraction						
Tropical forest	0.1	1.3	0.16	0.47	-18	-0.17	0.16
Temperate forest	0.04	1.8	0.15	0.37	-8.2	-0.35	0.15
Boreal forest	0.16	1.4	0.05	0.11	-7.2	-0.34	0.09
Tropical Savanna	-0.06	1.5	0.08	0.22	-12	-0.56	0.07
Temperate shrubland and grassland	-0.9	0.48	0.09	0.1	-14	-2.7	-0.3
	Change in pasture fraction						
Tropical forest	0.00	-0.92	-0.05	-0.32	4.6	0.21	-0.25
Temperate forest	-0.14	-0.6	0.03	-0.07	-5.5	-0.02	0.02
Boreal forest	-0.06	-1.1	-0.03	-0.06	-1.8	0.48	-0.04
Tropical Savanna	0.23	-0.44	0.05	-0.01	-1.4	0.27	-0.09
Temperate shrubland and grassland	0.55	0.23	-0.02	-0.00	-2.2	1.9	0.16
	Change in cropland fraction						
Tropical forest	-0.19	-1.4	-0.23	-0.49	24	0.07	-0.01
Temperate forest	0.05	-1.5	-0.19	-0.35	12	0.39	-0.18
Boreal forest	-0.28	-1.5	-0.09	-0.16	15	0.09	-0.16
Tropical Savanna	-0.11	-1.8	-0.15	-0.29	16	0.55	-0.02
Temperate shrubland and grassland	0.8	-1.5	-0.14	-0.2	23	2	0.33

