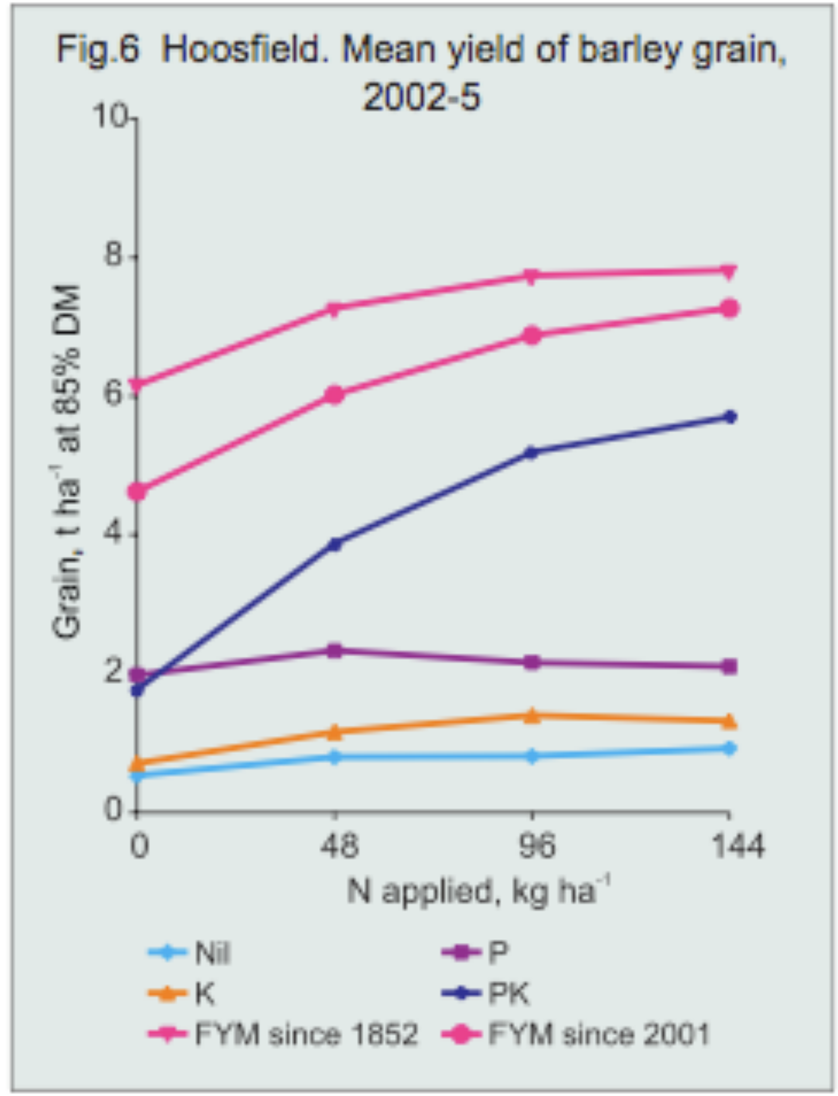
Broadbalk Continuous Wheat
Started in 1843



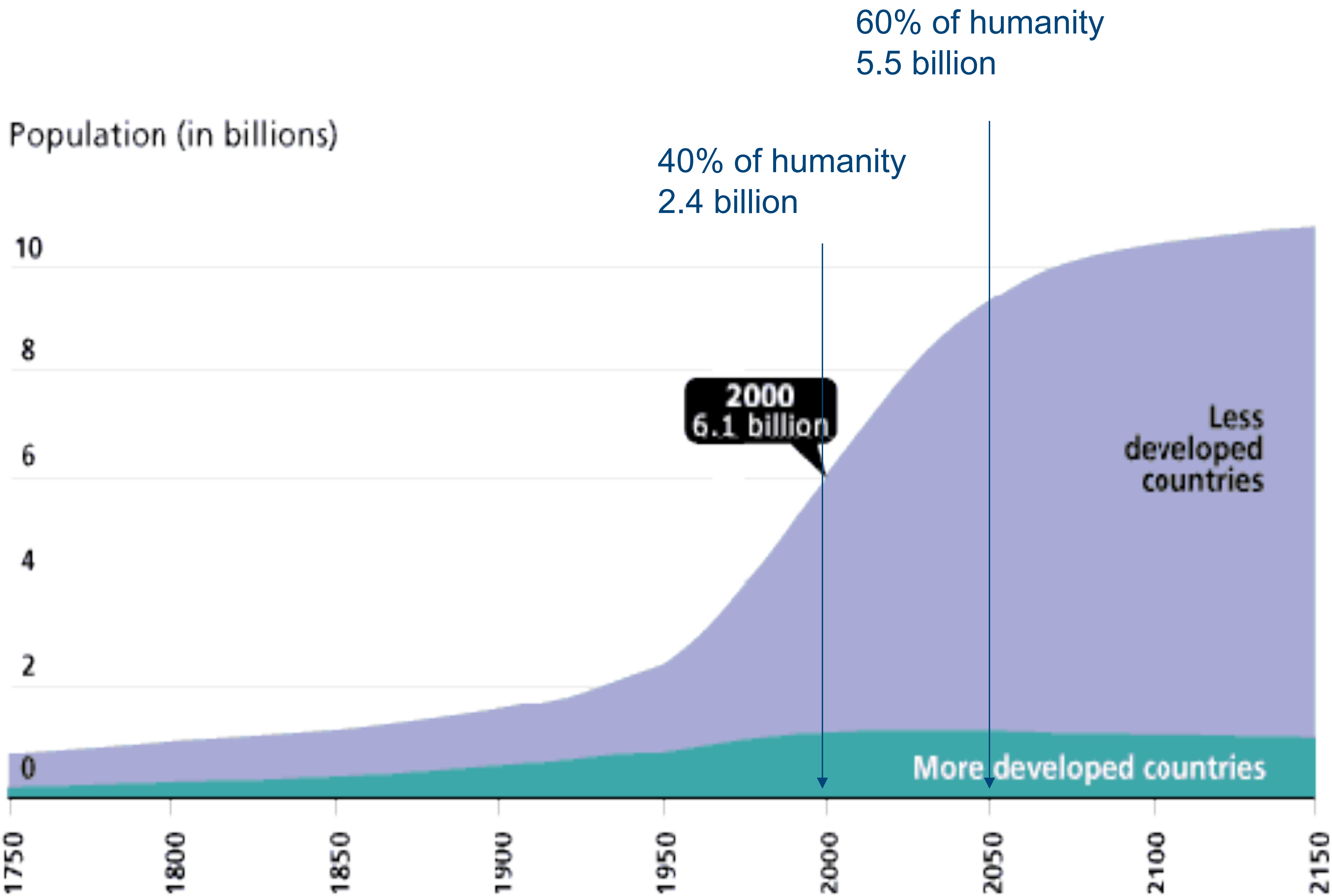
Hoosfield spring barley
Started in 1852

How much of humanity's "existential dependence" on synthetic N can be attributed to P?

"And so the question about the most importan
invention of the twentieth century—important
in the most fundamental existential terms for
the largest number of people– elicits almost
uniformly a wrong answer, as nothing comes
close to the Haber Bosch synthesis of ammon

Vaclav Smil

University of Manitoba



60% of humanity
5.5 billion
Population (in billions)
40% of humanity
2.4 billion
10
8
6
4
2
0
2000
6.1 billion
Less developed countries
More developed countries
1750
1800
1850
1900
1950
2000
2050
2100
2150

Saturating and topping up soil P vs. the danger of hitting the "change point"

Topping up P

- In order to build up soil P to the critical value for crop production, it may be necessary to accept a lower recovery of added P for a number of years. Once the critical level is achieved in many arable cropping systems, the amount of P required to maintain it is often similar to that removed in the (very high P-use efficiency).
- The optimum soil-P status is reached when the optimum P-application rate equals crop P removal (Sibbesen and Sharpley 1997)

TABLE A1.11

P offtake 1856–2001 by arable crops growing on plots that had received no P or a total of 1 410 kg ha^{-1} from 1856 to 1901 and none since, Exhaustion Land, Rothamsted

Period and number of years	Cropping[1]	Plot 7 (NPK)[2] P offtake		Plot 5 (N)[2] P offtake		Difference in annual P offtake
				(kg ha^{-1})		
		Total	Per year	Total	Per year	
1856–1875 20	Wheat	160	8.00	93	4.65	3.35
1876–1901 26	Potatoes	169	6.50	45	1.73	4.77
1902–1940 39	Barley	235	6.02	131	3.36	2.66
1941–1948 8	Barley	72	9.00	39	4.90	4.10
1949–1974 26	Barley	248	9.54	116	4.46	5.08
1976–1991 16	Barley	135	8.44	65	4.06	4.38
1992–2001 10	Wheat	96	9.63	42	4.18	5.45

[1] P in winter wheat and spring barley grain plus straw and in potato tubers.

[2] Except 1902–1940 when no N was applied.

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[1] P in winter wheat and spring barley grain plus straw and in potato tubers.

