Supplement

Spatiotemporal dynamics of soil phosphorus and crop uptake in global cropland during the twentieth century

Jie Zhang[1], Arthur H.W.Beusen[2,3], Dirk F.van Apeldoorn[2,4], José M. Mogollón[2], Chaoqing Yu[1], Alexander F. Bouwman[2,3]

[1]Department of Earth System Science, Tsinghua University, Beijing, 100084, China

[2]Department of Earth Sciences-Geosciences, Faculty of Geosciences, Utrecht University, P.O.Box 80021, 3508 TA Utrecht, The Netherlands

[3]PBL Netherlands Environmental Assessment Agency, P.O.Box 30314, 2500 GH The Hague, The Netherlands

[4]Farming Systems Ecology, Wageningen University, P.O.Box 430, 6700 AK Wageningen, The Netherlands

Correspondence to: Chaoqing Yu (chaoqingyu@tsinghua.edu.cn); A. F. Bouwman (a.f.bouwman@uu.nl)

Contents

S1. Statistics used

For the comparison between historical record of P uptake and model simulated P uptake of countries and regions, we used the coefficient of determination (R^2) and the normalized root mean square error (*NRMSE*, equation S1):

$$NRMSE = \frac{100}{\overline{M}} \sqrt{\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{n}}$$

(S1)

Where S_i is the simulated value, M_i is the measured value, $\overline{M}$ is the average of the measured values and n is the number of data pairs. The *NRMSE* is the coefficient of variance, which estimates the average deviation between simulations and measurements (Wallach et al., 2006). It is an unbounded measure which shows the (normalized) relative size of the average difference (Willmott, 1982). For the global scale, we consider *NRMSE* ≤ 50% to be acceptable following Beusen et al. (2015).

S2. Sensitivity analysis

S2.1 Method

In this study, the sensitivity of the modelled *LP*, *SP* and crop *uptake* to variations of 12 model parameters (n = 12, Eq. S2) were investigated for two years (1950 and 2000) based on parameter-specific distributions between the minimum and maximum range around the standard parameter values (Table 2). The Latin Hypercube Sampling (LHS) method, which is a stratified sampling method, was implemented by subdividing the range of each of the n parameters into disjunct equiprobable intervals (*Num* = 150, Eq. S2) and subsequently getting a specific parameter value from each interval and each run, based on the assumed uniform distribution within each interval (Saltelli et al., 2004; Saltelli et al., 2000; Helton and Davis, 2003). For each parameter i, we obtained *Num* sampled values. The sampled values of different model parameters were randomly paired. The parameter space was thus sampled with a limited number of representative samples, consisting *Num* combinations of *n* parameters

The uncertainty contributions of the input parameters to the model outputs can be further analyzed by combining LHS with linear regression, since the model output *Y* (here *LP*，*SP* and *uptake*) is approximated by a linear function of the parameters X_i :

$$Y = \beta_0 + \sum_{i=1}^{n}(\beta_i X_i) + e \quad \text{(S2)}$$

where β_i are ordinary regression coefficients, *e* is the error of the approximation. The coefficient of determination (R^2) was used to evaluate the linear regression model, which is the variation in *Y* as explained by *Y - e*. The regression coefficients β_i depend on the scale and dimension of X_i. Therefore, we use the standardized regression coefficient (SRC_i) which normalizes β_i using standard deviations for $Y(\sigma_Y)$ and $X(\sigma_{Xi})$ as follows:

$$SRC_i = \beta_i \frac{\sigma_{X_i}}{\sigma_Y} \quad \text{(S3)}$$

SRC_i can assume values [-1,1] and represents the relative change in *Y* ($\Delta Y/\sigma_y$) due to the relative change in *X* ($\Delta X_i/\sigma_{xi}$) with respect to their standard deviations. SRC_i is thus independent of the units, scale and size of the parameters A positive SRC_i implies a positive relationship, whereby a higher parameter value leads to a higher model output. Negative SRC_i indicate a negative relationship, whereas a higher parameter value induces a decreased model output.

The sum of squares of SRC_i values of all parameters is equal to R^2. SRC_i^2/R^2 is thus the contribution of variation of X_i to variation of *Y*. For example, an X_i with $SRC_i = 0.1$ adds 0.01 or 1% to *Y* for $R^2 = 1$ (i.e. a perfect fit). We calculated the *SRC* for 12 parameters in the DPPS model. Parameters with SRC values exceeding 0.2 and less than -0.2 are considered to be significantly influence the model (green for positive values > 0.2, red for negative values <-

0.2, see Table S4), with a minimal contribution of $0.2^2 = 0.04$ or 4% contribution to the variation of global results. This analysis can be conducted for country, region to global levels.