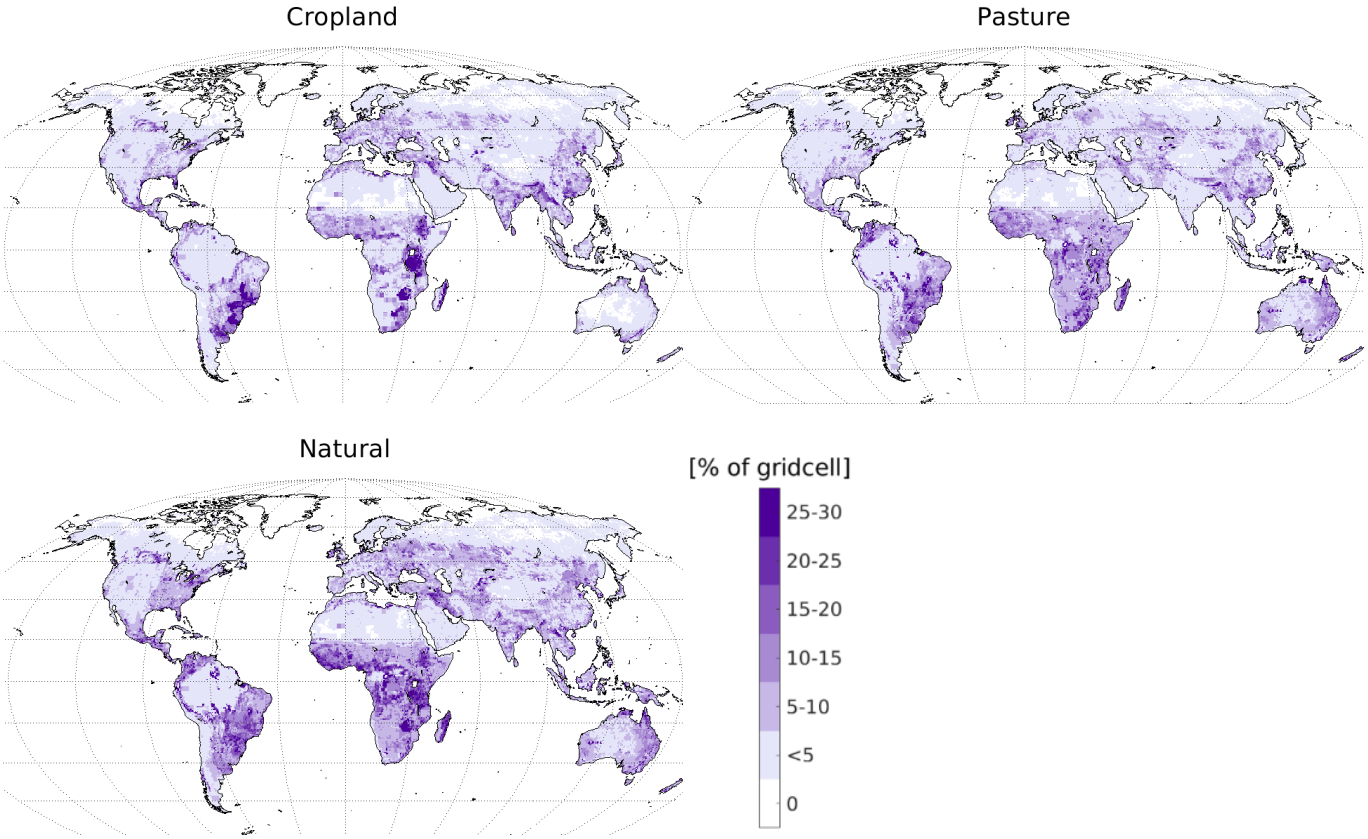


Fig. S1. Maps show the disagreement between 16 LULC scenarios for cropland, pasture and natural areas, calculated as the standard deviation of LULC changes from 2000-2004 to 2036-2040 across 16 scenarios. High deviations in cropland fractions in SE Africa and SE Brazil are caused by extreme changes in this class in all three scenarios of the MAgPIE model.