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1115

531

P recovery of fertilizer 584 or 41% (difference) or 79% (balance)

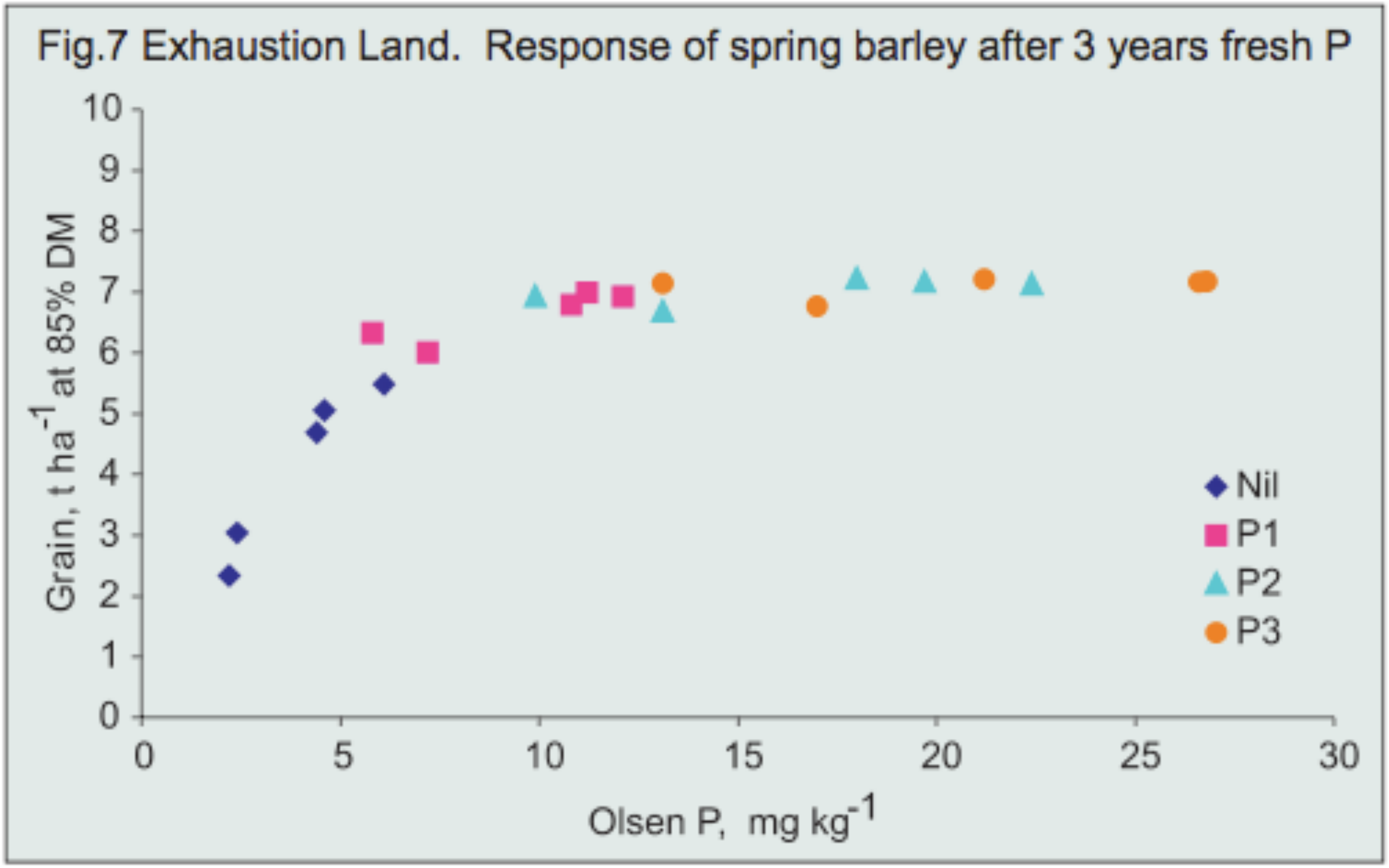


Fig.7 Exhaustion Land. Response of spring barley after 3 years fresh P
Grain, t ha-1 at 85% DM
Olsen P, mg kg-1
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
Nil
P1
P2
P3

TABLE 11

Relationship between P balance at the end of each treatment period and the change in soil P fractions, Exhaustion Land, Rothamsted

Plot, treatment & period	P balance	Change in firt five P fractions,kg P ha^{-1}					
		Resin	0.5 M $NaHCO_3$	0.1 M NaOH	1 M NaOH	0.5 M H_2SO_4	Total change
	(kg ha^{-1})				(kg P ha^{-1})		
No P							
1903–1993	-300	-49	-20	-195	-82	-19	-365
FYM applied							
1876–1901	1 035	193	129	133	107	335	917
Not applied							
1903–1993	-752	-259	-123	-159	-112	-164	-817
P fertilizer applied							
1856–1901	1 222	158	126	79	7	270	640
Not applied							
1903–1993	-644	-234	-138	-114	45	-253	-694

Source: Adapted from Blake *et al.* (2003).

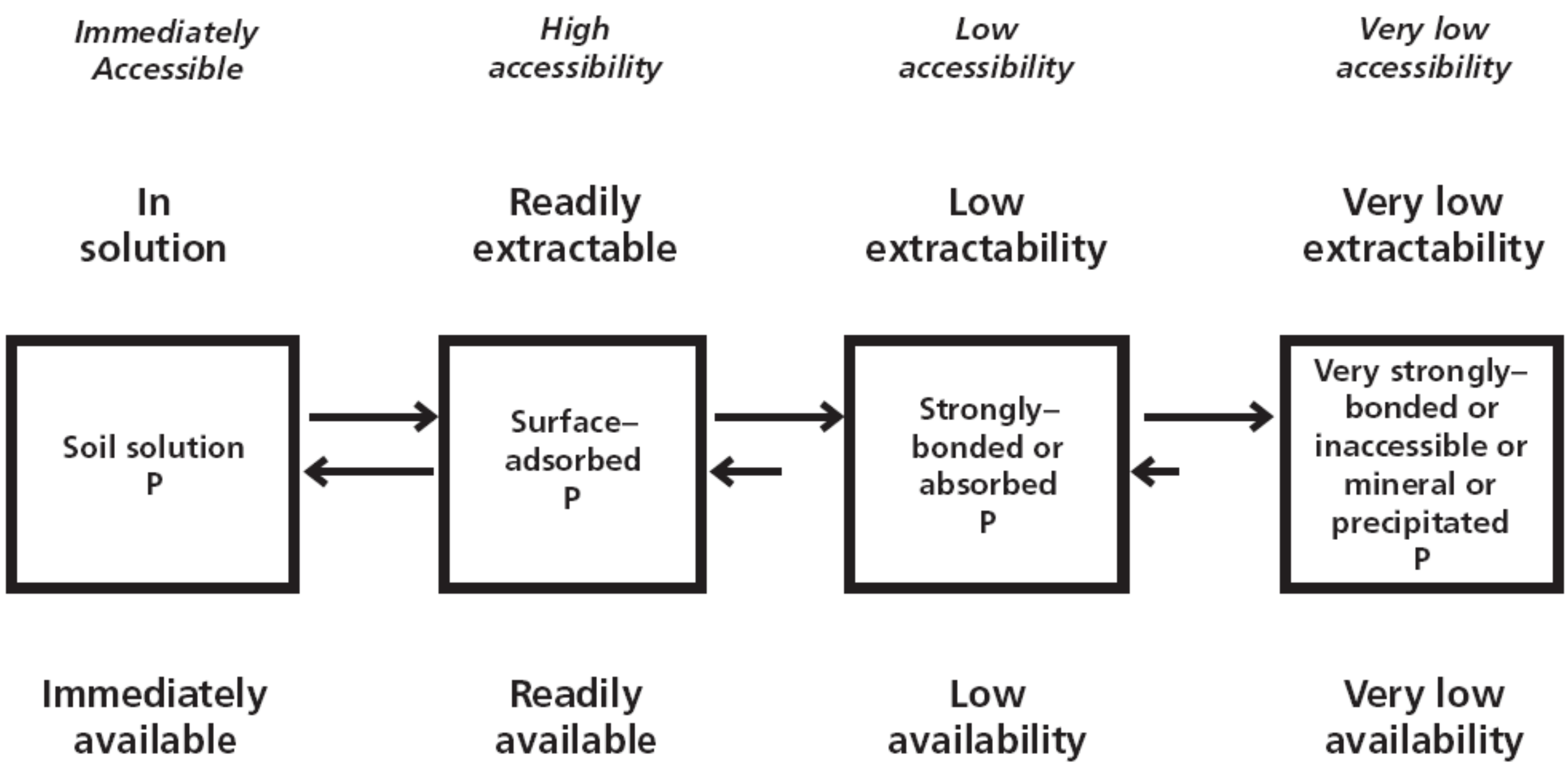


FIGURE 3
Conceptual diagram for the forms of inorganic P in soils categorized in terms of accessibility, extractability and plant availability

Syers, Johnston, Curtin 2008

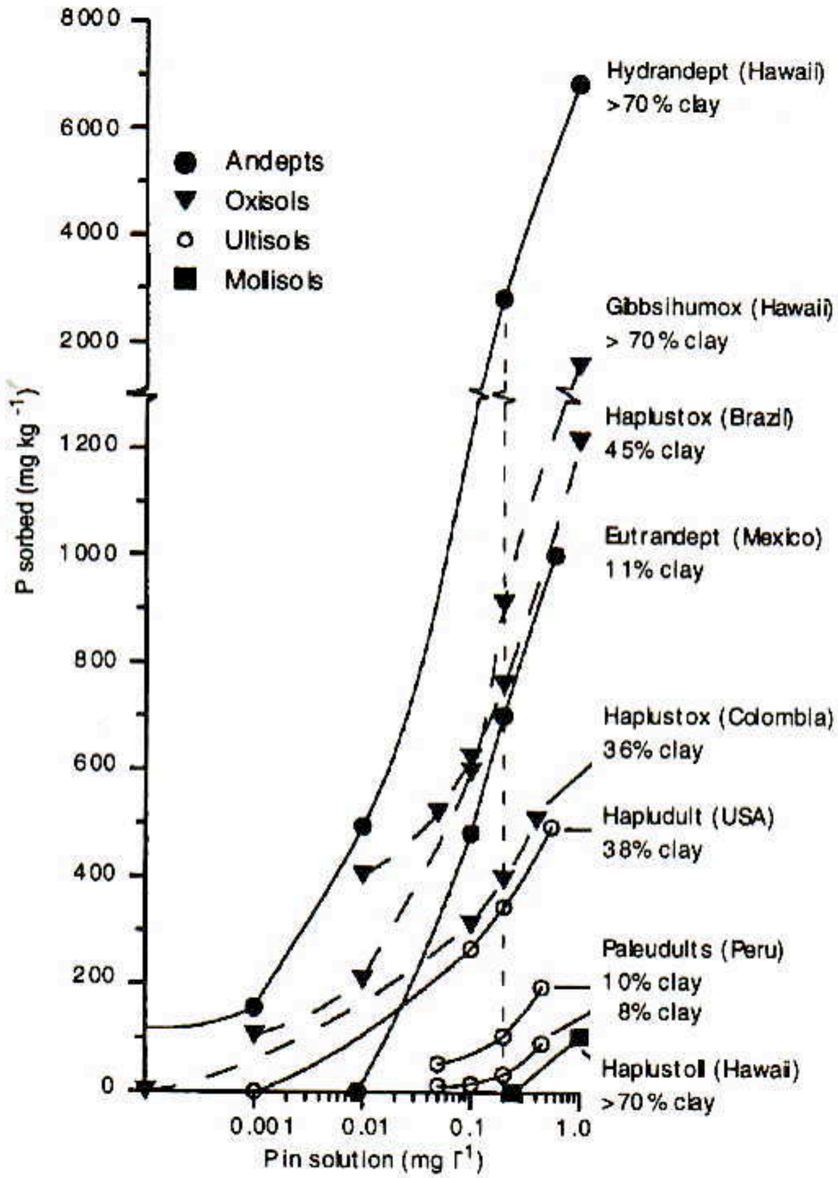


Figure 2. Examples of P sorption isotherms determined by the method of Fox and Kamprath (1970). Source: Sanchez and Uehara (1980).