S2.2 Results (see Table S4 in excel file Zhang_Table_S4.xlsx)

Results from the sensitivity analysis revealed that the main parameters influencing the model outputs are the initial labile and stable soil P pools, *max_uptake*, *fr_mobile* and *init_recovery* (Table S4).

At the global scale, the initial LP content from virgin soil (*LP_yang*), is the most important factor for global *LP* pool both in 1950 and 2000. *Fertilizer* is an important factor in 2000 but not in 1950, as the application of chemical fertilizers had not yet begun its exponential increase. Likewise, the initial total P content from virgin soil (*TP_yang*) exerts an important influence on the *SP* pool size. This influence is largest in 1950 in all regions, and in 2000 this influence is decreasing in industrialized countries due to the increasing impact of fertilizer and manure inputs on the pool sizes of both *LP* and *SP* (Table S4).

In all regions and countries, *max_uptake* and *fr_mobile* are important factors controlling crop uptake, with *SRC* values for *max_uptake* ranging from 0.29 to 0.60, and for *fr_mobile* from 0.42 to 0.57 in 2000. In 1950, *max_uptake* is an important globally, whereas *fr_mobile* only in certain regions. The importance of *init_recovery* increases with time, from SRC values often around 0.2 in 1950 to a range from 0.46 to 0.58 in 2000 (Table S4). *Fertilizer* is not important for uptake in 1950, but in 2000 it is important in industrialized countries and a number of transition countries like Brazil, Korea and China,. Likewise, the *LP* size is also increasingly important for crop P uptake, with values increasing from low in a range of countries in 1950 to 0.26-0.48 in 2000.

S3. Tables

Table S1. Region definition.

Region #	Country name	ISO	Region name
1	CANADA	124	Canada
2	SAINT PIERRE AND MIQUELON	666	USA
2	UNITED STATES	840	USA
2	UNITED STATES MINOR OUTLYING ISLANDS	581	USA
3	MEXICO	484	Mexico
4	ANGUILLA	660	Rest Central America
4	ANTIGUA AND BARBUDA	28	Rest Central America
4	ARUBA	533	Rest Central America
4	BAHAMAS	44	Rest Central America
4	BARBADOS	52	Rest Central America
4	BELIZE	84	Rest Central America
4	BERMUDA	60	Rest Central America
4	CAYMAN ISLANDS	136	Rest Central America
4	COSTA RICA	188	Rest Central America
4	CUBA	192	Rest Central America
4	DOMINICA	212	Rest Central America
4	DOMINICAN REPUBLIC	214	Rest Central America
4	EL SALVADOR	222	Rest Central America
4	GRENADA	308	Rest Central America
4	GUADELOUPE	312	Rest Central America
4	GUATEMALA	320	Rest Central America
4	HAITI	332	Rest Central America
4	HONDURAS	340	Rest Central America
4	JAMAICA	388	Rest Central America
4	MARTINIQUE	474	Rest Central America
4	MONTSERRAT	500	Rest Central America
4	NETHERLANDS ANTILLES	530	Rest Central America
4	NICARAGUA	558	Rest Central America
4	PANAMA	591	Rest Central America
4	PUERTO RICO	630	Rest Central America
4	SAINT KITTS AND NEVIS	659	Rest Central America
4	SAINT LUCIA	662	Rest Central America
4	SAINT VINCENT AND THE GRENADINES	670	Rest Central America
4	TRINIDAD AND TOBAGO	780	Rest Central America
4	TURKS AND CAICOS ISLANDS	796	Rest Central America
4	VIRGIN ISLANDS_BRITISH	92	Rest Central America
4	VIRGIN ISLANDS_U.S.	850	Rest Central America
5	BRAZIL	76	Brazil
6	ARGENTINA	32	Rest South America
6	BOLIVIA	68	Rest South America
6	BOUVET ISLAND	74	Rest South America
6	CHILE	152	Rest South America
6	COLOMBIA	170	Rest South America
6	ECUADOR	218	Rest South America
6	FALKLANDS ISLANDS (MALVINAS)	238	Rest South America