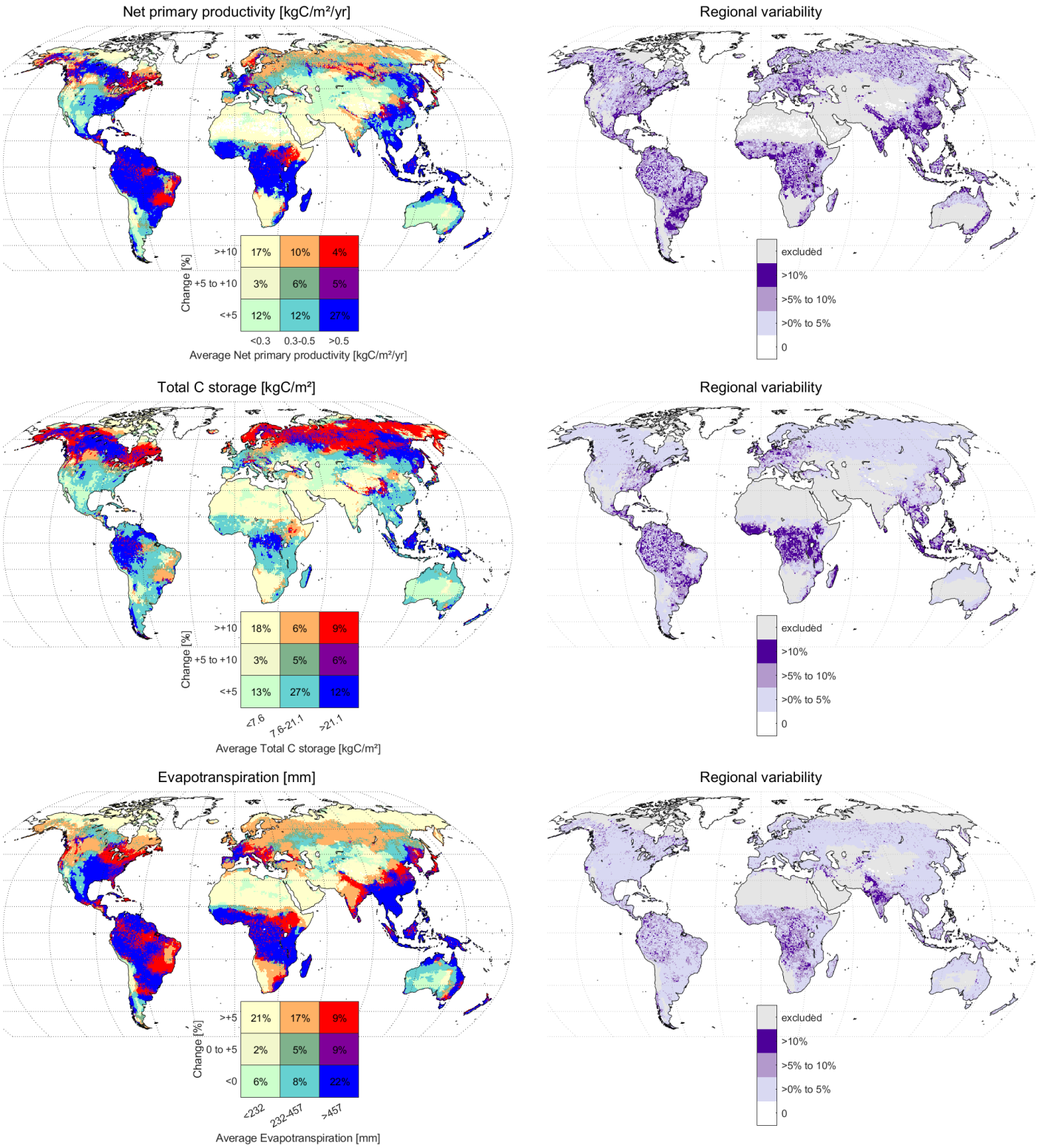


Fig. S2. Categories of the average level of the provision of NPP, total C storage and evapotranspiration in 2000-2004 and the change until 2036-2040 averaged over 16 land use scenarios and maps of regional variability in the change in ES indicators. See Fig. 4 in the main text for other ES indicators and a full description of the figure. Note that for evapotranspiration the lowest category in ES indicator change is negative.