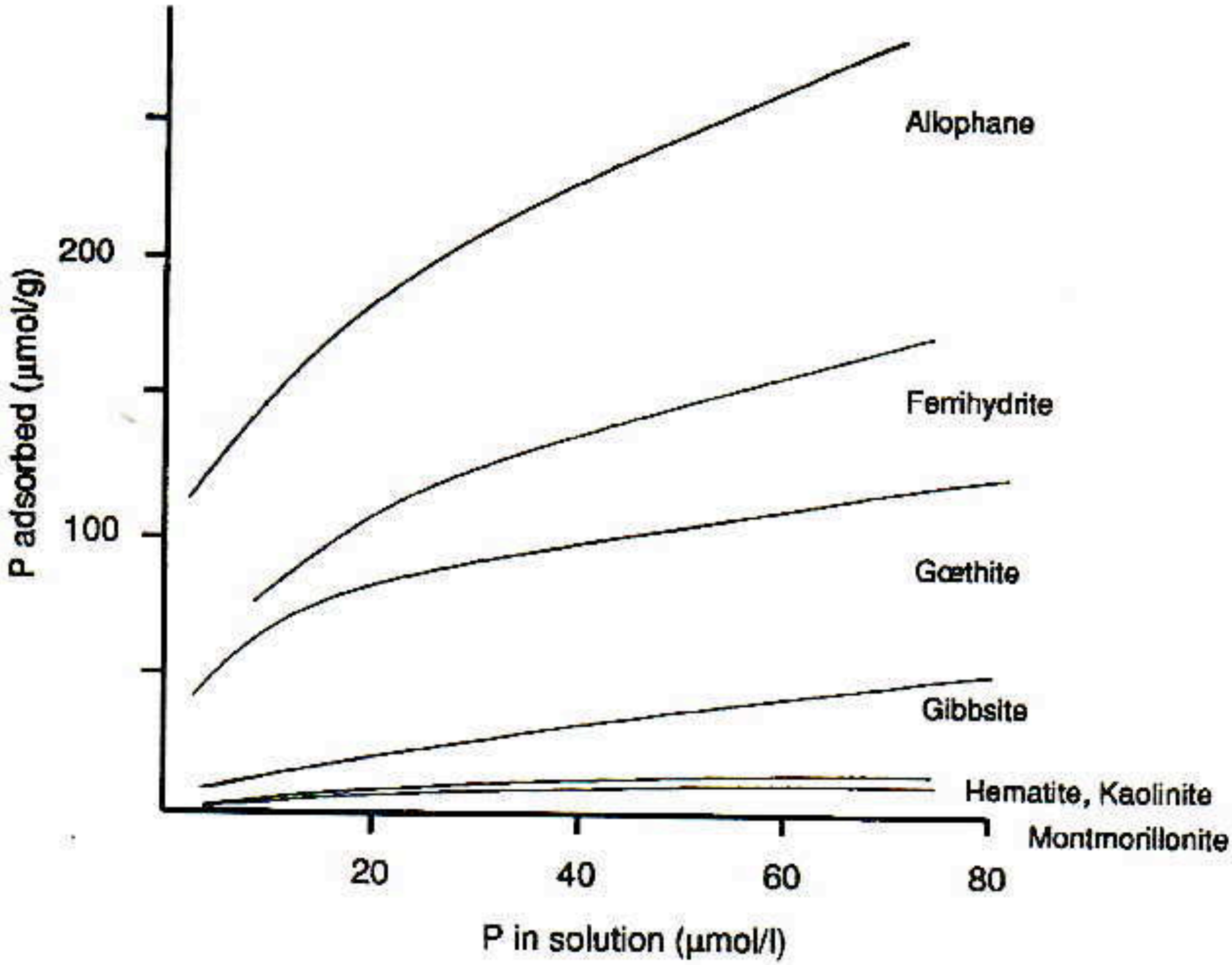


Figure 1. Sorption of P on various minerals (Sollins, 1991).

The "change point"

- An inflection point where P measured in field drainage waters (or in laboratory $CaCl_2$ soil extracts) shows a distinct linear increase with increasing Olsen-P (bicarbonate P).

