Impacts of future agricultural change on ecosystem service indicators

Supplementary Methods

SM1 Run setup

The first run performed in this study generated the calibration factors described in Sect. SM2. In the calibration run for Alexander et al. (2018), only four crop stand types were simulated in LPJ-GUESS, corresponding to the four LPJ-GUESS CFTs (Alexander et al., 2018). This meant that starchy roots, oilcrops, and pulses all received the same management inputs (i.e., fertilizer and irrigation). In the work presented here, we have separated these three into distinct stand types that all use the TeSW CFT but with different management inputs based on crop-specific historical datasets (Table SM7). This change results in different calibration factors being used here than in Alexander et al. (2018); the new calibration factors can be found in Fig. SM2.

A set of "yield-generating" experiments were then performed to produce potential crop yields and pasture grass production for input to PLUM. These consist of two phases: an initial and an alternating phase. The initial phase runs from 1850 to 2000, and is intended to reproduce historical land uses and crop yields in a way that is consistent with previously developed land-use histories.

The alternating phase, which begins in 2001, iterates between "potential runs" and "actual runs," the latter of which exist only to provide initial soil conditions to the potential runs (Fig. SM1). In the potential runs, the non-barren land in every gridcell is converted to 50% cropland and 50% pasture, with homogenized soil based on the state after the previous actual run (Fig. SM1). Cropland is subdivided into 36 equally-sized stands in a factorial experiment with the six crop stand types (excluding Miscanthus), three nitrogen fertilizer treatments (0, 200, and 1000 kgN ha^{-1} yr^{-1}, and two irrigation treatments (rainfed or fully irrigated). Potential runs begin every five years, with each lasting ten years. Only the last five years' yields are passed to PLUM, with the first five years being used to give LPJ-GUESS time to spin up crop phenological parameters. Thus, for example, the potential run covering 2006–2015 generates output for 2011–2015, which is used in PLUM to determine land uses and managements for 2016–2020 (Fig. SM1). Actual runs each last five years, with the land system state being saved after each for input to the potential runs.

SM2 Mapping of MIRCA, LPJ-GUESS, and PLUM crop types

MIRCA crop types are mapped to the LPJ-GUESS crop stand types as described in Table SM7. Some MIRCA categories were excluded: sugarcane, citrus, date palm, grapes/vine, cotton, cocoa, coffee, other annuals, other perennials, and fodder grasses. A dummy crop type, ExtraCrop, was created to partition this unmapped fraction of cropland away from cropland considered in PLUM. Additionally, 10.3% of mapped crop types were moved to ExtraCrop, corresponding to the cropland fraction not harvested due, e.g., to crop failures or fallow periods (FAOSTAT, 2018c, b). In all, approximately 38% of cropland was in ExtraCrop over 2001–2010. LPJ-GUESS plants ExtraCrop, which receives no irrigation or fertilizer, with either winter wheat (TeWW) or spring wheat (TeSW) based on sowing constraints derived from long-term climate history in each gridcell. By not applying management inputs to ExtraCrop, we likely underestimate the effects of future land use and management changes on water use and nitrogen losses in absolute terms; however, this allows us to focus solely on the ecosystem services impacts of the crops explicitly included in PLUM.

To generate yields of a crop not included in LPJ-GUESS (e.g., oilcrops), a separate stand is simulated and planted with spring wheat, and a calibration factor then later multiplied onto the resulting yields to generate a wider range of crop yields as input to PLUM (Table SM7). (For consistency, calibration factors are also used for crops such as rice that are included in both LPJ-GUESS and PLUM.) These calibration factors are derived from a comparison of the LPJ-GUESS simulated yields with the crop yields reported in the FAOSTAT database (FAOSTAT, 2018c, a). A historical "calibration run" from 1901–2005 was used to generate gridded yields for 1995–2005; these were aggregated to the country level, with simulated country-year data points being regressed (with Y-intercept set to zero) against the values derived from FAOSTAT.