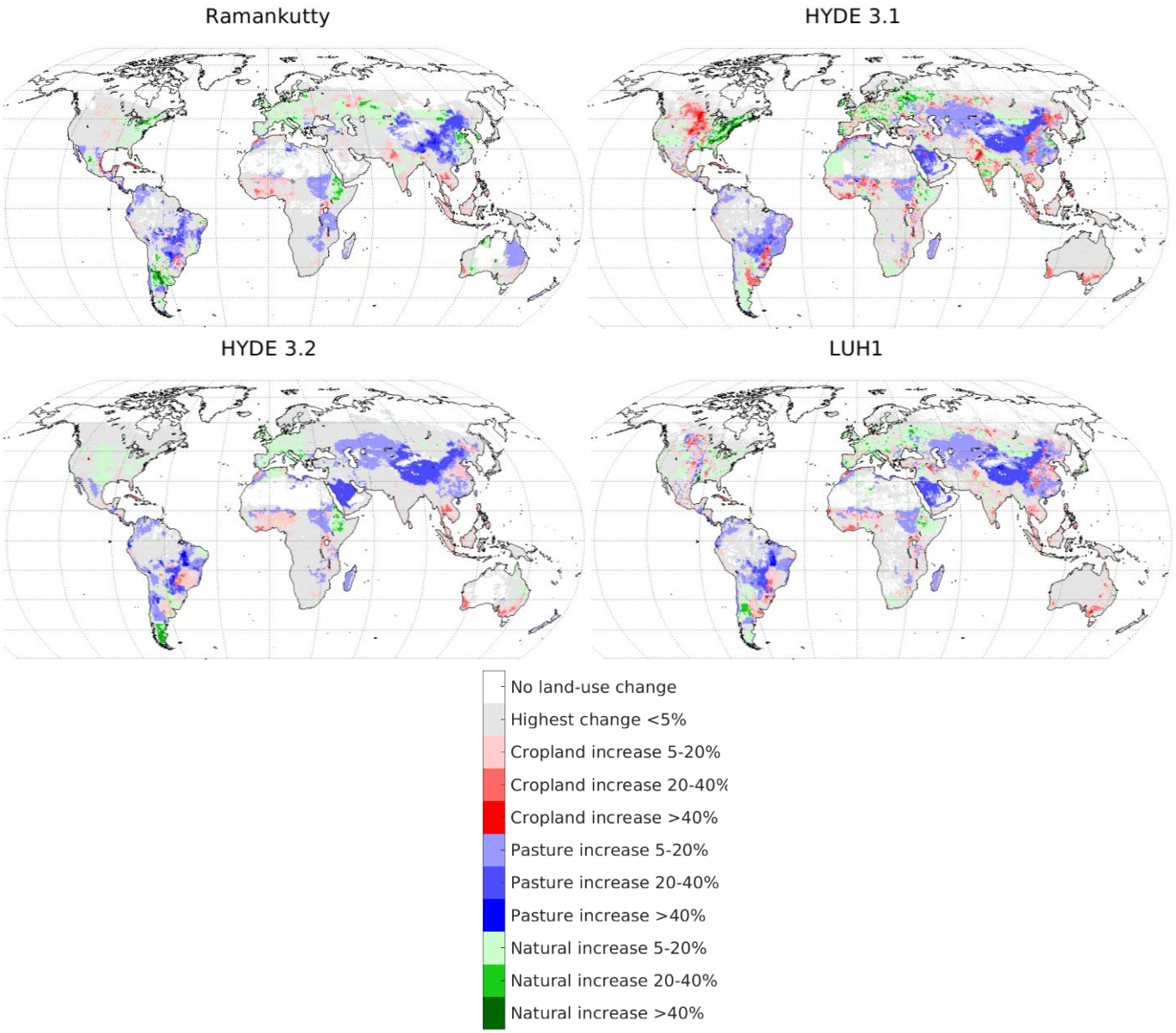


Fig. S3. Categories of dominant land-use/land-cover changes from 1960-1964 to 1996-2000 for historical reconstructions after Hurtt et al. (2011), Klein Goldewijk (2016), Klein Goldewijk et al. (2010, 2011) and Ramankutty et al. (2008). The analysis is identical to the one of Fig. 2.