6	FRENCH GUIANA	254	Rest South America
6	GUYANA	328	Rest South America
6	PARAGUAY	600	Rest South America
6	PERU	604	Rest South America
6	SOUTH GEORGIA AND THE SOUTH SANDWICH ISLANDS	239	Rest South America
6	SURINAME	740	Rest South America
6	URUGUAY	858	Rest South America
6	VENEZUELA	862	Rest South America
7	ALGERIA	12	NorthernAfrica
7	EGYPT	818	NorthernAfrica
7	LIBYAN ARAB JAMAHIRIYA	434	NorthernAfrica
7	MOROCCO	504	NorthernAfrica
7	TUNISIA	788	NorthernAfrica
7	WESTERN SAHARA	732	NorthernAfrica
8	BENIN	204	Western Africa
8	BURKINA FASO	854	Western Africa
8	CAMEROON	120	Western Africa
8	CAPE VERDE	132	Western Africa
8	CENTRAL AFRICAN REPUBLIC	140	Western Africa
8	CHAD	148	Western Africa
8	CONGO	178	Western Africa
8	CONGO_THE DEMOCRATIC REPUBLIC OF THE	180	Western Africa
8	CÔTE D'IVOIRE	384	Western Africa
8	EQUATORIAL GUINEA	226	Western Africa
8	GABON	266	Western Africa
8	GAMBIA	270	Western Africa
8	GHANA	288	Western Africa
8	GUINEA	324	Western Africa
8	GUINEA-BISSAU	624	Western Africa
8	LIBERIA	430	Western Africa
8	MALI	466	Western Africa
8	MAURITANIA	478	Western Africa
8	NIGER	562	Western Africa
8	NIGERIA	566	Western Africa
8	SAINT HELENA	654	Western Africa
8	SAO TOME AND PRINCIPE	678	Western Africa
8	SENEGAL	686	Western Africa
8	SIERRA LEONE	694	Western Africa
8	TOGO	768	Western Africa
9	BURUNDI	108	EasternAfrica
9	COMOROS	174	EasternAfrica
9	DJIBOUTI	262	EasternAfrica
9	ERITREA	232	EasternAfrica
9	ETHIOPIA	231	EasternAfrica
9	KENYA	404	EasternAfrica
9	MADAGASCAR	450	EasternAfrica
9	MAURITIUS	480	EasternAfrica
9	MAYOTTE	175	EasternAfrica
9	RÉUNION	638	EasternAfrica
9	RWANDA	646	EasternAfrica

9	SEYCHELLES	690	EasternAfrica
9	SOMALIA	706	EasternAfrica
9	SUDAN	736	EasternAfrica
9	UGANDA	800	EasternAfrica
10	SOUTH AFRICA	710	Southern Africa
11	ANDORRA	20	Western Europe
11	AUSTRIA	40	Western Europe
11	BELGIUM	56	Western Europe
11	DENMARK	208	Western Europe
11	FAROE ISLANDS	234	Western Europe
11	FINLAND	246	Western Europe
11	FRANCE	250	Western Europe
11	GERMANY	276	Western Europe
11	GIBRALTAR	292	Western Europe
11	GREECE	300	Western Europe
11	HOLY SEE (VATICAN CITY STATE)	336	Western Europe
11	ICELAND	352	Western Europe
11	IRELAND	372	Western Europe
11	ITALY	380	Western Europe
11	LIECHTENSTEIN	438	Western Europe
11	LUXEMBOURG	442	Western Europe
11	MONACO	492	Western Europe
11	NETHERLANDS	528	Western Europe
11	NORWAY	578	Western Europe
11	PORTUGAL	620	Western Europe
11	SAN MARINO	674	Western Europe
11	SPAIN	724	Western Europe
11	SVALBARD AND JAN MAYEN	744	Western Europe
11	SWEDEN	752	Western Europe
11	SWITZERLAND	756	Western Europe
11	UNITED KINGDOM	826	Western Europe
12	ALBANIA	8	Central Europe
12	BOSNIA AND HERZEGOVINA	70	Central Europe
12	BULGARIA	100	Central Europe
12	CROATIA	191	Central Europe
12	CYPRUS	196	Central Europe
12	CZECH REPUBLIC	203	Central Europe
12	ESTONIA	233	Central Europe
12	HUNGARY	348	Central Europe
12	LATVIA	428	Central Europe
12	LITHUANIA	440	Central Europe
12	MACEDONIA_THE FORMER YUGOSLAV REPUBLIC OF	807	Central Europe
12	MALTA	470	Central Europe
12	POLAND	616	Central Europe
12	ROMANIA	642	Central Europe
12	SLOVAKIA	703	Central Europe
12	SLOVENIA	705	Central Europe
12	YUGOSLAVIA	891	Central Europe
13	TURKEY	792	Turkey

