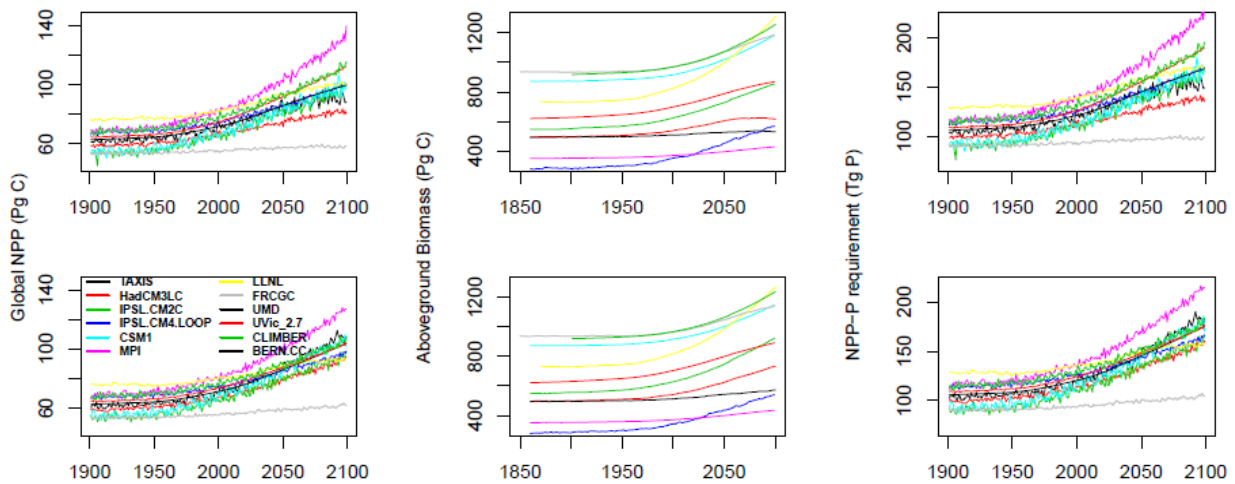
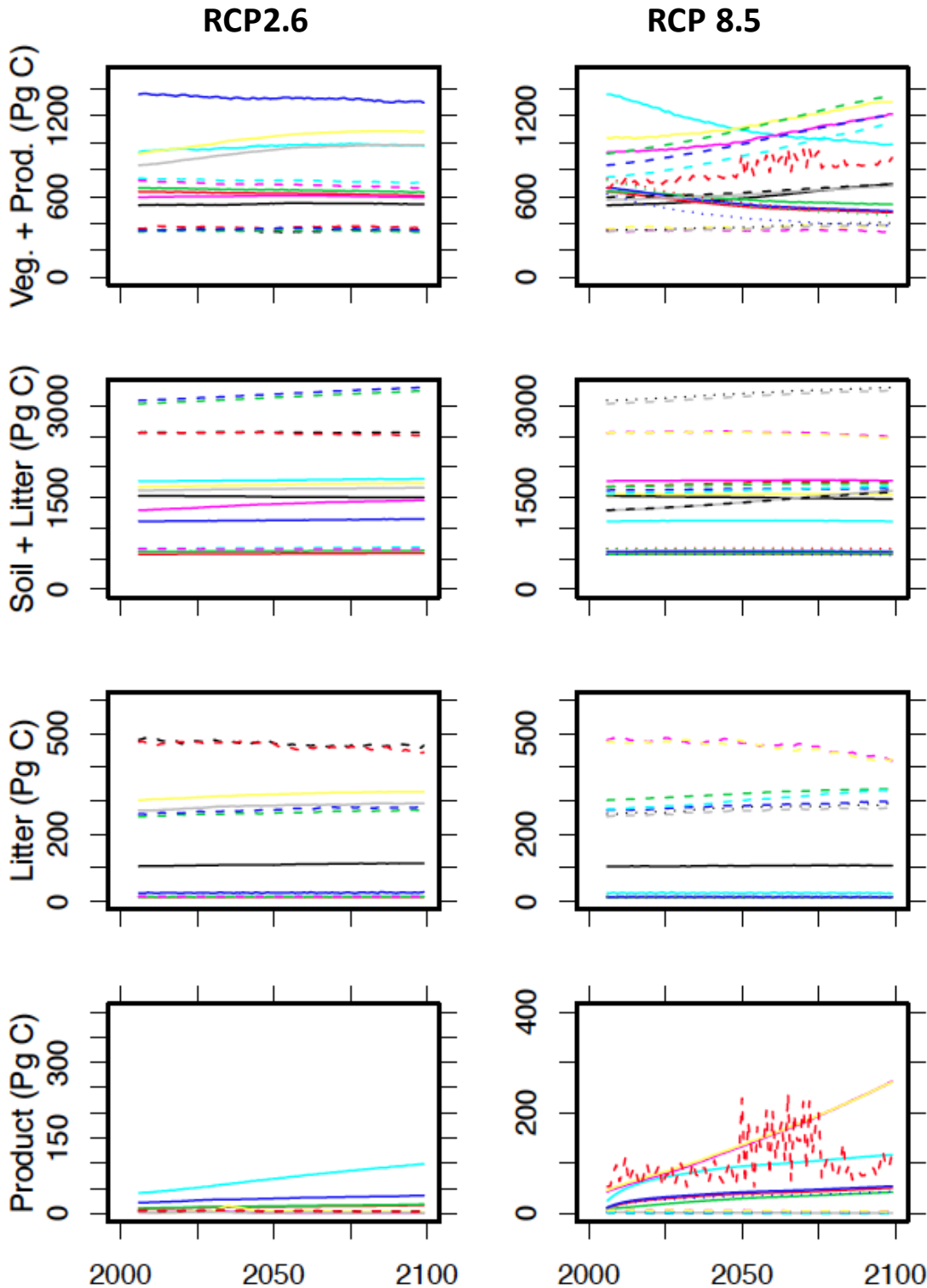