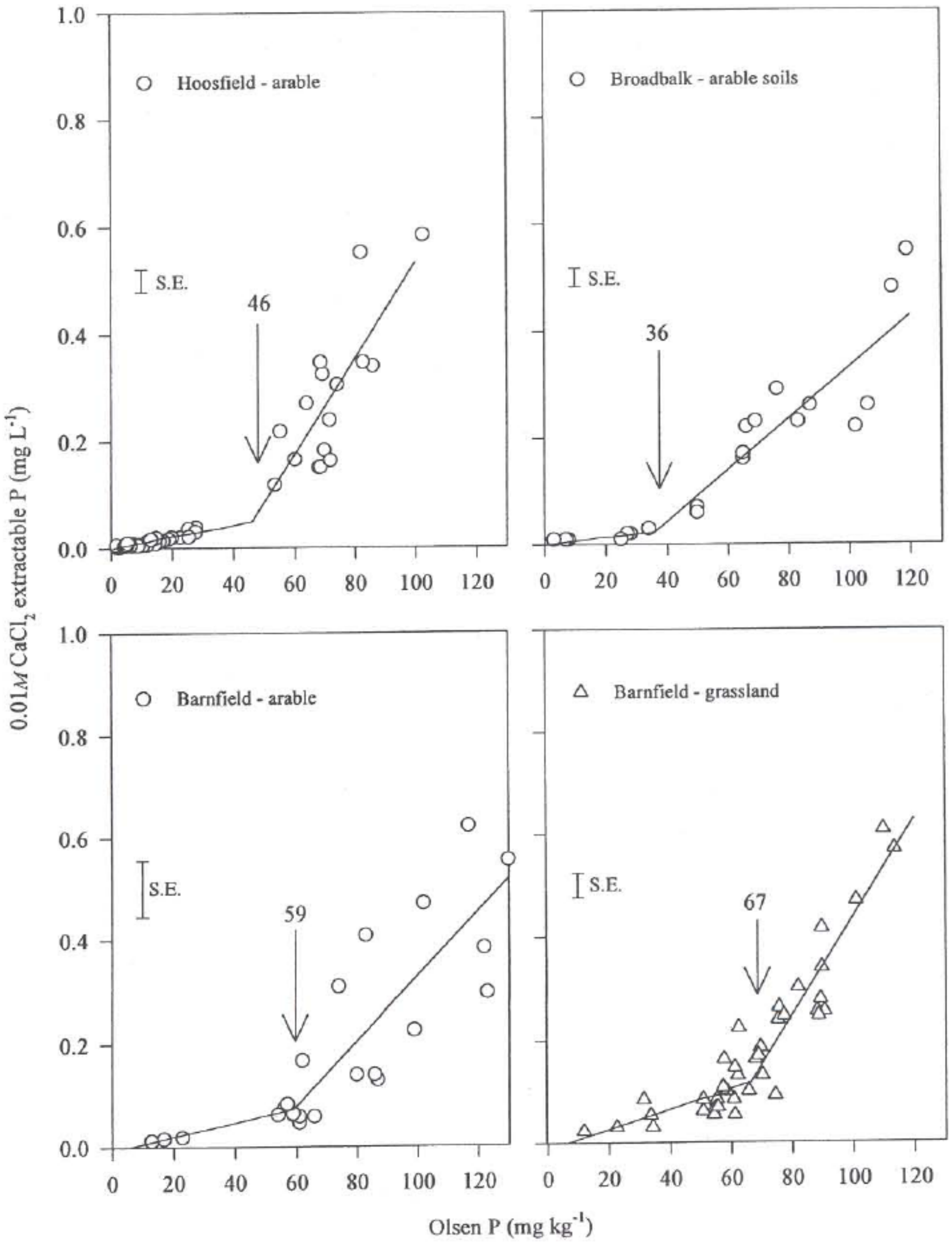


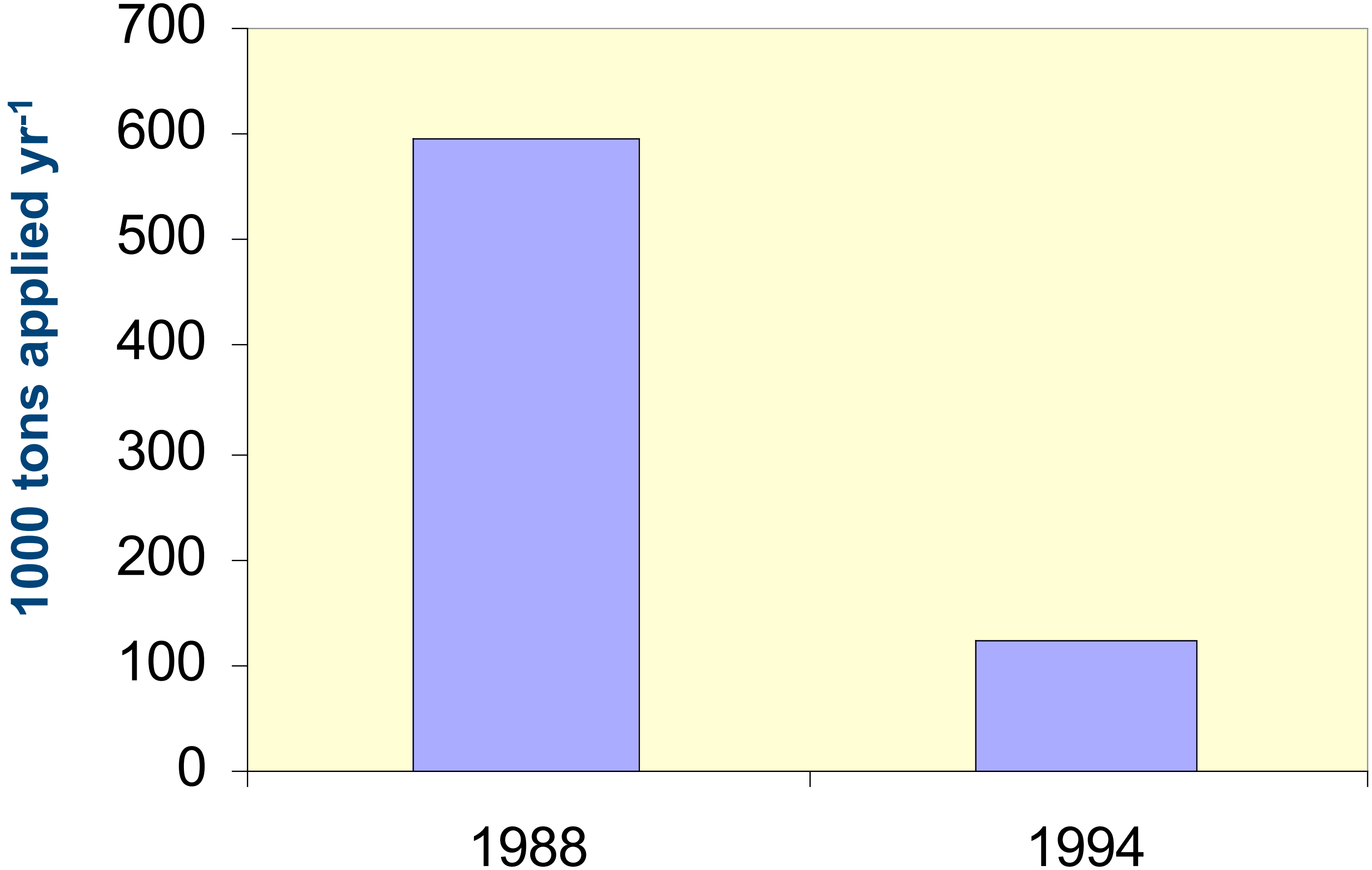
Fig. 1. Relationship between concentrations of $CaCl_2$-P and Olsen P of the Hoosfield, Broadbalk and Barnfield arable soils and the Barnfield grassland soil (split line model fitted shows the change point as indicated by the arrow; S.E. = standard error).

Change Point and topping up

- Does the “optimum soil P status” maintain soils anywhere near the change point?
- How easy is the proximity to the two states managed by farmers?
- Do soils below the change point still present a significant eutrophication hazard?

The dependence of organic agriculture on historic P fertilization or net transfers of fertilizer P in manure

Change in fertilizers applied in Cuba following the break-up of the Soviet Union



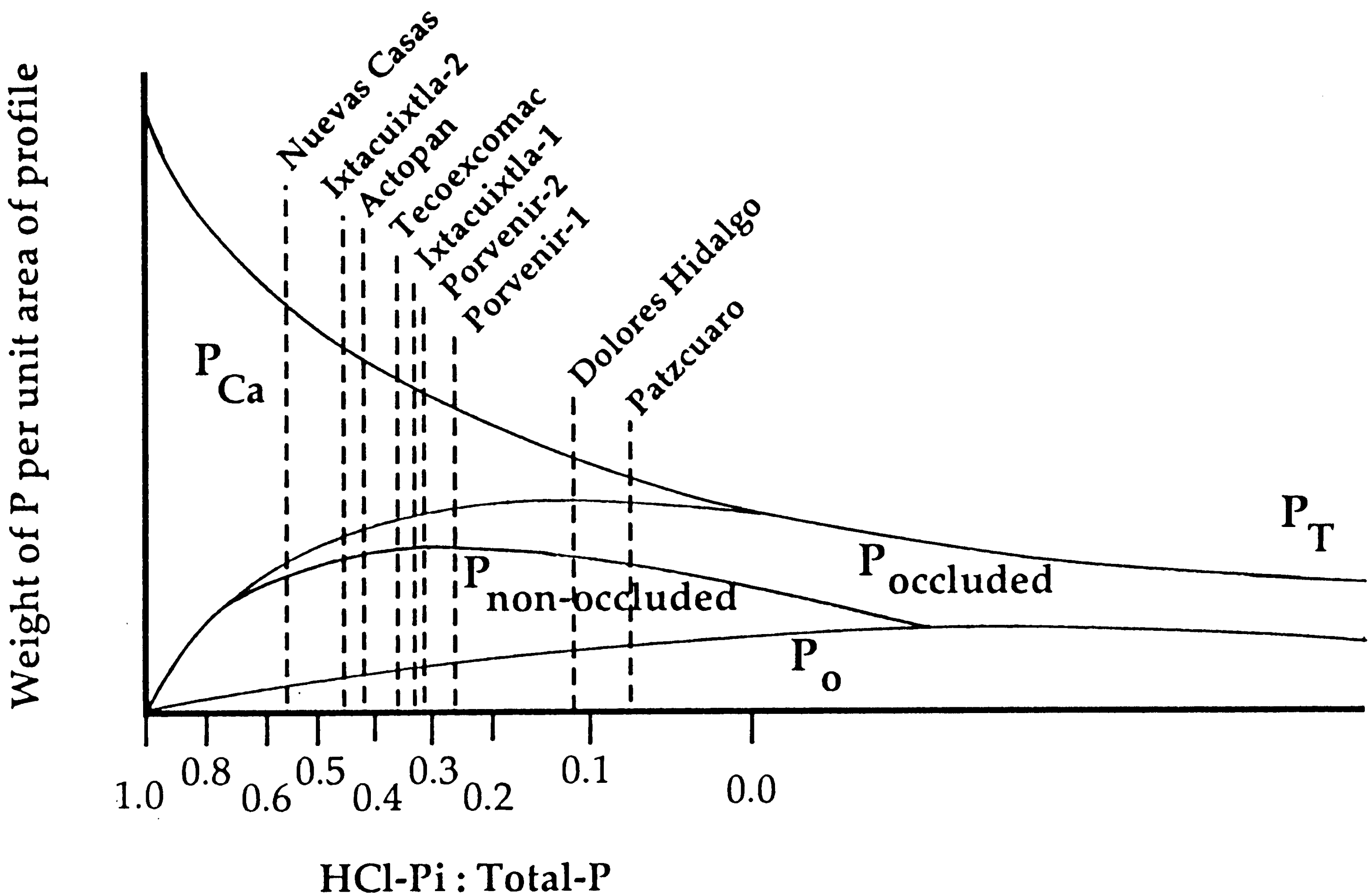
If nutrient returns of P in organic matter (livestock or humanure) were improved, and P losses were reduced, could endogenous P supplies be used to top up?

Alternative agroecosystem models

P inputs	**kg ha^{-1} yr^{-1}**
Soil mineral weathering	0.05 - 1.0 (5.0 possible)
Atmospheric deposition	0.07 - 1.7
Total	0.12 - 2.7

Other P inputs that may be significant in particular ecosystems include: pollen, volcanic ash, fossil fuel combustion (e.g., fly ash), forest fires, ocean spray

Newman (1995)


Nuevas Casas
Ixtacuixtla-2
Actopan
Tecoexcomac
Ixtacuixtla-1
Porvenir-2
Porvenir-1
Dolores Hidalgo
Patzcuaro
P_{Ca}
P_T
$P_{occluded}$
$P_{non\text{-}occluded}$
P_o
Weight of P per unit area of profile
1.0
0.8
0.6
0.5
0.4
0.3
0.2
0.1
0.0
HCl-Pi : Total-P