14	BELARUS	112	Ukraine +
14	MOLDOVA_REPUBLIC OF	498	Ukraine +
14	UKRAINE	804	Ukraine +
15	KAZAKSTAN	398	Asia-Stan
15	KYRGYZSTAN	417	Asia-Stan
15	TAJIKISTAN	762	Asia-Stan
15	TURKMENISTAN	795	Asia-Stan
15	UZBEKISTAN	860	Asia-Stan
16	ARMENIA	51	Russia +
16	AZERBAIJAN	31	Russia +
16	GEORGIA	268	Russia +
16	RUSSIAN FEDERATION	643	Russia +
17	BAHRAIN	48	Middle East
17	IRAN_ISLAMIC REPUBLIC OF	364	Middle East
17	IRAQ	368	Middle East
17	ISRAEL	376	Middle East
17	JORDAN	400	Middle East
17	KUWAIT	414	Middle East
17	LEBANON	422	Middle East
17	OMAN	512	Middle East
17	QATAR	634	Middle East
17	SAUDI ARABIA	682	Middle East
17	SYRIAN ARAB REPUBLIC	760	Middle East
17	UNITED ARAB EMIRATES	784	Middle East
17	YEMEN	887	Middle East
18	INDIA	356	India
19	KOREA_DEMOCRATIC PEOPLE'S REPUBLIC OF	408	Korea
19	KOREA_REPUBLIC OF	410	Korea
20	CHINA	156	China +
20	HONG KONG	344	China +
20	MACAU	446	China +
20	MONGOLIA	496	China +
20	TAIWAN_PROVINCE OF CHINA	158	China +
21	BRUNEI DARUSSALAM	96	SoutheasternAsia
21	CAMBODIA	116	SoutheasternAsia
21	LAO PEOPLE'S DEMOCRATIC REPUBLIC	418	SoutheasternAsia
21	MALAYSIA	458	SoutheasternAsia
21	MYANMAR	104	SoutheasternAsia
21	PHILIPPINES	608	SoutheasternAsia
21	SINGAPORE	702	SoutheasternAsia
21	THAILAND	764	SoutheasternAsia
21	VIET NAM	704	SoutheasternAsia
22	EAST TIMOR	626	Indonesia +
22	INDONESIA	360	Indonesia +
22	PAPUA NEW GUINEA	598	Indonesia +

23	JAPAN	392	Japan
24	AMERICAN SAMOA	16	Oceania
24	AUSTRALIA	36	Oceania
24	CHRISTMAS ISLAND	162	Oceania
24	COCOS (KEELING) ISLANDS	166	Oceania
24	COOK ISLANDS	184	Oceania
24	FIJI	242	Oceania
24	FRENCH POLYNESIA	258	Oceania
24	FRENCH SOUTHERN TERRITORIES	260	Oceania
24	GUAM	316	Oceania
24	HEARD ISLAND AND MCDONALD ISLANDS	334	Oceania
24	KIRIBATI	296	Oceania
24	MARSHALL ISLANDS	584	Oceania
24	MICRONESIA_FEDERATED STATES OF	583	Oceania
24	NAURU	520	Oceania
24	NEW CALEDONIA	540	Oceania
24	NEW ZEALAND	554	Oceania
24	NIUE	570	Oceania
24	NORFOLK ISLAND	574	Oceania
24	NORTHERN MARIANA ISLANDS	580	Oceania
24	PALAU	585	Oceania
24	PITCAIRN	612	Oceania
24	SAMOA	882	Oceania
24	SOLOMON ISLANDS	90	Oceania
24	TOKELAU	772	Oceania
24	TONGA	776	Oceania
24	TUVALU	798	Oceania
24	VANUATU	548	Oceania
24	WALLIS AND FUTUNA	876	Oceania
25	AFGANISTAN	4	Rest Southern Asia
25	BANGLADESH	50	Rest Southern Asia
25	BHUTAN	64	Rest Southern Asia
25	BRITISH INDIAN OCEAN TERRITORY	86	Rest Southern Asia
25	MALDIVES	462	Rest Southern Asia
25	NEPAL	524	Rest Southern Asia
25	PAKISTAN	586	Rest Southern Asia
25	SRI LANKA	144	Rest Southern Asia
26	ANGOLA	24	Rest Southern Africa
26	BOTSWANA	72	Rest Southern Africa
26	LESOTHO	426	Rest Southern Africa
26	MALAWI	454	Rest Southern Africa
26	MOZAMBIQUE	508	Rest Southern Africa
26	NAMIBIA	516	Rest Southern Africa
26	SWAZILAND	748	Rest Southern Africa
26	TANZANIA_UNITED REPUBLIC OF	834	Rest Southern Africa
26	ZAMBIA	894	Rest Southern Africa
26	ZIMBABWE	716	Rest Southern Africa
Greenland and Antarctica are not included in the datafiles			
	GREENLAND	304	Greenland
	ANTARCTICA	10	Antarctica

Table S2. P excretion rates for livestock in IMAGE-GNM.