Supplementary Information



Supplementary Figure S1: Projected terrestrial carbon fluxes and stocks, and P requirements

Simulated coupled (top panels) and uncoupled (lower panels) response of terrestrial carbon fluxes and stocks from the C4MIP climate carbon cycle model ensemble. The NPP-P requirement is estimated based on the stoichiometric ratios of Kattge *et al.*⁷¹, assuming that woody NPP is one-third of total NPP and active tissues (leaves/roots) are two-thirds.



Supplementary Figure S2: Time series plot of the 21st century evolution of carbon pools treated in this analysis from Supplementary Table S3.

Please note the wide range of variability across all pools, for example, more than 1000 PgC uncertainty in vegetation and in soil carbon stocks. In addition, directional changes in vegetation carbon stocks vary significantly in RCP 8.5 in addition to interannual variability where year-to-year changes in land cover change can influence vegetation and product pools of carbon.

Supplementary Table S1. Detailing results shown in Fig. 4. Effects of atmospheric nitrogen deposition on lake-water N:P ratio ↑ = increases, ↓ = decreases

Species and/or community studies and pollutant sources	Study site	Main results	Reference
Lakes	Field	↑ N:P water	72
Lakes	Meta-analyses of published data	↑ N:P water	12
Lakes	Field	↑ N:P water	73
Lakes	Meta-analyses of field data	↑ N:P water	74
Lakes	Field	↑ N:P water	75
Lakes	Field	↑ N:P water	76

Supplementary Table S2. Detailing results shown in Fig. 4. Effects of water eutrophication on river and estuaries water N:P ratio. \uparrow = increases, \downarrow = decreases

Species and/or community studies and pollutant sources	Study site	Main results	Reference
Lakes	Field	\uparrow N:P in cropland areas \downarrow N:P in pasture areas	18
Urban and crop waste loadings in estuary (Turkey)	Field	\downarrow N:P	77
Urban and crop waste loadings in estuary (USA)	Field	\uparrow N:P	78
Urban and crop waste loadings in estuary (China)	Field	\uparrow N:P	79
Loadings from 2 estuaries in Chesapeake Bay	Field	\uparrow N:P in Choptank River \downarrow N:P in Patuxent River	80
Great river loadings	Review	\uparrow N:P	81
San Francisco estuary (California)	Field	\uparrow N:P	82
Krka river estuary (Adriatic sea)	Field	\uparrow N:P	83
Urban and crop waste loadings in estuary (China)	Field	\uparrow N:P	84
Outh Norway watersheds	Field	\uparrow N:P	85
Pearl river estuary (China)	Field	\uparrow N:P	86
Loadings from Rhine to sea (periode 1950-1985)	Field	\uparrow N:P	87
Grand Bay (Alabama)	Field	\downarrow N:P	88
Northern Gulf of Mexico	Field	\uparrow N:P	89
Mississippi river (USA)	Field	\uparrow N:P	89
Areas of Adriatic	Field	\downarrow N:P	89
Po river (Italy)	Field	\downarrow N:P	89
Izmir Bay (Turkey)	Field	\downarrow N:P	90
German Bight	Field	\uparrow N:P	91
Gulf of Nicoya (Costa Rica)	Field	\uparrow N:P	92
Urban and crop waste	Field	\uparrow N:P	93

loadings in estuary (China)			
Gulf of Trieste (Adriatic sea)	Field	↑ N:P	94
Urban and crop waste loadings in estuary (Argentina)	Field	↑ N:P	95
Urban and crop waste loadings in some estuaries (England)	Field	↑ N:P	96
Diverse mangrove areas (India)	Field	↑ N:P	97
Northern of Gulf of Mexico	Field	↑ N:P	98
Urban and crop waste loadings in North sea from Belgium to Gemany (1977-2000)	Field	↑ N:P	99
Sewage treatment waste loadings in coastal waters (Brazil)	Field	↑ N:P	100
Loadings from Changjiang river (China)	Field	↑ N:P	101
Great river loadings	Review	↑ N:P	14
Mississippi River loadings in Gulf of Mexico	Field	↑ N:P	102
Acton (Ohio)	Field	↑ N:P	103
Pleasant Hill (Ohio)	Field	↑ N:P	103
Burr oak	Field	↓ N:P	103
Urban and crop waste loadings in a water reservoir (Brazil)	Field	↑ N:P	104
Sewage treatment waste loadings in water reservoirs (Brazil)	Field	↑ N:P	105
Baiyangdian Lake (China)	Field	↑ N:P	106
Urban waste loadings in coastal ocean waters (China)	Field	↑ N:P	107
Hong Kong Harbour area	Field	↑ N:P	108 and 109
Urban and crop waste loadings in estuary (China)	Field	↑ N:P	110
Loadings from Pearl River (China)	Field	↑ N:P	111