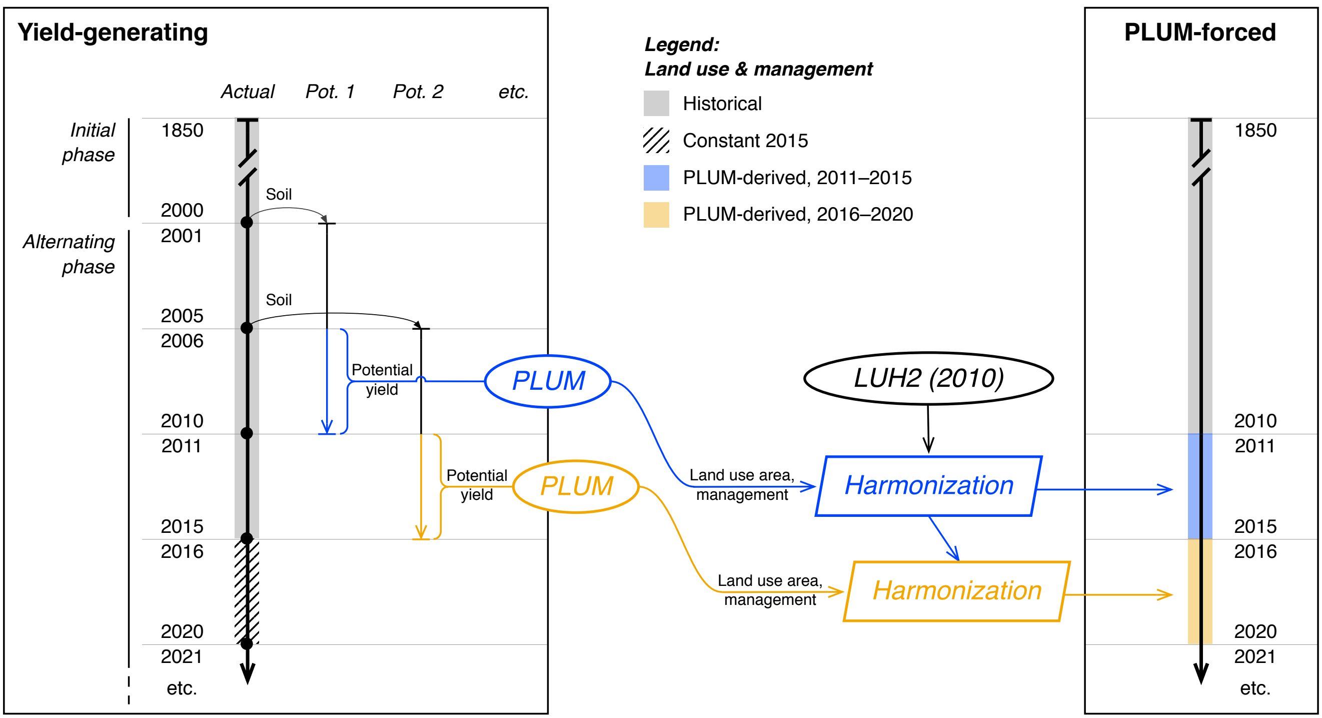

Figure SM1. Information flow between LPJ-GUESS and PLUM. Historical land use and management is time-varying for land use fractions through 2015 but constant for crop mix, fertilizer application, and per-crop irrigated fraction (see Sect. 3.3.1). Adapted from Figure SI-1 in Alexander et al. (2018).

Table SM1. Guide to the runs performed.

Run name	Years	Purpose	Number
Calibration	1901–2005	Simulate 1995–2005 crop yields for calibrating against FAOSTAT data.	1
Yield-generating, actual	1850–2100	1850–2010: Historical simulation for comparison with PLUM-forced future runs. All: Provide soil state for yield-generating potential runs.	1850–2010: 1 2011–2100: 4 (RCP-SSP combinations)
Yield-generating, potential	1850–2100	Generate potential yield for each crop type under different fertilization and irrigation treatments, for use in PLUM.	1850–2010: 1 2011–2100: 4 (RCP-SSP combinations)
PLUM-forced	2011–2100	Simulate terrestrial vegetation and ecosystem service indicators under land-use and -management trajectories specified by PLUM.	17: (standard, constant-CO_2+ climate)*(4 PLUM outputs) + constant-LU*(3 RCPs) + onlyCO_2*3 RCPs + onlyClimate*3 RCPs

Table SM2. Input data used for each portion of calibration run. Zhang et al. (2017) manure data extended as specified in Methods.

Years	Climate	LU	Crop fractions	Fert.	Irrig.
1850–1900	–	–	–	–	–
1901–2005	CRU-NCEP v7 CRUp	LUH2	MIRCA @2000	AgMIP@ 2000 + Zhang et al. @2000	MIRCA @2000*
2006–2010	–	–	–	–	–
2011–2015	–	–	–	–	–
2016–2100	–	–	–	–	–

–: Time period not simulated in given run.
DATASET @YYYY: Using value from DATASET at year YYYY.
*: Irrigation specified by fraction of crop fully rainfed or fully irrigated.

Table SM3. Input data used for each portion of "actual" yield-generating runs. Zhang et al. (2017) manure data extended as specified in Methods.