Category	P excretion in kg $head^{-1}$ $year^{-1}$
1. Beef cattle	10.5[a]/8.7[b]/7.0[c]
2. Dairy cattle	22.7[a]/17.5[b]/10.5[c]
3. Buffaloes	7.9
4. Pigs	1.8
5. Poultry	0.1
6. Sheep and goats	1.5
7. Horses	7.3[d]/6.5[c]
8. Asses	4.4
9. Mules	4.4
10. Camels	8.0

[a] = Canada, USA, Japan;
[b] = OECD Europe;
[d] = Canada, USA, OECD Europe, Japan;
[c] = all other countries.

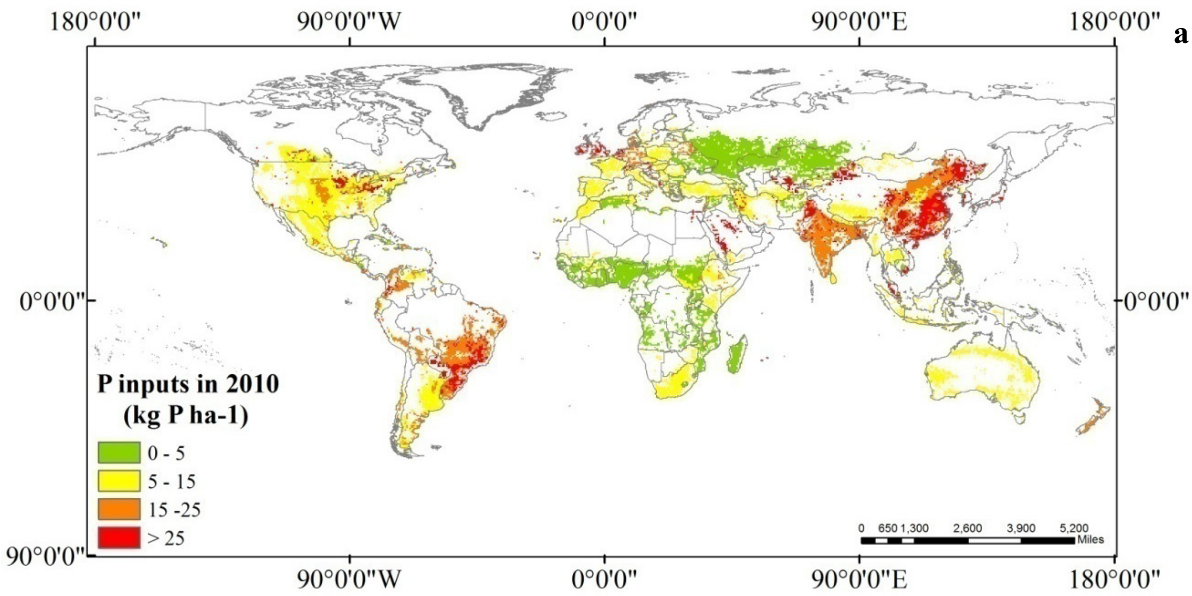
Table S3. Crop groups used as a basis for calculating crop P uptake, P content on dry matter basis, and dry matter content.

Crops	Name	P content (-)	Dry matter (-)
1	Wheat	0.0034	0.880
2	Rice	0.0025	0.880
3	Maize	0.0029	0.880
4	Barley	0.0036	0.880
5	Millet	0.0030	0.850
6	Sorghum	0.0030	0.850
7	Other cereals	0.0031	0.870
8	Potato	0.0005	0.212
9	Sweet potato	0.0003	0.272
10	Cassava	0.0004	0.326
11	Other root crops	0.0004	0.270
12	Plantain	0.0003	0.653
13	Sugar beet	0.0004	0.260
14	Sugar cane	0.0004	0.232
15	Pulses	0.0025	0.850
16	Vegetables	0.0003	0.070
17	Banana	0.0002	0.257
18	Citrus	0.0001	0.103
19	Fruit crops	0.0001	0.131
20	Oil crops	0.0050	0.920
21	Rapeseed	0.0056	0.910
22	Oil palm	0.0031	0.940
23	Soybean	0.0050	0.850
24	Groundnut	0.0042	0.942
25	Sunflower	0.0045	0.920
26	Sesame seed	0.0056	0.940
27	Coconut	0.0004	0.896
28	Cocoa	0.0026	1
29	Coffee	0.0022	1
30	Tea	0.0150	0.525
31	Tobacco	0.0006	0.21
32	Cotton	0.0053	0.92
33	Fiber crops	0.0095	1
34	Rubber	0.0000	1