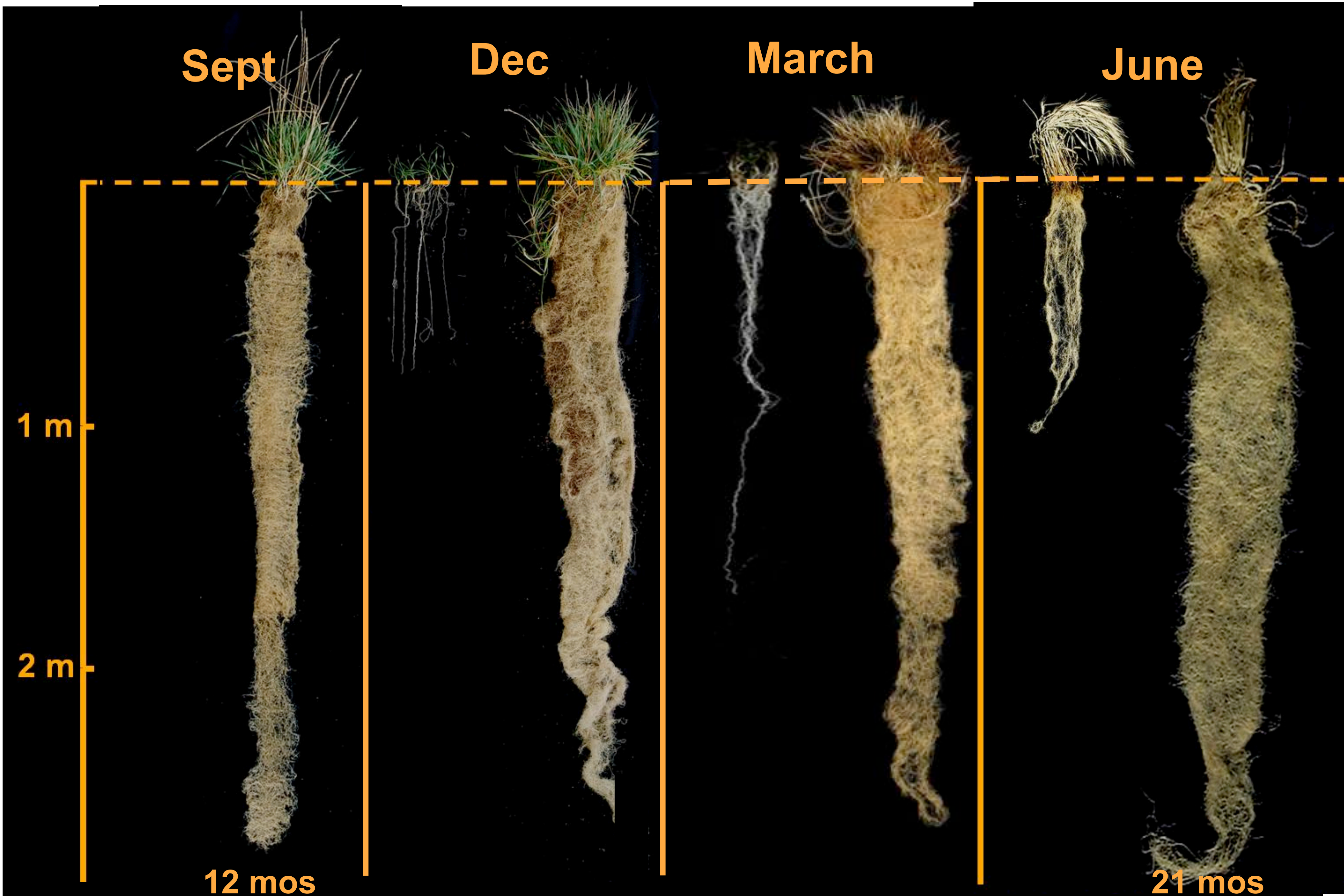
P inputs from weathering

Reference or site	kg P ha^{-1} yr^{-1}
Newman--review (1995)	0.05-1 (5 possible)
Smil (2000)	1.3
Hopi continuous maize (P in harvest)	2.2
Hayed prairie meadow (Glover)	5.9
Broadbalk continuous wheat, U.K.	3.7
Park Grass perennial meadow	5.3

P export in harvests from fertilized agriculture

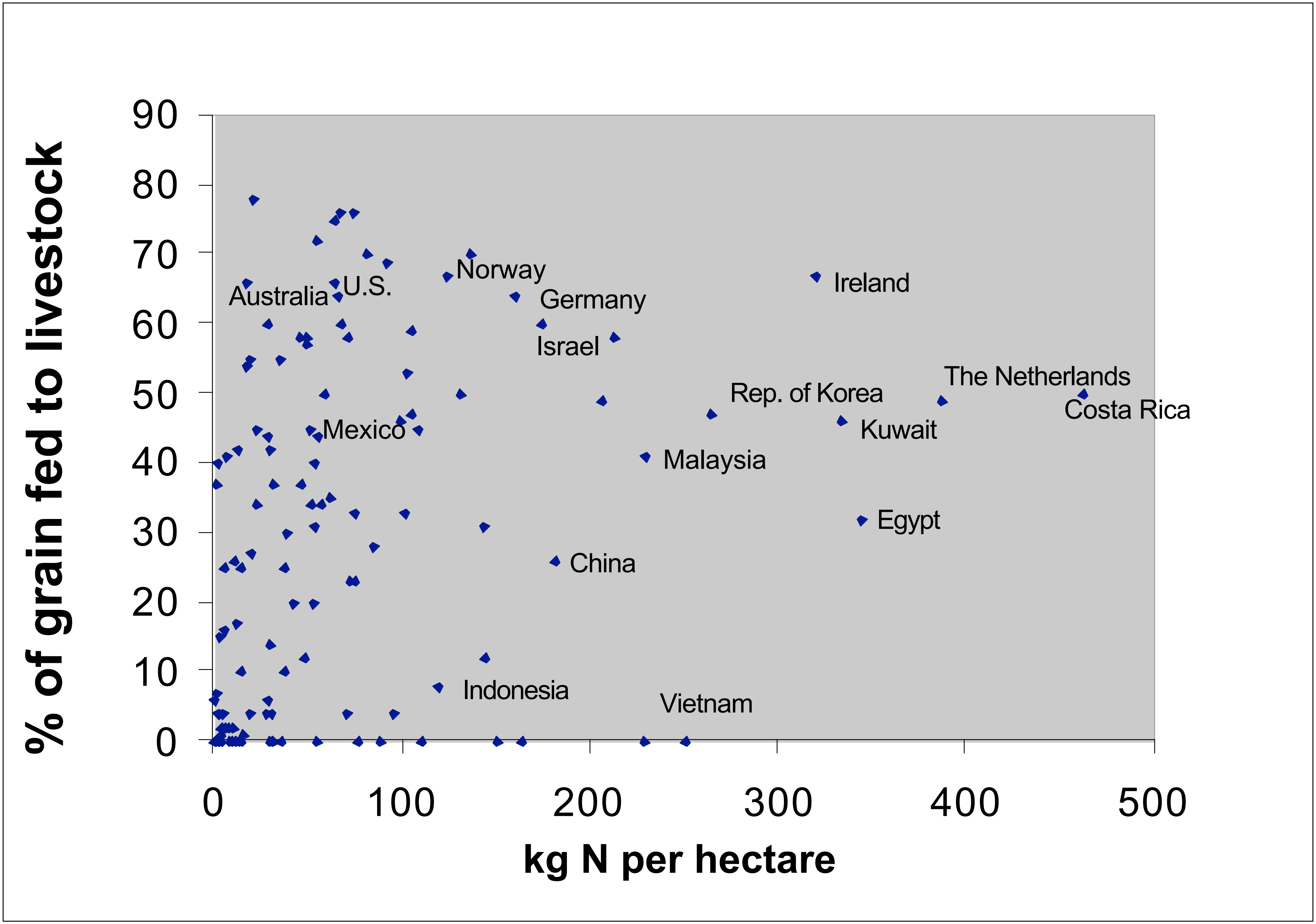
Crop	kg P ha^{-1} yr^{-1}
cereals	15-35
legumes and root crops	15-25
vegetables and fruits	5-15

Smil 2000



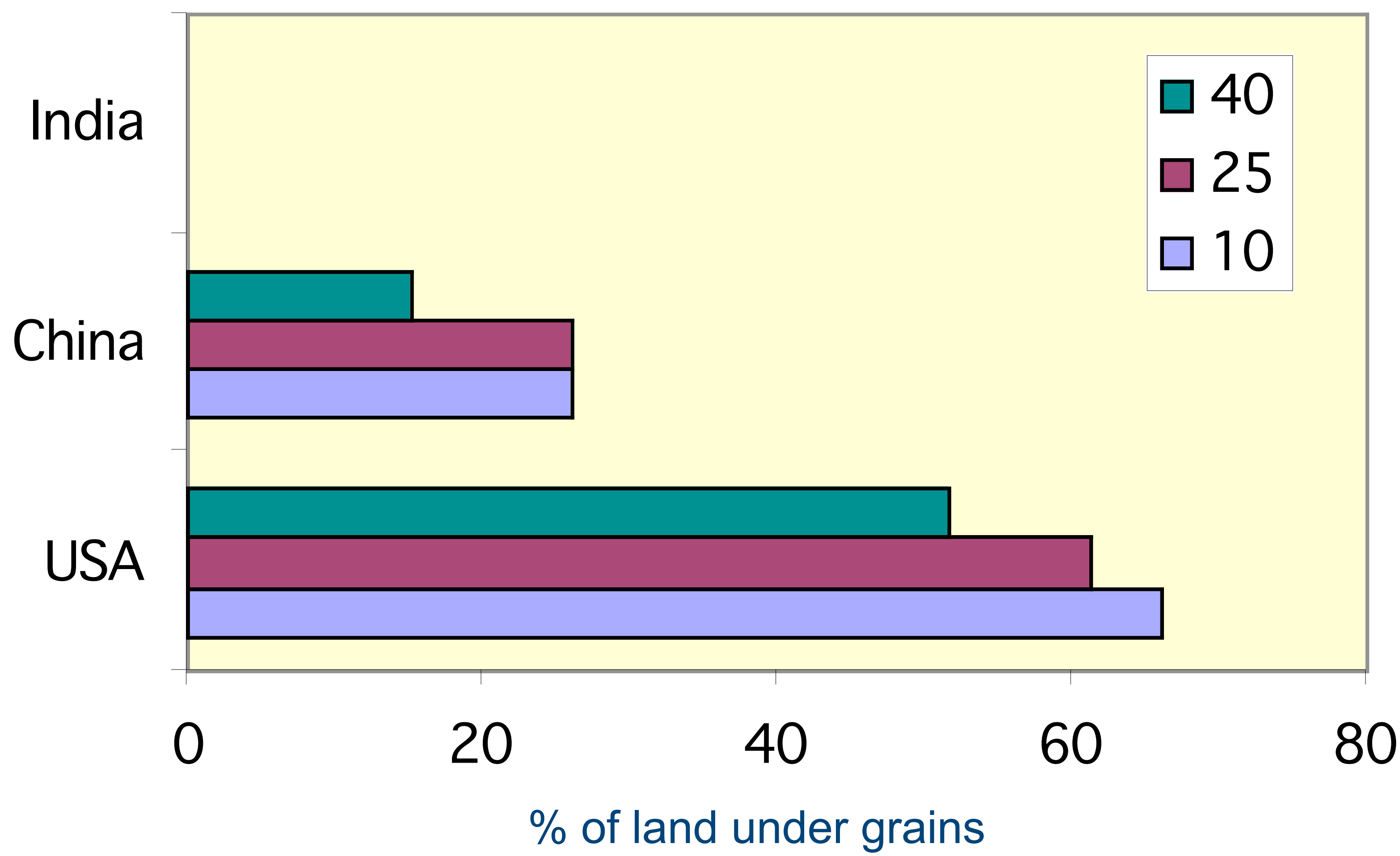
Annual wheat (on left in each panel) and Perennial wheatgrass