Supplementary Table S3. Detailing results shown in Fig. 4. Effects of increases in water N:P ratio on organisms N:P ratio. ↑= increases, ↓= decreases.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
Calamazo ponds (Michigan)	Field	↑ N:P	112
Trinidad and Tobago streams	Field	↑ N:P	113
Lakes	Field	↑ N:P	81
Freshwater	Mesocosm experiment	↑ N:P	114
	Microcosm	↑ N:P	115
Lakes	Field	↑ N:P	116
Douglas River (North Australia)	Field	↑ N:P	117
Lake Erken (Sweden)	Field	↑ N:P	118

Supplementary Table S4. Detailing results shown in Fig. 4. Effects of increases in water N:P ratio on organisms growth rate (GR), defined as the biomass accumulation in function of time. ↑ = increases, ↓ = decreases.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
	Laboratory and stream mesocosm experiment	↓ GR	119
	microcosm	No conclusive effects	120
	microcosm	↓ GR	121

Supplementary Table S5. Detailing results shown in Fig. 4. Relationships of increases in water N:P ratio with ecosystem structure.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
La Caldera lake (Spain)	Field	Community composition	122
Scotland streams	Field	Community composition	123
Lakes	Field	Community composition	124
Lakes	Field	Community composition	125
Lakes	Field	Community composition	126
Lakes	Field	Community composition	127
World coastal areas, oceans and rivers	Review	Changes in species abundance	128
Lake Rusalka (Poland)	Field	Community composition	129
Lakes	Field	Community composition	130
	Microcosm	Community composition	131
	Microcosm	Community composition	132
Changliang River (China)	Field	Community composition	93
	Microcosm	Community composition	133
Lakes	Field	Community composition	134
Lakes	Field	Changes in species abundance	135
Dutch coastal areas	Field	Community composition	136
Izmir Bay	Field	Community composition	137
Lakes	Field	Community composition	103
Water reservoir (Brazil)	Field	Community composition	105
Freshwater	Mesocosm	Community composition	138

Supplementary Table S6. Detailing results shown in Fig. 4. Relationships of increases in water N:P ratio with ecosystem functional traits.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
Spain stream	Field	Changes in nutrient cycling	139
La Caldera lake (Spain)	Field	Changes in nutrient cycling	122
Louro Lagoon (Spain)	Field	Changes in ecosystem N ₂ -fixation	140
Lakes	Field	Changes in nutrient cycling	126
Lake	Field	Changes in ecosystem N ₂ -fixation	141
Lakes (Washington)	Field	Changes in ecosystem N ₂ -fixation	142
	Microcosm	Changes in nutrient cycling	133
Eel River (California)	Field	Changes in nutrient cycling	143
Spain stream	Field	Changes in nutrient cycling	139

Supplementary Table S7. Detailing results shown in Fig. 4. Relationships of increases in organisms N:P ratio with ecosystem structural traits.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
Lake	Field	Changes in species abundance and life stage	144
Alpine streams	Field	Changes in community composition	145
Lakes	Field	Changes in community composition	130
Caribbean region	Field	Changes in community composition	146
Lake	Field	Changes in species abundance and sexual form abundance within species	147
Antarctic ocean	Field	Changes in community composition	148

Supplementary Table S8. Detailing results shown in Fig. 4. Relationships of increases in organisms N:P ratio with ecosystem functional traits.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
Lake Eire	Field	Nutrient cycling	149
Mediterranean forest streams	Field	Nutrient cycling	130
	Microcosms	Changes in nutrient uptake and cycling	150
Lakes	Field	Changes in nutrient cycling	151
Lake	Field	Changes in nutrient cycling	152
Lakes	Field	Changes in nutrient cycling	125
Lakes	Field	Changes in nutrient cycling	126
Freshwater ecosystems	Metadata study	Changes in nutrient cycling	153
	Microcosm and mesocosm	Changes in nutrient cycling	154
Water reservoirs (Ohio)	Field	Changes in nutrient cycling	155
	Microcosm	Changes in nutrient cycling	156
Andean rivers	Field	Changes in nutrient cycling	157
Huanghai Sea	Field	Changes in nutrient cycling	158
Lakes	Field	Changes in nutrient cycling	76
Diverse streams (USA)	Field	Changes in nutrient cycling	159
Lake	Field	Changes in nutrient cycling	160 and 161
Lake	Field manipulation experiment	Changes in nutrient cycling	162
Lakes	Metadata study	Changes in nutrient cycling	163
Lakes	Metadata study	Changes in nutrient cycling	164
Lake	Field	Changes in nutrient cycling	165
Lake	Field	Changes in nutrient cycling	166
Rio "Las Marias" (Venezuela)	Field	Changes in nutrient cycling	167
Lake	Field	Changes in reproduction function	147