Years	Climate	LU	Crop fractions	Fert.	Irrig.
1850–1900	CMIP5 IPSL-CM5A-MR	LUH2	MIRCA @2000	LUH2 + Zhang et al.	LUH2*
1901–2005	↓	↓	↓	↓	↓
2006–2010	↓	↓	↓	↓	↓
2011–2015	↓	↓	↓	↓	↓
2016–2100	↓	LUH2 @2015	↓	LUH2 @2015 + Zhang et al. @2015	↓

DATASET @YYYY: Using value from DATASET at year YYYY.
*: Irrigation specified by fraction of crop fully rainfed or fully irrigated.

Table SM4. Input data used for each portion of "potential" yield-generating runs.

Years	Climate	LU	Crop fractions	Fert.	Irrig.
1850–1900	–	–	–	–	–
1901–2005	–	–	–	–	–
2006–2010	CMIP5 IPSL-CM5A-MR	Ice/water from LUH2; vegetated 50-50 cropland and pasture	Even crop × fertilizer × irrigation factorial stands	0, 200, or 1000 kgN ha^{-1}	Rainfed or fully irrigated
2011–2015	↓	↓	↓	↓	↓
2016–2100	↓	↓	↓	↓	↓

–: Time period not simulated in given run.

Table SM5. Input data used for each portion of PLUM-forced runs. Zhang et al. (2017) manure data extended as specified in Methods.

Years	Climate	LU	Crop fractions	Fert.	Irrig.
1850–1900	CMIP5 IPSL-CM5A-MR	LUH2	MIRCA @2000	LUH2 + Zhang et al.	MIRCA @2000*
1901–2005	↓	↓	↓	↓	↓
2006–2010	↓	↓	↓	↓	↓
2011–2015	↓	PLUM	PLUM	PLUM	PLUM†
2016–2100	↓	PLUM	PLUM	PLUM	PLUM†

DATASET @YYYY: Using value from DATASET at year YYYY.
*: Irrigation specified by fraction of crop fully rainfed or fully irrigated.
†: irrigation specified as fraction of maximum irrigation demand fulfilled.

Table SM6. Parameters used in PLUM. For more information, see Alexander et al. (2018) main text and supplement.

Parameter	SSP1	SSP3	SSP4	SSP5
Irrigation cost, w_{cost} (USD m^{-2})	0.000440	0.000232	0.000350	0.000232
Fertilizer cost, f_{cost} (USD t^{-1})	2.2	1.5	1.8	1.1
Other intensity cost, m_{cost} (USD at max management input)	0.8	0.7	0.7	0.6
Land cover change cost, lc_{change}: Natural to agricultural (USD ha^{-1})	107	31	54	38
Land cover change cost, lc_{change}: Pasture to cropland (USD ha^{-1})	290	205	232	161
Land cover change cost, lc_{change}: Cropland to pasture (USD ha^{-1})	575	366	432	300
Minimum natural or managed forest cover	19.5%	4.5%	6.2%	4.5%
Technology yield change rate, δ, above that from intensification of production	0.44%	0.00%	0.20%	0.30%
International market price sensitivity, λ	0.4	0.4	0.4	0.4
International import tariff, i_{tariff}	–20%	43%	19%	–36%
Transport costs, t_{cost} (USD t^{-1})	63	43	57	37
Annual change in imports allowed	2.2%	1.4%	1.7%	2.6%