How different dietary scenarios determine the need for P fertilizers


% of grain fed to livestock
kg N per hectare
0
10
20
30
40
50
60
70
80
90
0
100
200
300
400
500
Norway
Ireland
Australia
U.S.
Germany
Israel
The Netherlands
Rep. of Korea
Costa Rica
Kuwait
Mexico
Malaysia
Egypt
China
Indonesia
Vietnam

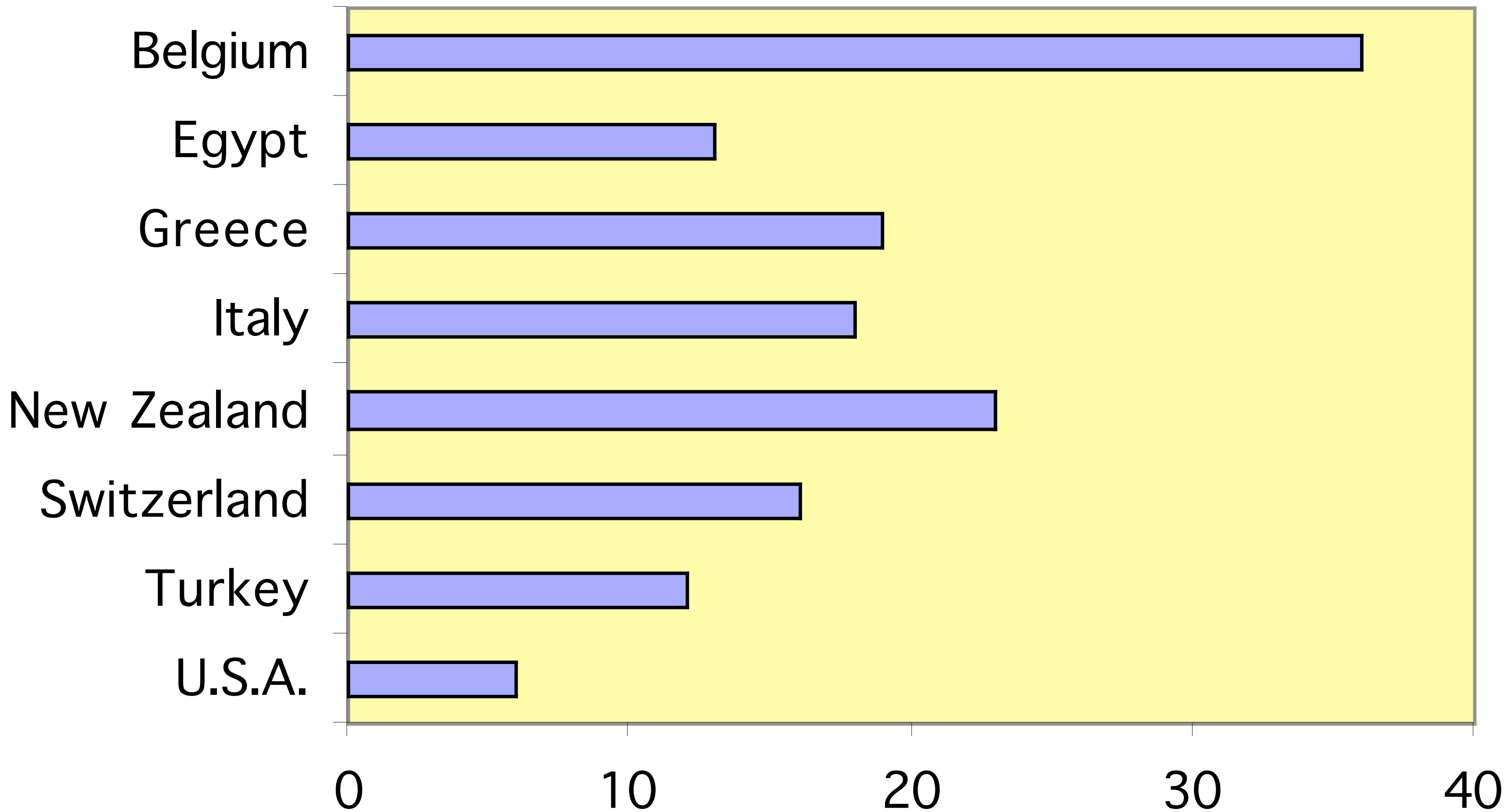
FAO and WRI

% of land under grain cultivation that could be freed up if the protein derived from meat were reduced to 40, 25 or 10 percent of daily requirements



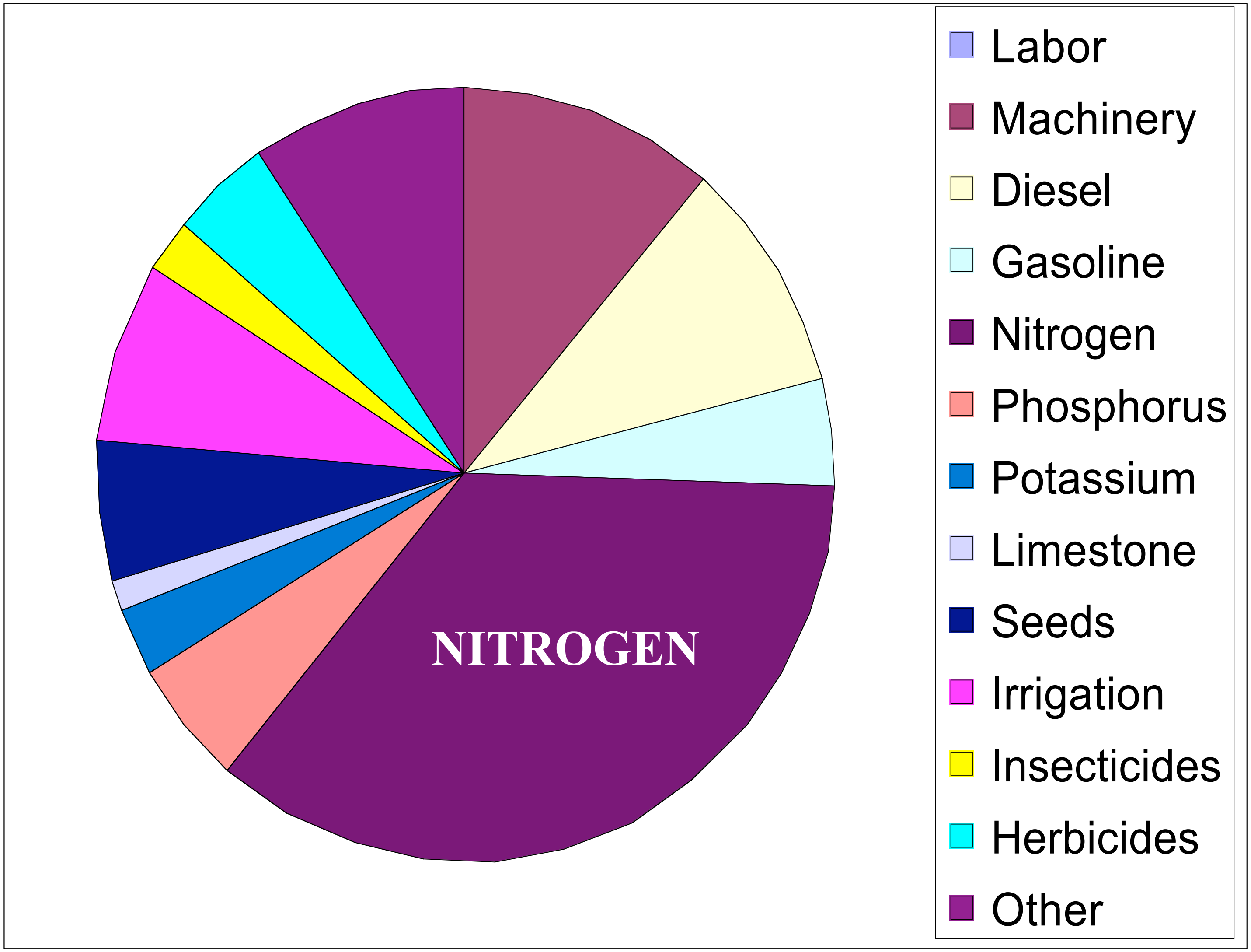
Crews and Peoples (2004)

% of land under domestic grain production that could be freed-up if per capita food supply was reduced to 3000 Cal day^{-1}



From Crews and Peoples (2004)