Supplementary Table S9. Detailing results shown in Fig. 4. Relationships of increases in organisms N:P ratio with organism growth rate (GR) defined as the biomass accumulation in function of time. ↑ = increases ↓ = decreases.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
Antarctic ocean	Field	↓ GR in intraspecific comparisons	168
Antarctic ocean	Field	No related in bacteria in interspecific comparisons	168
La Caldera lake (Spain)	Field	↓ GR	169
	Microcosm	No related	170
	Microcosm	↓ GR (when nutrients are no limiting)	171
	Microcosm	No conclusive relationships	172
	Microcosm	↓ GR	173
	Review metadata	↓ GR	174
Baltic Sea	Field	↑ GR	175
	Microcosm experiment	↓ GR	133
	Review metadata	↓ GR	20
	Microcosm	↓ GR	176
Lake	Field	↓ GR (when nutrients are no limiting)	177
	Microcosm	↓ GR	115
Lakes	Field	↓ GR	178
	Mesocosm	↓ GR	179
Lake	Field	↓ GR (when nutrients are no limiting)	180
La Caldera lake (Spain)	Field	↓ GR in phytoplanktos	181
La Caldera lake (Spain)	Field	No related in bacteria	181
	Review metadata study	↓ GR (when nutrients are no limiting)	182
	Microcosm	No related	183

Supplementary Table S10. Detailing results shown in Fig. 4. Relationships of organism's growth rate (GR), defined as the biomass accumulation in function of time, with ecosystem structural traits.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
Lake	Field	Community composition	184
	Mesocosm	Community composition	185
	Review	Changes in web community function	186

Supplementary Table S11. Detailing results shown in Fig. 4. Effects of atmospheric N deposition on soil/litter N:P ratio. ↑= increases, ↓= decreases.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
Northwest Germany	Field	↑ N:P	187
Netherlands	Field	↑ N:P	188
Denbighshire (Wales)	Field	↑ N:P	189
Great Britain grasslands	Field	No conclusive results	190

Supplementary Table S12. Detailing results shown in Fig. 4. Effects of increases in soil/litter N:P ratio on organisms N:P ratio. ↑= increases, ↓= decreases.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
	Metadata analysis	↑ N:P	191
	Greenhouse	↑ N:P	192
	Review	↑ N:P	193
	Common garden	↑ N:P	194
Soil toposequence	Field	↑ N:P	195
Meadows	Field	↑ N:P	196
	Common garden	↑ N:P	197
	Common garden	↑ N:P	198
	Metadata analysis	↑ N:P	191

Supplementary Table S13. Detailing results shown in Fig. 4. Effects of increases in soil N:P ratio on organisms growth rate (GR) defined as the biomass accumulation in function of time. ↑ = increases, ↓ = decreases.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
	Review	↓ GR	193
Grassland community	Common garden experiment	↓ GR	199
	Common garden	↓ GR	197
	Common garden	↓ GR	198

Supplementary Table S14. Detailing results shown in Fig. 4. Relationships of increases in soil/litter N:P ratio with ecosystem structural traits.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
Mount St. Helens (Washington)	Field and greenhouse	Changes in species abundance	200
Mount St. Helens (Washington)	Field	Community composition	201
Forest (Czech Republic)	Field	Decrease in species richness	202
Grassland (The Netherlands)	Field	Community composition	203
Grassland (The Netherlands)	Field	Decrease in species richness	204
Shrublands (Mongolia)	Field	Changes in species richness	25
Austria forest	Field	Community composition	205
	Metadata analyses	Community composition	196
New Zealand forest	Field	Community composition	206

Supplementary Table S15. Detailing results shown in Fig. 4. Relationships of increases in soil/litter N:P ratio with ecosystem functional traits.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
	Metadata analysis	Changes in nutrient cycling	191
Mount St. Helens (Washington)	Field	Changes in N ₂ fixation	201
Forest (Spain)	Field	Changes in nutrient cycling	207
	Microcosm	Changes in nutrient cycling	208
Meadows (Switzerland)	Field	Changes in nutrient cycling	209
Amazonian forest (French Guiana)	Field	Changes in nutrient cycling	210
Austria forest	Field	Changes in nutrient cycling	206
Forest (Australia)	Field	Changes in nutrient cycling	211
Steppe (Mongolia)	Field	Changes in plant nutrient uptake	212

Supplementary Table S16. Detailing results shown in Fig. 4. Effects of increases in organism's N:P ratio on organisms growth rate (GR). ↑= increases. ↓= decreases.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
	Metadata analysis	↓ GR (when nutrients are no limiting)	213
Tropical forest (Panama)	Field	↓ GR (when nutrients are no limiting)	214
	Common garden	↑ GR	215
	Metadata analysis	↓ GR (when nutrients are no limiting)	216
Fens (USA)	Field	↓ GR	217
	Review	↓ GR	26
	Common garden	↓ GR (when nutrients are no limiting)	218
	Microcosm	↓ GR	174
Forest (California)	Field and greenhouse	No relationships	219
	Review	↓ GR	220
	Common garden	↓ GR	221
	Review	↓ GR	222
	Metadata analysis	↓ GR	182
Panama	Field and common garden	↓ GR	197
	Microcosm	↓ GR	223
European wetlands	Field	↓ GR	224
	Common garden	↓ GR (when nutrients are no limiting)	225