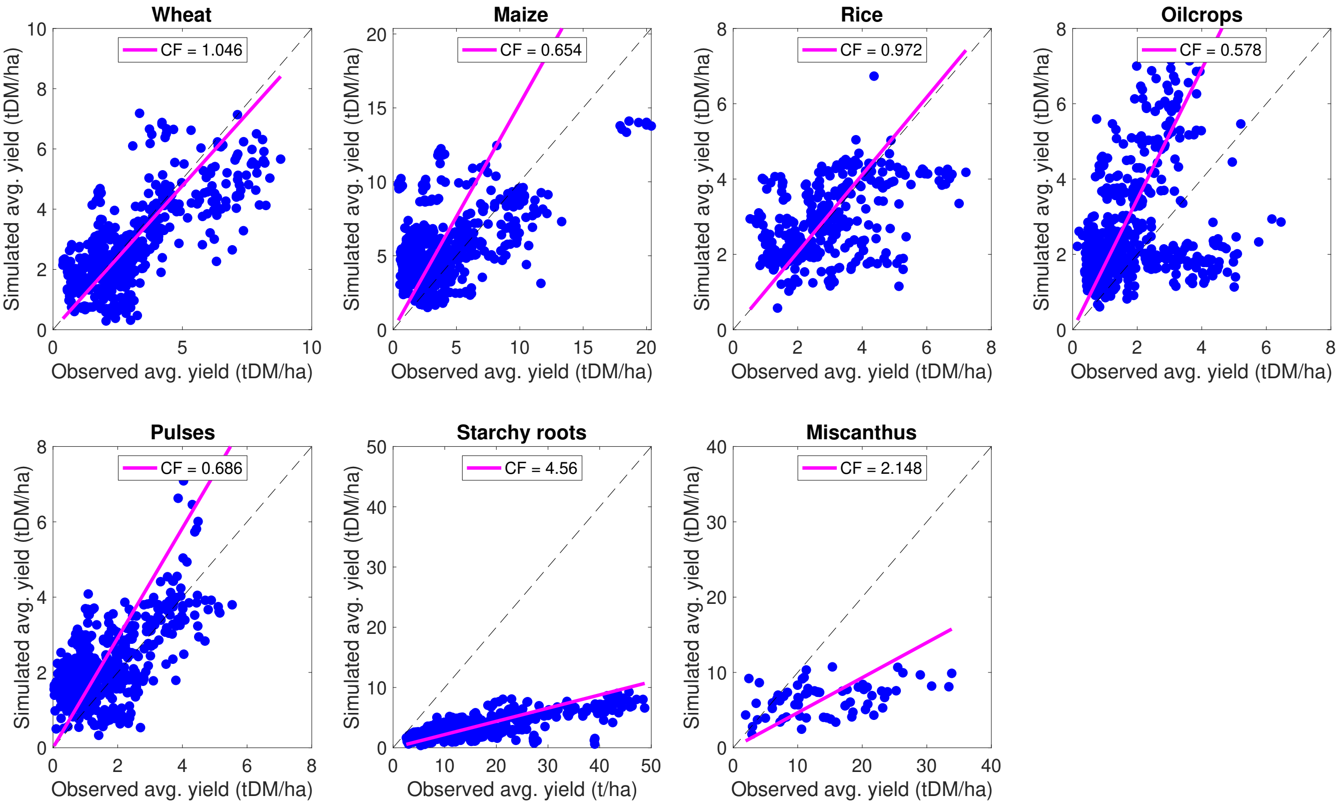

Figure SM2. Scatter plots between observed and LPJ-GUESS yield , with regression line used to determine calibration factors. Each point represents one country's yield in a single year. Corresponds to Fig. SI-2 in Alexander et al. (2018).

Table SM7. Mapping between different crop types used in this study. The first column gives the crop types used by PLUM, which are also the stand types simulated by LPJ-GUESS. The second column shows which CFTs LPJ-GUESS simulates in those stands, and the calibration factor for adjusting the yield for use in PLUM. Table adapted from Alexander et al. (2018).

Stand type = PLUM crop	CFT (calibration factor)	MIRCA (crop fraction) or AgMIP (calibration-run fertilizer) crop types	LUH2 crops (actual-run fertilizer and irrigated fraction)	FAO crops (calibration area; from FAOSTAT's "Production: Crops")	FAO crops (calibration production tonnage; from FAOSTAT's "Commodity Balance: Crops primary equivalent")
CerealsC3	TeWW or TeSW (1.056)	Wheat, Barley, Rye	All: C3ann	Wheat, Barley, Rye	Wheat and products, Barley and products, Rye and products
CerealsC4	TeCo (0.738)	Maize, Millet, Sorghum	All: C4ann	Maize, Millet, Sorghum	Maize and products, Millet and products, Sorghum and products
Rice	TrRi (1.052)	Rice	C3ann	Rice paddy	Rice (paddy equivalent)
Oilcrops	TeSW (0.687)	Sunflower, Soybeans, Groundnuts/ Peanuts, Rapeseed/Canola, Oilpalm	Area-weighted average of C3nfx (Soybeans, Groundnuts/Peanuts) and C3ann (others)	Coconuts, Seed cotton, Groundnuts with shell, Karite nuts (sheanuts), Castor oil seed, Tung nuts, Jojoba seed, Safflower seed, Poppy seed, Melonseed, Tallowtree seed, Kapok fruit, Linseed, Hempseed, Oilseeds nes, Olives, Oil palm fruit, Rapeseed, Mustard seed, Sesame seed, Soybeans, Sunflower seed	Oilcrops
Pulses	TeSW (0.865)	MIRCA: Pulses; AgMIP: Groundnuts, Soybeans	All: C3nfx	Pulses total	Pulses
Starchy roots	TeSW (5.443)	Potatoes, Sugarbeet, Cassava	All: C3ann	Roots and tubers total	Starchy roots
Miscanthus	TeCo (2.148)	n/a (only simulated in PLUM-forced runs)	n/a (only simulated in PLUM-forced runs)	n/a (calibrated against BetyDB data)	n/a (calibrated against BetyDB data)
ExtraCrop	n/a	MIRCA: Sugarcane, citrus, date palm, grapes/vine, cotton, cocoa, coffee, other annuals, other perennials, fodder grasses	n/a (no fertilizer or irrigation)	n/a (not calibrated)	n/a (not calibrated)

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