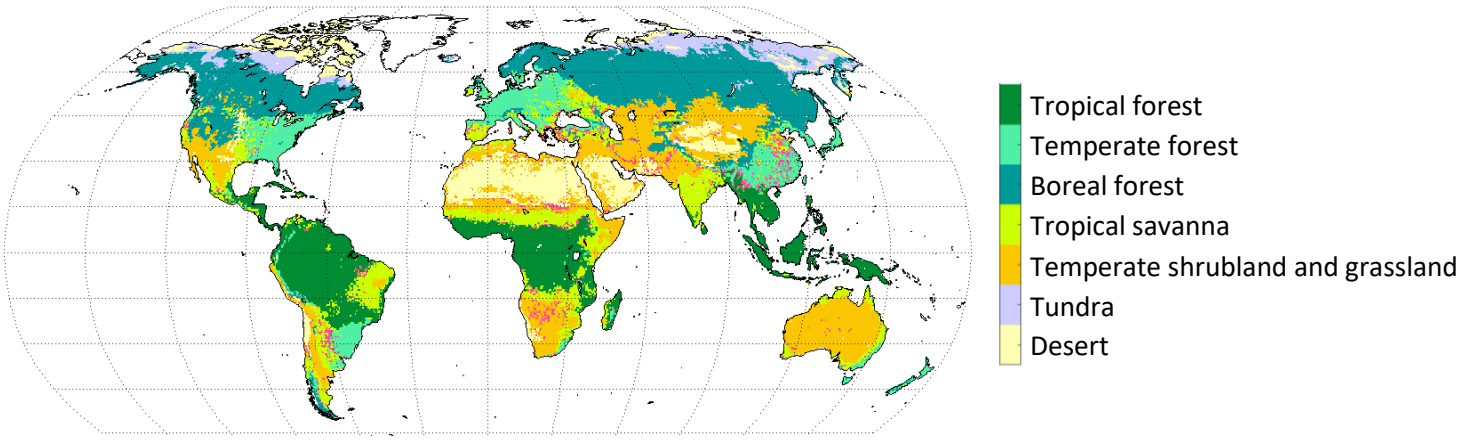
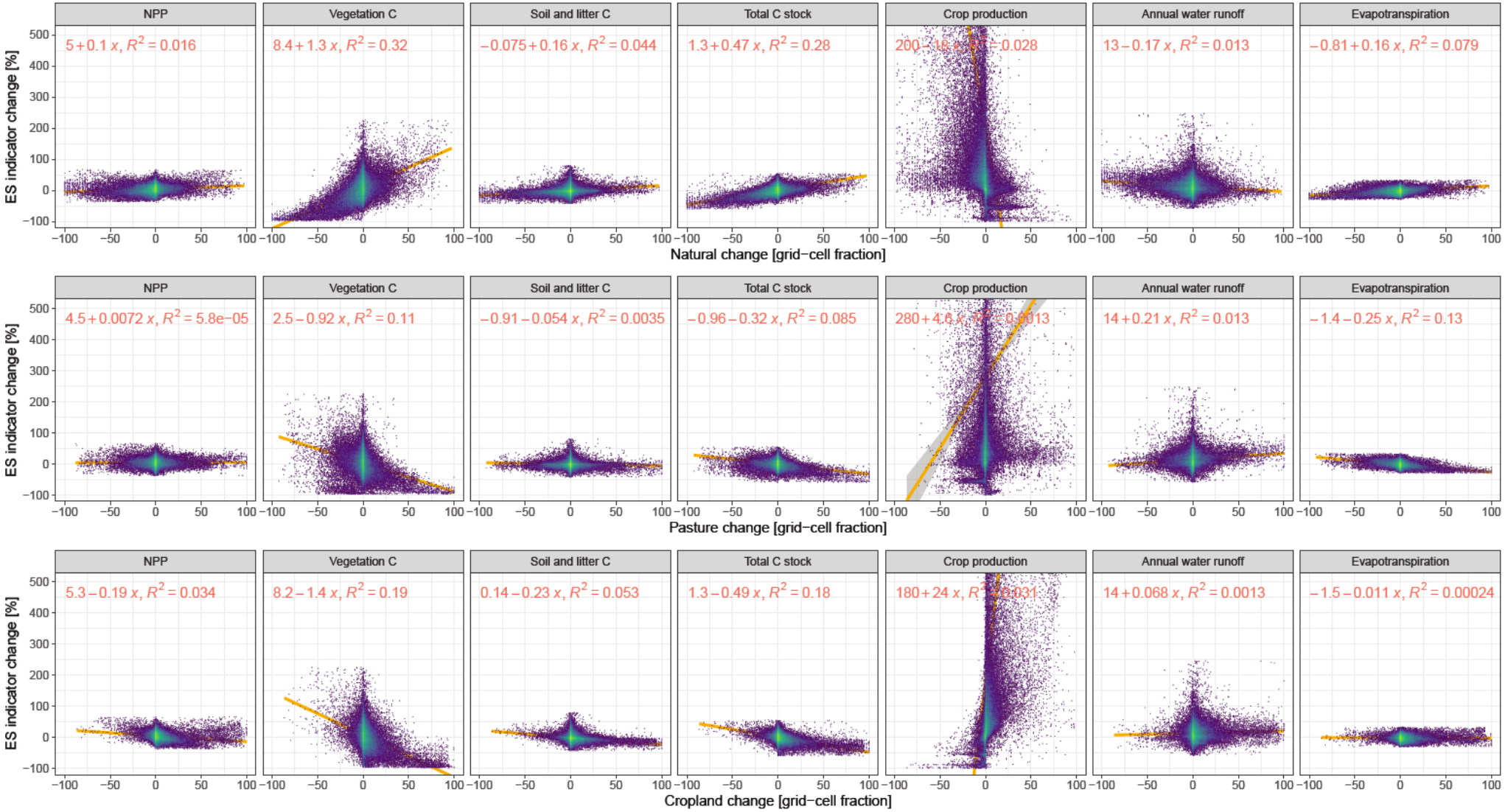


Fig. S4. Biomes classified based on leaf area index aggregated for 2000-2004 for the simulation LUH1_26Be. Classification methodology follows Smith et al. (2014).

Fig. S5. Direct correlation of the per grid-cell changes in ES indicators with the corresponding changes in cropland, pasture and natural land fraction across all scenarios as an example for the tropical forest biome. Regression line slope values are given in Table S8 to summarize the relationship between ES indicator change and LULC change.