Supplementary Table S17. Detailing results shown in Fig. 4. Relationships of increases in organisms N:P ratio with ecosystem structural traits.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
French forest	Field	Successional stages	226
China forest	Field	Community composition	227
North American wetlands	Field	Community composition	228
Argentina shrubland	Field	Increases diversity	229
	Review	Community composition	230
	Review	Community composition	231
Alaska plant communities	Field	Community composition	232
Australian Shrubland and forest	Field	Community composition	233
Tropical forest of Costa Rica	Field	Community composition	234
	Greenhouse	Community composition	235
	Metadata analysis	Community composition	236
	Microcosm	Community composition	237
Hawaiian forest	Field	Community composition	238
Belvidere Bog (Vermont)	Field	Changes trophic web structure	239

Supplementary Table S18. Detailing results shown in Fig. 4. Relationships of increases in organisms N:P ratio with ecosystem functional traits.

Species and/or community studies and pollutant sources	Study site	Main results	Reference
Colorado forest	Field	Nutrient cycling	240
European Sphagnum communities	Field	Nutrient cycling	241
Tropical forest (Panama)	Field	Water use-efficiency	96
	Greenhouse	Changes in the relationships between photosynthetic capacity and production	242
Wetland (New Zealand)	Field	Nutrient cycling	243
Belvidere Bog (Vermont)	Field	Changes in nutrient transfer throughout trophic web	239

Supplementary Table S19. Parameters used to produce the threshold plots in Fig. 5. The range of the parameter values were used to estimated uncertainty in model exceedance for the phosphorus and nitrogen thresholds. Note that the phosphorus fluxes correspond to Fig. 2 of this study.

Parameter	Value	Sensitivity	Description	Reference Number
P_w	6502:1	See P_{aw}	C:P mass ratio for wood	71
P_a	407:1	See P_{aw}	C:P mass ratio for active tissues	71
P_{aw}	3454:1	50%	C:P mean mass ratio for vegetation assuming 50:50 split of P_a and P_w	
P_s	50:1	50%	C:P mass ratio for soil carbon	244
NP_w	16:1	50%	N:P mass ratio for wood	71
NP_s	5:1	50%	N:P mass ratio for soil	245
$N_{deposition}$	Lower: 0.52 Upper: 2.98+0.27/2	Lower and upper bounds	Accumulation of N from atmospheric deposition (Pg N), (adjusted so that the estimate reflects the 5–10% actually used by plants) including a correction of 0.27/2 to account for reduced leaching losses (where the total 0.27 Pg N reduced leaching loss is split between $N_{deposition}$ and $N_{fixation}$, below)	7
$N_{fixation}$	Lower: 0.64 Upper: 2.87+0.27/2	Lower and upper bounds	Accumulation of N from biological fixation (Pg N), including a correction of 0.27/2 to account for reduced leaching losses	7
N_{total}	Lower: 1.16 Upper: 6.12	Upper and lower bounds	Total accumulation of $N_{deposition}$ and $N_{fixation}$ (Pg N)	7
P_{labile}	13.2	0.4 (lower bound only)	Size of labile P pool (Pg P) assuming 2–20% availability of the lower and upper total soil P pool in Fig. 1 (40–200 Pg P).	This study
P_{dust}	0.0031	None	Rate of mean of atmospheric dust deposition uncertainty (Pg P yr ⁻¹). Assumed constant for 21 st century accumulation.	3
$P_{fertilizer}$	0.024	None	Sum of industrial and manure P additions (Pg P yr ⁻¹). Assumed constant until 2050, then reduced to 30% for 2050 to 2099 for accumulation calculation	This study
$P_{weathering}$	0.01	10% increase over 100 years	Rate of release from weathering of parent material (Pg P yr ⁻¹) estimated as the mean of upper and lower bounds in Fig. 1, 0.002 and 0.02 (Pg P yr ⁻¹). Accumulation for 2099 assumes a 10% increase (0.1% per year) due to climate and enzymatic-related increases in weathering.	This study
$P_{leaching}$	0.014	None	Rate of leaching losses (Pg P yr ⁻¹).	246
$P_{landuse}$	0.022	Not included in threshold calculation (approx. equal to P_{rivers})	Rate of production from land use change (Pg P yr ⁻¹).	
P_{rivers}	0.0325	Not included in threshold calculation (approx. equal to $P_{landuse}$)	Rate of loss to rivers (Pg P yr ⁻¹). Mean of 19 and 46 PgP yr ⁻¹ in Fig. 2.	
$P_{occlusion}$	0.002	None	Rate of P bound to soil and unavailable to plants (Pg P yr ⁻¹).	246

Notice that for the estimates in change in P and N demand, the fluxes are calculated over a 100 year time span and are compared with changes in terrestrial carbon over the same time period. Because the accumulation of carbon is quite non-linear due to increasing CO₂ fertilization effects a per year flux could be misleading.