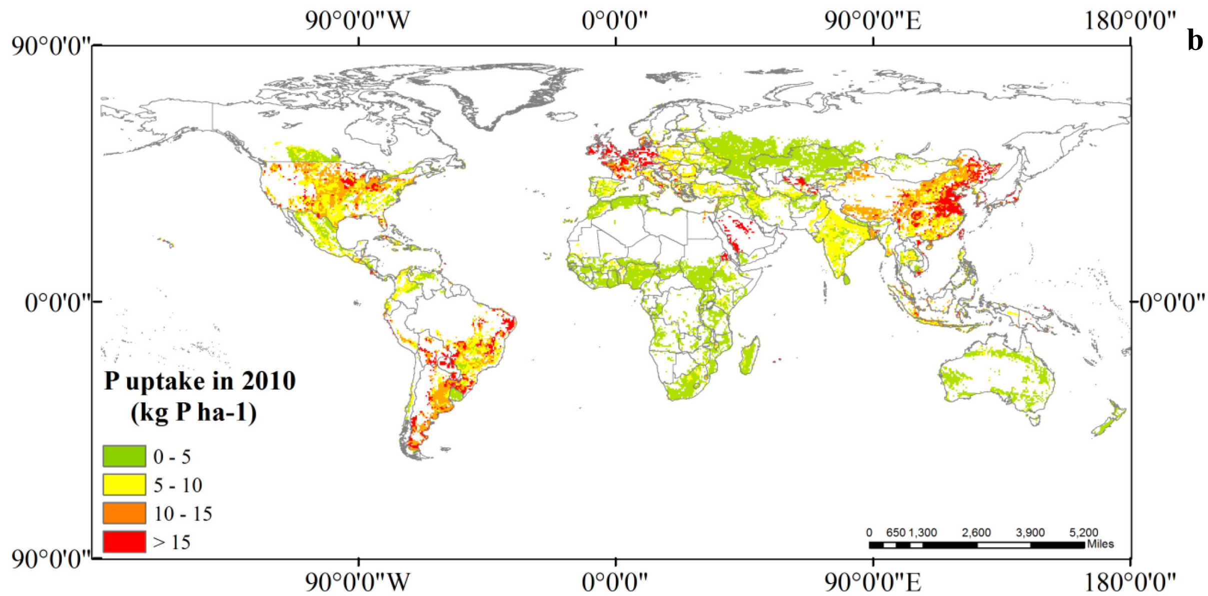
Table S4. Sensitivity results of world regions and selected countries.

This table showed the detailed results of model sensitivity analysis. See separate Excel file "Zhang_Table_S4.xlsx"

S4. Figures



180°0'0"
90°0'0"W
0°0'0"
90°0'0"E
180°0'0"
a
0°0'0"
0°0'0"
P inputs in 2010
(kg P ha-1)
0 - 5
5 - 15
15 -25
> 25
0 650 1,300 2,600 3,900 5,200
Miles
90°0'0"
90°0'0"W
0°0'0"
90°0'0"E
180°0'0"



90°0'0"W
0°0'0"
90°0'0"E
180°0'0"
90°0'0"
b
0°0'0"
0°0'0"
P uptake in 2010
(kg P ha-1)
0 - 5
5 - 10
10 - 15
> 15
0 650 1,300 2,600 3,900 5,200
Miles
90°0'0"
90°0'0"W
0°0'0"
90°0'0"E
180°0'0"