Proportion of total energy cost of different inputs into US corn production



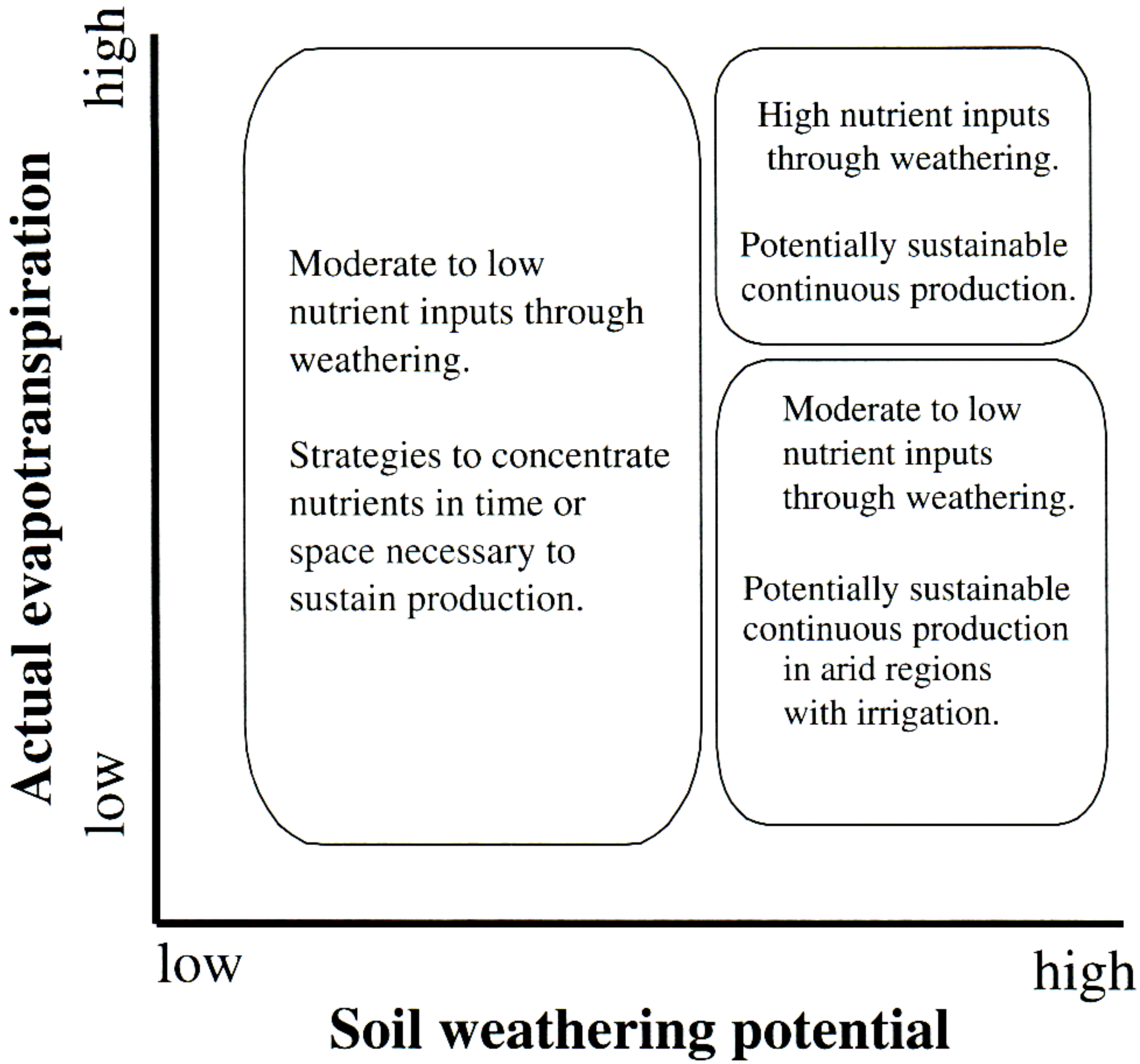
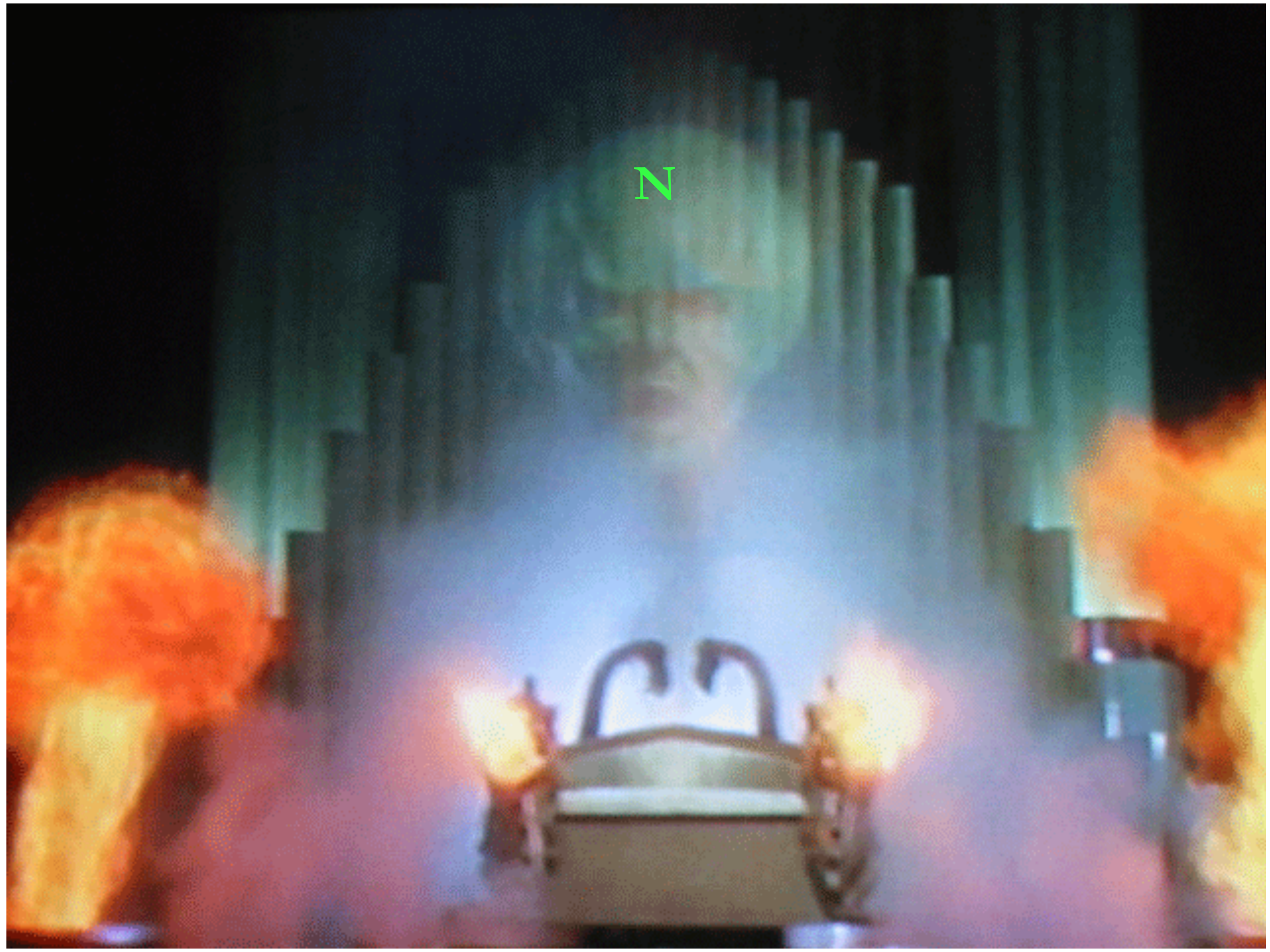

Actual evapotranspiration
high
low
Soil weathering potential
low
high
Moderate to low nutrient inputs through weathering.
Strategies to concentrate nutrients in time or space necessary to sustain production.
High nutrient inputs through weathering.
Potentially sustainable continuous production.
Moderate to low nutrient inputs through weathering.
Potentially sustainable continuous production in arid regions with irrigation.

Table 2. Examples of calculated weathering potential index (WPI) values[56] and percentages of calcium (%Ca) and phosphorus (%P) for selected parent materials[54].

Rock type	WPI	%Ca	%P
Rhyolite	2.5	0.81	0.03
Granite	7	1.31	0.05
Gneiss	7	0.09	0.04
Schist	7	0.81	0.04
Diorite	13	4.67	0.13
Andesite	14	4.82	0.09
Basalt	18	6.72	0.15
Gabbro	22	6.80	0.11

$$\frac{100\times \text{moles}(K_2O + Na_2O + CaO + MgO - H_2O)}{\text{moles}\ (SiO_2 + TiO_2 + Al_2O_3 + Fe_2O_3 + Cr_2O_3 + K_2O + Na_2O + CaO + MgO - H_2O)}.$$

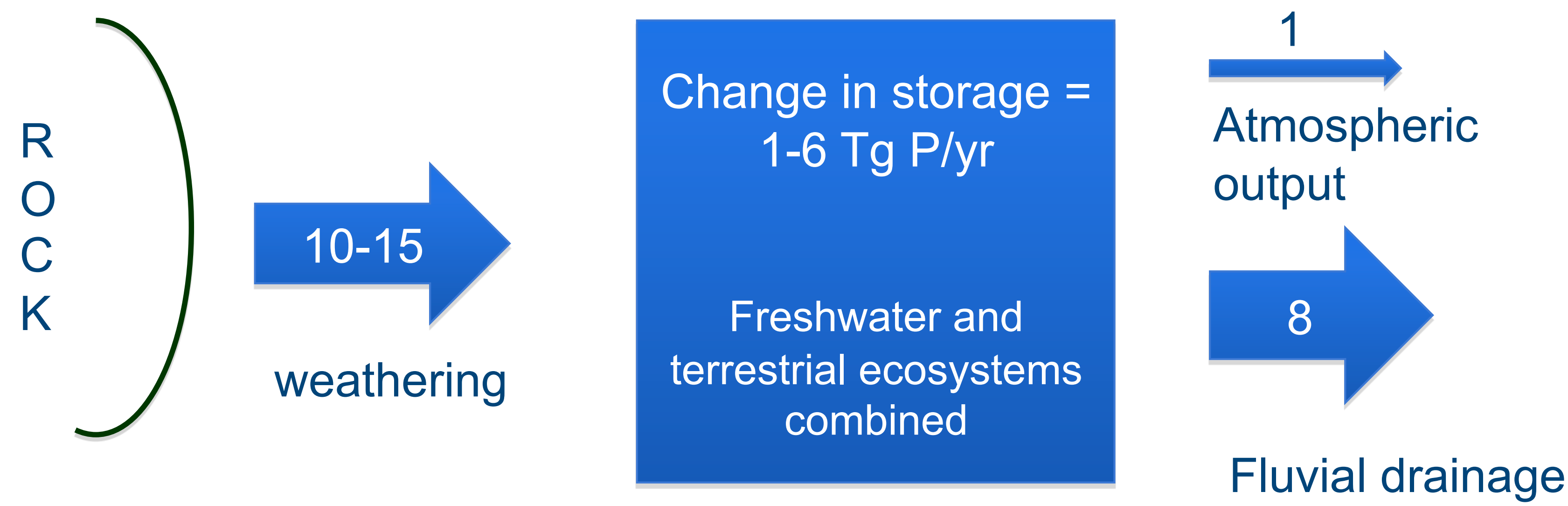
Pay no attention to the element behind the screen