Supplementary Table S20. List of models available from the PCMDI node of the Earth System Grid Federation.

The list represents only those models where both soil and vegetation carbon stocks were available. The RCP simulations begin in 2006 and with all model simulations edited to end in common year 2099. Litter and product pool carbon were not available as separate variables for all models and it was assumed in these cases that either the litter carbon pool was already merged with soil carbon, or that land-cover change was not included in the model simulation. The ensemble mean was calculated in cases where more than one model simulation was provided.

Model ID	Model Name	Ensemble (n)	RCP 2.6			RCP 8.5		
			Veg+Soil	Litter	Products	Veg+Soil	Litter	Products
1	CanESM2	5	✓	✓		✓	✓	
2	CCSM4	6	✓	✓	✓	✓	✓	✓
3	CESM1 BGC	1				✓	✓	✓
4	CESM1 CAM5	3	✓	✓	✓	✓	✓	✓
5	CESM1	3	✓	✓	✓	✓	✓	✓
	WACCM							
6	CMCC CESM	1				✓		
7	GFDL ESM2G	1	✓		✓	✓		✓
8	GFDL ESM2M	1				✓		✓
9	HadGEM2 CC	3				✓		✓
10	HadGEM2 ES	4	✓		✓	✓		✓
11	INMCM4	1				✓		✓
12	IPSL CM5A LR	4	✓	✓	✓	✓	✓	✓
13	IPSL CM5A MR	1	✓	✓	✓	✓	✓	✓
14	IPSL CM5B LR	1				✓	✓	✓
15	MIROC ESM CHEM	1	✓	✓	✓	✓	✓	✓
16	MIROC ESM	1	✓	✓	✓	✓	✓	✓
17	MPI ESM LR	3	✓	✓		✓	✓	
18	MPI ESM MR	1	✓	✓		✓	✓	
19	NorESM1 ME	1	✓	✓		✓	✓	
20	NorESM1 M	1	✓	✓		✓	✓	
21	SP CCSM4	1				✓	✓	✓

Supplementary Table S21. Detailing the data used to update the phosphorus cycle shown in Figure 2.

Study Type	P fluxes in Tg yr ⁻¹ and stocks in Tg	Reference
Review and modeling data	Global P deposition 0.56 (oceans)	3
Review	Global P deposition 3 (continents), 0.3 (oceans)	4
Review	Terrestrial fluxes to ocean 19 Dissolved P in Ocean surface 2600 Ocean biota P content 50 Dissolved P in Ocean deep waters 80000 Annual coast detrital P 19 P content in terrestrial plants 2400-3000 Annual P extracted from mines 12-17 Plants uptake 600 P in litter 600 Annual P rock weathering 2-20	45
Review	Ocean biota 50-140	67
Review	Commercial fertilizer application 14.2 Livestock slurry plus crop manure application as fertilizers 9.8	68
Review and modeling data	Terrestrial fluxes to ocean 46 Human driven P leaching from land 13.5-25 Fertilizer leaching 5 Land use 20 Annual P extracted from mines 17	70
Review	Annual P sediment in deep Ocean 4.7-6 (2-3 from natural origin and 2-3 from human activities) Total P in soils 120000 Land use 20 Plants P uptake 200 P in litter 200 P in sedimentary reservoir 8400000000	247
Review	P in low latitude croplands 9.81-11.61 P in Mid and high latitude croplands 11.99-14.19	248
Review	Terrestrial fluxes to ocean 46 P in aerosols 3 Annual P deposited in coastal sediments 46 P dissolved in deep ocean waters 120000 P in terrestrial plants 500-3000 P in terrestrial animals 30-50 P in humans 3 P in atmospheric deposition 3-3.2 Stable organic P in soils 600-7400	249
Review	Mineable P reserves (economic viable with current prices) 1400-3200 (potentially exploitable) 4400-8800	250
Review	P atmospheric deposition in oceans 1 Terrestrial fluxes to ocean 22 Human driven P leaching from land 13.5 Total terrestrial fluxes to ocean 22 Fluxes to ocean of human origin 13.5 Annual P accumulated in deep ocean sedimentary areas 4.7 Annual P fluxes in ocean 100	251

Review	Dissolved P in Ocean surface 2700 Ocean biota P content 140 Dissolved P in Ocean deep waters 87000 P in sedimentary reservoirs 4000000000 Annual rock weathering 10-30 Atmospheric P deposition on oceans 1 Atmospheric P deposition on continents 3.2 Annual P mined 19.8 Annual P in fertilizers 17 Total P in soils 200000 Total P in terrestrial plants 3000	252
Experimental study	Labile soil P 2-20% of total soil P Dissolved P-immediately available to plants 1-4% of total soil P	253
Experimental study	Labile soil P 2-20% of total soil P Dissolved P-immediately available to plants 1-4% of total soil P	254
Review	Stable inorganic P in soil 36000	255

Supplementary Methods

Estimating nutrient demand for the changes in vegetation and soil carbon stocks between 2000 and 2099