References

Eitelberg, D. A., van Vliet, J., Doelman, J. C., Stehfest, E. and Verburg, P. H.: Demand for biodiversity protection and carbon storage as drivers of global land change scenarios, Glob. Environ. Chang., 40, 101–111, doi:10.1016/j.gloenvcha.2016.06.014, 2016.

Fader, M., Rost, S., Müller, C., Bondeau, A. and Gerten, D.: Virtual water content of temperate cereals and maize: Present and potential future patterns, J. Hydrol., 384(3–4), 218–231, doi:10.1016/j.jhydrol.2009.12.011, 2010.

Hempel, S., Frieler, K., Warszawski, L., Schewe, J. and Piontek, F.: A trend-preserving bias correction – The ISI-MIP approach, Earth Syst. Dyn., 4(2), 219–236, doi:10.5194/esd-4-219-2013, 2013.

Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D. P. and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, Clim. Change, 109, 117–161, 2011.

Klein Goldewijk, C. G. M.: A historical land use data set for the Holocene; HYDE 3.2, DANS [online] Available from: http://dx.doi.org/10.17026/dans-znk-cfy3, 2016.

Klein Goldewijk, K., Beusen, A. and Janssen, P.: Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1, The Holocene, 20(4), 565–573, doi:10.1177/0959683609356587, 2010.

Klein Goldewijk, K., Beusen, A., Van Drecht, G. and De Vos, M.: The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years, Glob. Ecol. Biogeogr., 20(1), 73–86, doi:10.1111/j.1466-8238.2010.00587.x, 2011.

Krause, A., Pugh, T. A. M., Bayer, A. D., Doelman, J. C., Humpenöder, F., Anthoni, P., Olin, S., Bodirsky, B. L., Popp, A., Stehfest, E. and Arneth, A.: Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators, Biogeosciences, 14(21), 4829–4850, doi:10.5194/bg-14-4829-2017, 2017.

Lamarque, J.-F., Kyle, G. P., Meinshausen, M., Riahi, K., Smith, S. J., van Vuuren, D. P., Conley, A. J. and Vitt, F.: Global and regional evolution of short-lived radiatively-active gases and aerosols in the Representative Concentration Pathways, Clim. Change, 109(1–2), 191–212, doi:10.1007/s10584-011-0155-0, 2011.

Lamarque, J. F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K. and Van Vuuren, D. P.: Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: Methodology and application, Atmos. Chem. Phys., 10(15), 7017–7039, doi:10.5194/acp-10-7017-2010, 2010.

Liu, X., Yu, L., Sia, Y., Zhang, C., Lu, H., Yu, C. and Gong, P.: Identifying patterns and hotspots of global land cover transitions using the ESA CCI land cover dataset, Remote Sens. Lett., 9(10), 972–981, doi:10.1080/2150704X.2018.1500070, 2018.

Portmann, F. T., Siebert, S. and Döll, P.: MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling, Global Biogeochem. Cycles, 24(1), 1–24, doi:10.1029/2008GB003435, 2010.

Ramankutty, N., Evan, A. T., Monfreda, C. and Foley, J. A.: Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000, Global Biogeochem. Cycles, 22, 1–19, 2008.

Smith, B., Wårlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J. and Zaehle, S.: Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation

model, Biogeosciences, 11, 2017–2054, doi:10.5194/bgd-10-18613-2013, 2014.

Tans, P. and Keeling, R.: Trends in atmospheric carbon dioxide, National Oceanic & Atmospheric Administration, Earth System Research Laboratory (NOAA/ESRL) & Scripps Institution of Oceanography. [online] Available from: http://www.esrl.noaa.gov/gmd/ccgg/%0Atrends/ (last access: 18 October 2016), 2015.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O. and Schewe, J.: The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework, PNAS, 111(9), 3228–3232, doi:10.1073/pnas.1312330110, 2014.

Winkler, K., Fuchs, R., Rounsevell, M. and Herold, M.: Global land use changes are four times greater than previously assumed, Nat. Commun. (in Rev., n.d.)

Zaehle, S., Ciais, P., Friend, A. D. and Prieur, V.: Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions, Nat. Geosci., 4(9), 601–605, doi:10.1038/ngeo1207, 2011.