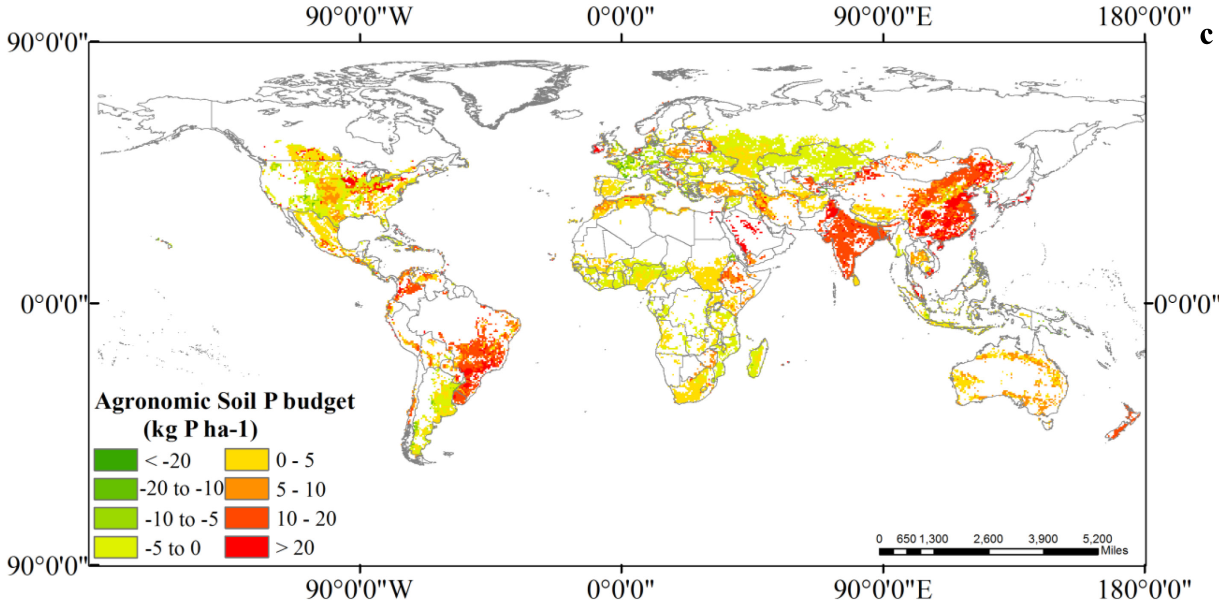
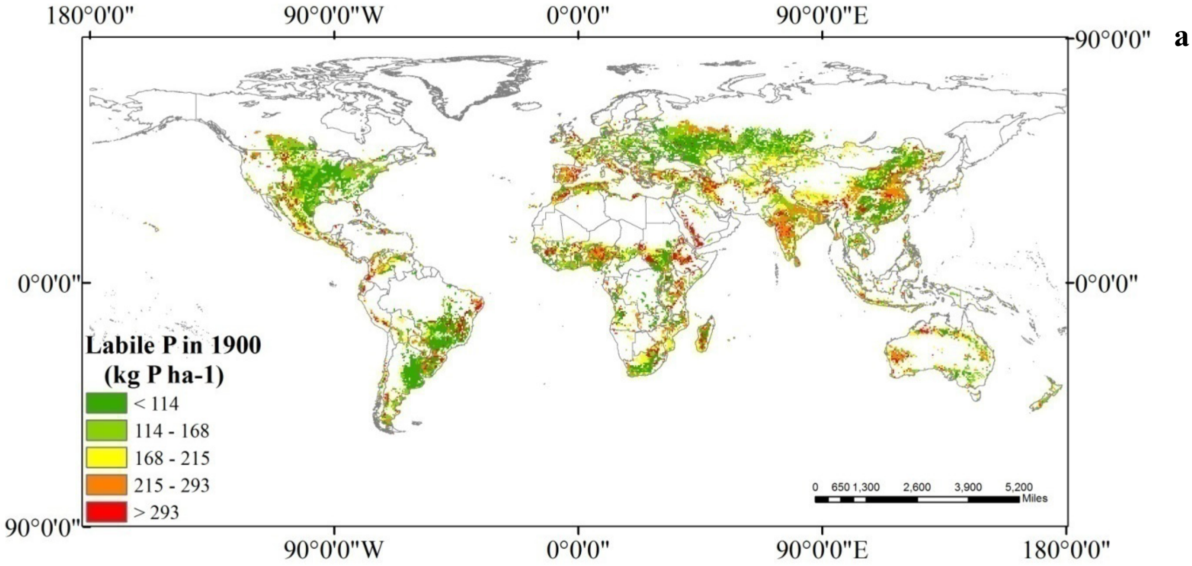


Figure S1.Global P inputs (a), uptake (b) and agronomic P budget (c) for cropland in 2010. Inputs per hectare refer to mineral fertilizer and manure; uptake is the P withdrawal in harvested parts of crops and agronomic P budget per hectare is the difference between inputs and uptake, which is different from soil P budget, since deposition and runoff are not included in agronomic P budget. We can produce the grid maps for every year for the period 1900-2010 and here we only show 2010 as an example.