We estimated the change in demand for phosphorus and nitrogen considering changes in vegetation and soil carbon stocks projected by the C4MIP and CMIP5 earth system models to occur between the years 2000 and 2099, after applying C:P and N:P ratios from a literature survey to active tissues (leaves and fine roots), wood, and soil carbon pools. The C4MIP and CMIP5 models were used in the Fourth and Fifth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). After estimating global phosphorus and nitrogen demand, the change in demand for phosphorus and nitrogen was regionalized from the original gridded data for CMIP5 or based on land area and known fractional distributions of global biomass stocks²⁵⁶ in the case where gridded data were not available for the C4MIP models. To estimate nutrient demand for croplands, we used cereal-crop yield projections from the Millennium Ecosystem Assessment (MA) report²⁵⁷ implementing a similar stoichiometric approach as used for the earth system model analysis (both described in detail below).

A sensitivity analysis was also carried out to evaluate C:P and N:P ratio uncertainties, assuming that plants have some adaptive flexibility, including changes in nutrient resorption efficiency²⁵⁸ as resources become progressively limiting by adjusting the ratios by 50%, based on experimental evidence²⁵⁹ and the range of uncertainty. In addition, we modified the rate of phosphorus release from weathering of parent material assuming sensitivity to changes in climate or sensitivity to changes in the rate of turnover of immobilized phosphorus via CO₂-enhanced root exudation of the phosphatase enzyme²⁶⁰, or from potentially faster rates of organic matter decomposition from phosphorus stored in high-latitude soils²⁶¹. The results from the sensitivity analysis showed that the estimate in the change in N and P demand were a much smaller source of uncertainty than the assumptions for the nutrient supply. The labile-phosphorus pool exists as an additional source of uncertainty because while it represents phosphorus that can easily move among plants, microbes, and soluble and mineralized organic pools³², field observations demonstrate much of this labile-phosphorus pool is unavailable for increased plant uptake because it is immobilized in microbial biomass. To address this uncertainty, we assumed for the standard scenario that this P pool was unavailable, but provided an alternative scenario where we assumed that the pool was available for plant uptake. Following the approach of Hungate *et al.*⁷, for nitrogen, only net fluxes of nitrogen from increased nitrogen deposition and fixation were considered.

The values used for the nutrient ratios, nutrient inputs and pools, and assumptions for the regionalization of the C4MIP global values are presented in Table S2. First, the potential change in carbon stock between the years 2000 (2006 for CMIP5) and 2099 was estimated for vegetation and soils, in absence of nutrient limitation:

$$\Delta_{Cveg} = Cveg_{2099} - Cveg_{2000} \quad (1)$$

$$\Delta_{Csoil} = Csoil_{2099} - Csoil_{2000} \quad (2)$$

For the standard scenario, fixed, global C:P and N:P ratios from literature were used to scale changes in vegetation and soil phosphorus and nitrogen nutrient demand from the potential change in carbon stocks (Table 1):

$$\Delta_{Pveg} = \Delta_{Cveg} P_{aw} \quad (3)$$

$$\Delta_{Nveg} = \Delta_{Pveg} NP_w \quad (4)$$

$$\Delta_{Psoil} = \Delta_{Csoil} P_s \quad (5)$$

$$\Delta_{Nsoil} = \Delta_{Psoil} NP_s \quad (6)$$

Based on these estimates for the change in phosphorus and nitrogen, we derived an independent value for vegetation C:N mass ratio of 221 and a soil C:N mass ratio of 8.5, which was close to observed ratios^{7,71} and confirms the consistency of the choice of C:P and N:P ratios with previous studies. For example, in the study of Hungate et al.⁷ a vegetation C:N ratio of 200 and a soil C:N ratio of 15 was used to estimate N demand from changes in carbon stocks.

For C4MIP, where only the global values were available, the global nutrient demand was separated into two regions by partitioning the change in vegetation carbon (C_{veg}) and the related phosphorus and nitrogen demand as 55% to tropical and 45% to extratropical biomass²⁵³. For soils in both CMIP experiments, we considered mineral carbon only (excluding peatlands), and in C4MIP separated the change in global soil-carbon stock to 10.5% tropical (based on biome area in Zhao and Running, 2010²⁶²), and 89.5% extratropical.

The total global and regional terrestrial phosphorus and nitrogen demand change was estimated as the sum of the soil and vegetation nutrient demand:

$$\Delta_{Ptotal} = \Delta_{Pveg} + \Delta_{Psoil} \quad (7)$$

$$\Delta_{Ntotal} = \Delta_{Nveg} + \Delta_{Nsoil} \quad (8)$$

Four socio-economic development projections of cereal-crop yields for the year 2050 from the Millennium Ecosystem Assessment (MA)²⁵⁷ were used to estimate future phosphorus and nitrogen demand. In the Millennium Ecosystem Assessment, an Integrated Assessment model was used to estimate future crop yields based on projections of gross domestic product (GDP), population growth and other variables from their relationships with food production. To reduce uncertainties in our stoichiometric approach for estimating crop-phosphorus demand, we calculated a global cropland C:P ratio from more detailed crop-based assessments of global total food production phosphorus demand

(12.3 Tg P yr⁻¹) from MacDonald et al.⁶⁸ (2011) and nitrogen demand (88.1 Tg N yr⁻¹ or 55% of 148 Tg N yr⁻¹) from Liu et al.²⁶³. Using the year 2000 global food production from MA of 1568.7 Tg C yr⁻¹ (including cereals, maize, rice, tubers/roots, oil crops, and pulse crops) resulted in ratios of 127:1 for C:P and 18:1 for C:N; these ratios were then used to estimate nutrient demand in the four 2050 scenarios.

Estimating nutrient supply for the changes in vegetation and soil carbon stocks between 2000 and 2099

The change in nitrogen supply was estimated from changes in the accumulation of plant-available N-deposition (where only 5-10% of total deposited nitrogen becomes plant available) and N-fixation (where Hungate et al.⁷ assumed a low (10%) and high (45%) scenario for increased N-fixation under elevated CO₂), while accounting for declines in leaching from increased plant uptake, following the approach of Hungate et al.⁷. We split the global estimate of N-deposition to 80% extratropical and 20% tropical¹⁰, while N-fixation was split based on observed relative biome contributions to global N-fixation as estimated by Cleveland et al.²⁶⁴, with 50% occurring in the tropics, 50% in extratropics. These assumptions led to a global increase from 2000-2099 in plant available nitrogen between 1.2 to 6.1 Pg N and an increase of 0.7-3.9 Pg N for extratropical and 0.4 to 2.1 Pg N for tropical regions. We did not consider changes in nitrogen supply for croplands and assumed that nitrogen demand is relatively unconstrained by the large supply of atmospheric N₂ available to sustain the Haber-Bosch process (fertilizer production) into the future¹.

The change in phosphorus supply was estimated from the global phosphorus pools and fluxes presented in Fig. 2. Previous observations and modelling have shown that phosphorus uptake tends to be less than measured available labile phosphorus, despite terrestrial phosphorus limitation being observed across many ecosystems – as evidenced by high C:P ratios and from fertilization studies^{8, 62,265}. The dynamics of the labile-phosphorus pool remain quite uncertain but it is considered to be unavailable to plants due to competition with microbial uptake^{32,266}. To address this uncertainty, in our standard scenario we assumed that the labile pool was inaccessible and instead assumed that the net accumulation of inputs of phosphorus during 2000–2099 resulted from global dust inputs (3.1 Tg P yr⁻¹), weathering (11.0 Tg P yr⁻¹), and increased turnover or access to deeper soil-phosphorus reserves²⁶¹ assuming a highly uncertain annual increase in access to these pools of 0.1% per year²⁶⁷ or 10% over 100 years. Losses of soil phosphorus were calculated for leaching (32.5 Tg P yr⁻¹), wind erosion (3.0 Tg P yr⁻¹), and occlusion (2.0 Tg P yr⁻¹), the process of phosphorus adsorption into clay structure,^{267,268} and precipitation in salts of iron and calcium), assuming that present-day rates remain constant. All global phosphorus weathering and dust inputs, and leaching losses were scaled to regional fluxes by the regional land fractions (i.e., 11% for tropics and 89% for extratropics). For the labile-phosphorus pool, the global value was first estimated as 13.2 Pg P, the product of the mean of the low and high values total P pool values presented in Figure 2 (40-200 Pg P, average 120 Pg P) and the percentage of this pool

assumed to be labile P (2-20%, average 11%). The global value was weighted by both land area and by regional soil-phosphorus concentrations (28 mg P kg⁻¹ soil for tropical biomes and 43.6 mg P kg⁻¹ soil for the extra-tropical system) as compiled by Johnson et al.²⁶⁶. The following equation estimates the net change in global terrestrial phosphorus supply for 100 years (y) assuming a 10% increase in weathering rates over this time period.

$$\Delta P_{global supply} = y * (P_{weathering} + P_{dust} + P_{fertilizer}) - y * (P_{leaching} + P_{occlusion} + P_{aerosols}) \quad (9)$$

Because of uncertainties in changes in future phosphorus fertilizer additions for croplands^{269,270}, we took a different approach. We assumed that the rate of phosphorus demand increased annually at an exponential rate from the estimated phosphorus demand from crop yield in 2000 and crop yield in 2050. Integrating the phosphorus demand over this time period yielded the total phosphorus that would need to be mined or applied from manure to sustain global food production (cereals and pulse crops, oil and roots/tubers) for the next 50 years. The range of phosphorus extraction was compared to the upper and lower mineable-phosphorus estimates in Fig. 2 (1400 to 3200 Tg P) to identify the approximate year when 50% depletion would occur. Based on the MA projections for regional changes in cereal crop yields (6 economic zones; OECD, Asia, Russia, Sub-Saharan Africa, and Northern Africa and Middle East were considered), we estimated the phosphorus demand for 2000 and 2050 (with a C:P ratio of 127:1) and calculated the present-day phosphorus inputs from fertilizer and manure from the gridded data of Potter and Ramankutty²⁷¹.

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