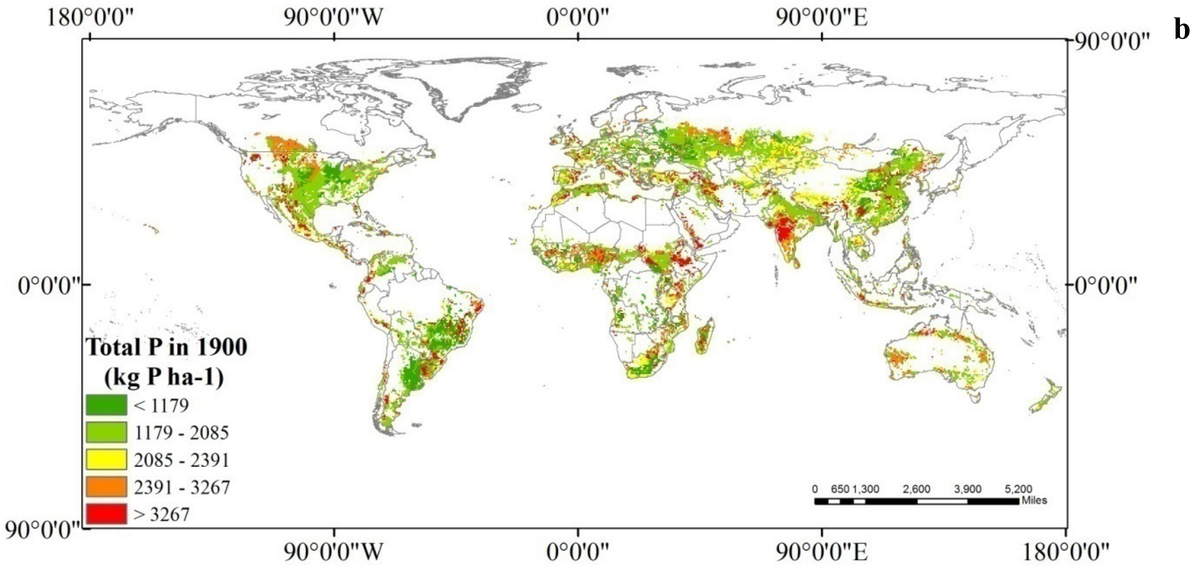


Figure S2. The global distribution of labile and total P in global agricultural land soils in 1900. We can produce the grid maps for every year for the period 1900-2010 and here we only show 1900 as an example.

S5. Movies

Movie S1. Labile Phosphorus (LP) pool distribution in kg P ha^{-1} for all grid cells of the global cropland, presented with 4-year intervals for the period 1900-2010.

Movie S2. Stable Phosphorus (SP) pool distribution in kg P ha^{-1} for all grid cells of the global cropland, presented with 4-year intervals for the period 1900-2010

Movie S3. Crop P uptake in kg P ha^{-1} for all grid cells of the global cropland, presented with 4-year intervals for the period 1900-2010

S6. Figures data

The supplement zip file includes the directory “Figures data”, which contains the asci files for Figures 2-5, Figure 6 (a, b, c), Figure SI1 (a, b, c) and SI2 (a, b).

References

Beusen, A., Van Beek, L., Bouwman, L., Mogollón, J., and Middelburg, J.: Coupling global models for hydrology and nutrient loading to simulate nitrogen and phosphorus retention in surface water–description of IMAGE–GNM and analysis of performance, Geoscientific model development, 8, 4045-4067, 2015.

Helton, J. C., and Davis, F. J.: Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems, Reliability Engineering & System Safety, 81, 23-69, 2003.

Saltelli, A., Chan, K., and Scott, E. M.: Sensitivity analysis, Wiley and Sons, Chichester, 2000.

Saltelli, A., Tarantola, S., Campolongo, F., and Ratto, M.: Sensitivity analysis in practice. A guide to assessing scientific models, Wiley and Sons, Chichester, 2004.

Wallach, D., Makowski, D., and Jones, J.: Working with dynamic crop models: Evaluation, Analysis, Parameterization and Applications. Elsevier BV, 2006.

Willmott, C. J.: Some comments on the evaluation of model performance, Bulletin of the American Meteorological Society, 63, 1309-1313, 1982.