Tim Crews
Environmental Studies Program
Prescott College
Prescott, Arizona


P

PREINDUSTRIAL GLOBAL TERRESTRIAL P FLUX



Change in storage =

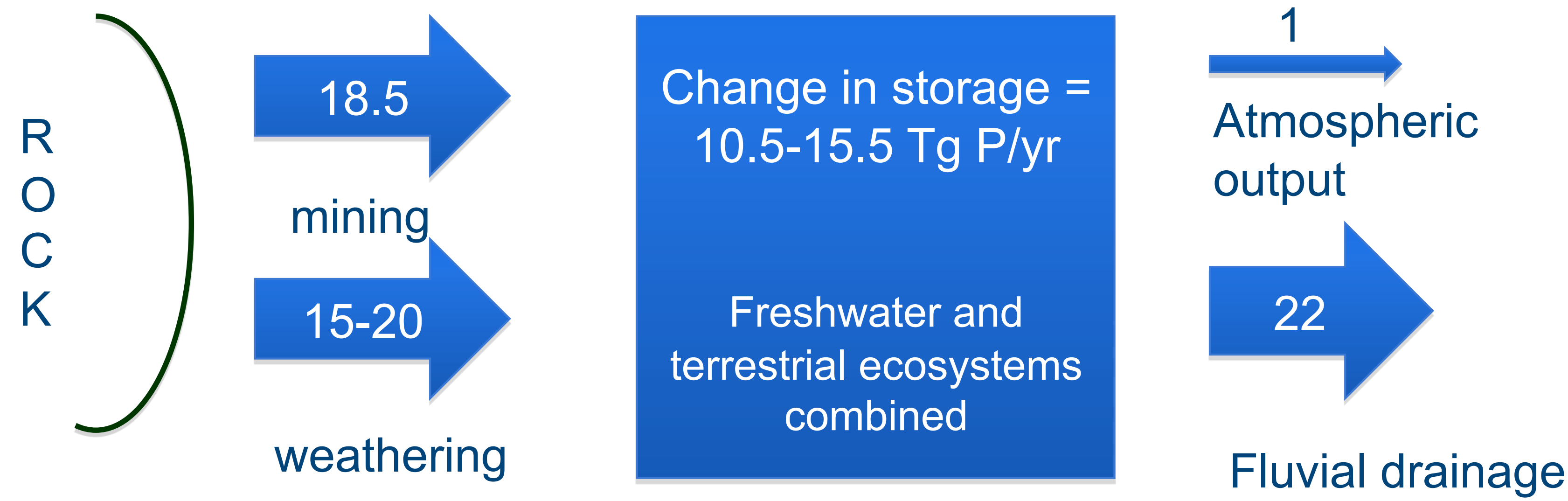
$$10 - (1 + 8) = 1$$

to

$$15 - (1 + 8) = 6$$

Bennett et al. 2001

CURRENT GLOBAL TERRESTRIAL P FLUX



Change in storage =

(15 + 18.5) – (1 + 22) = 10.5
to
(20 + 18.5) – (1 + 22) = 15.5

Bennett et al. 2001

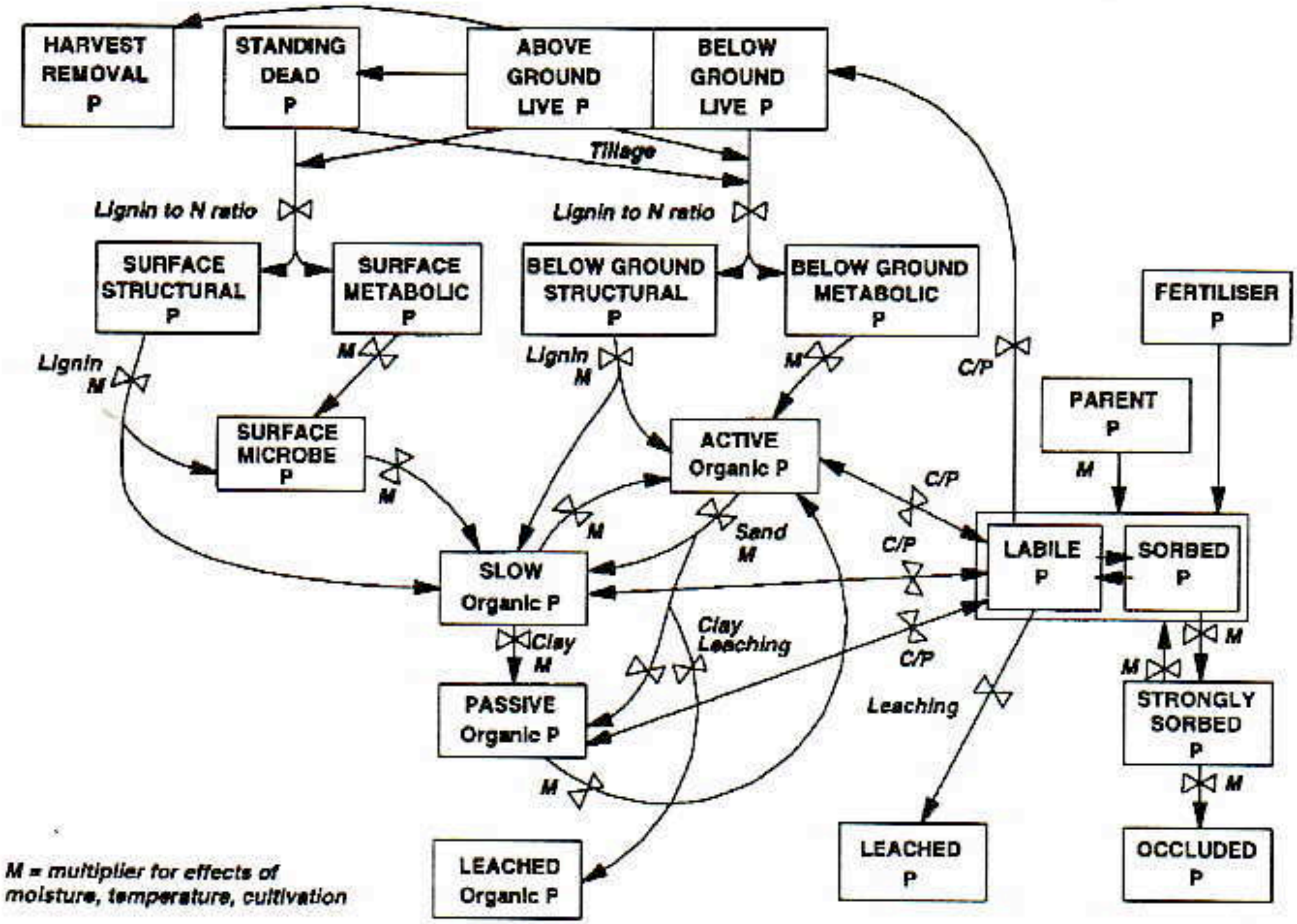
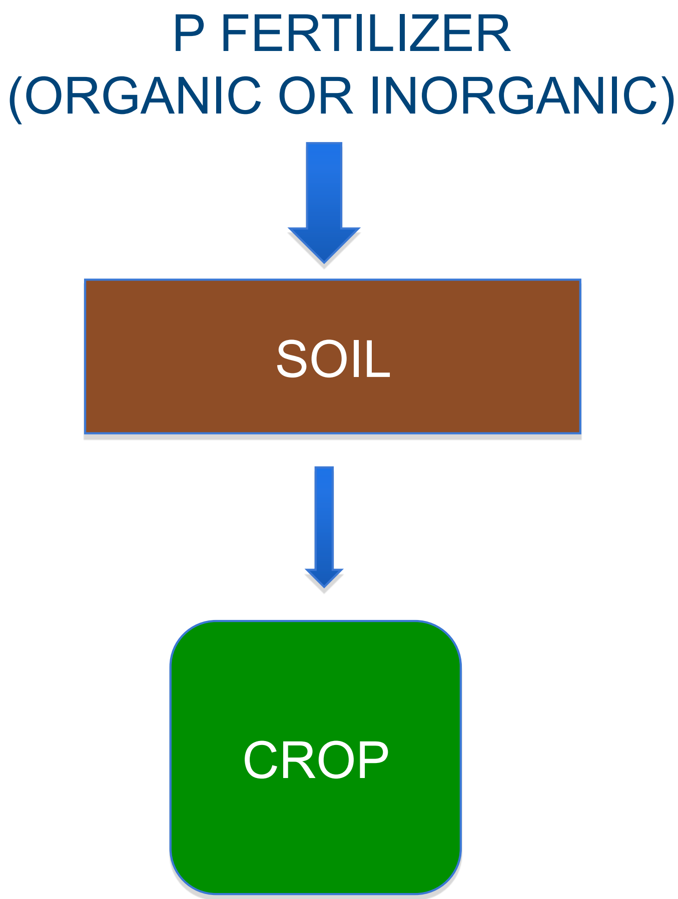
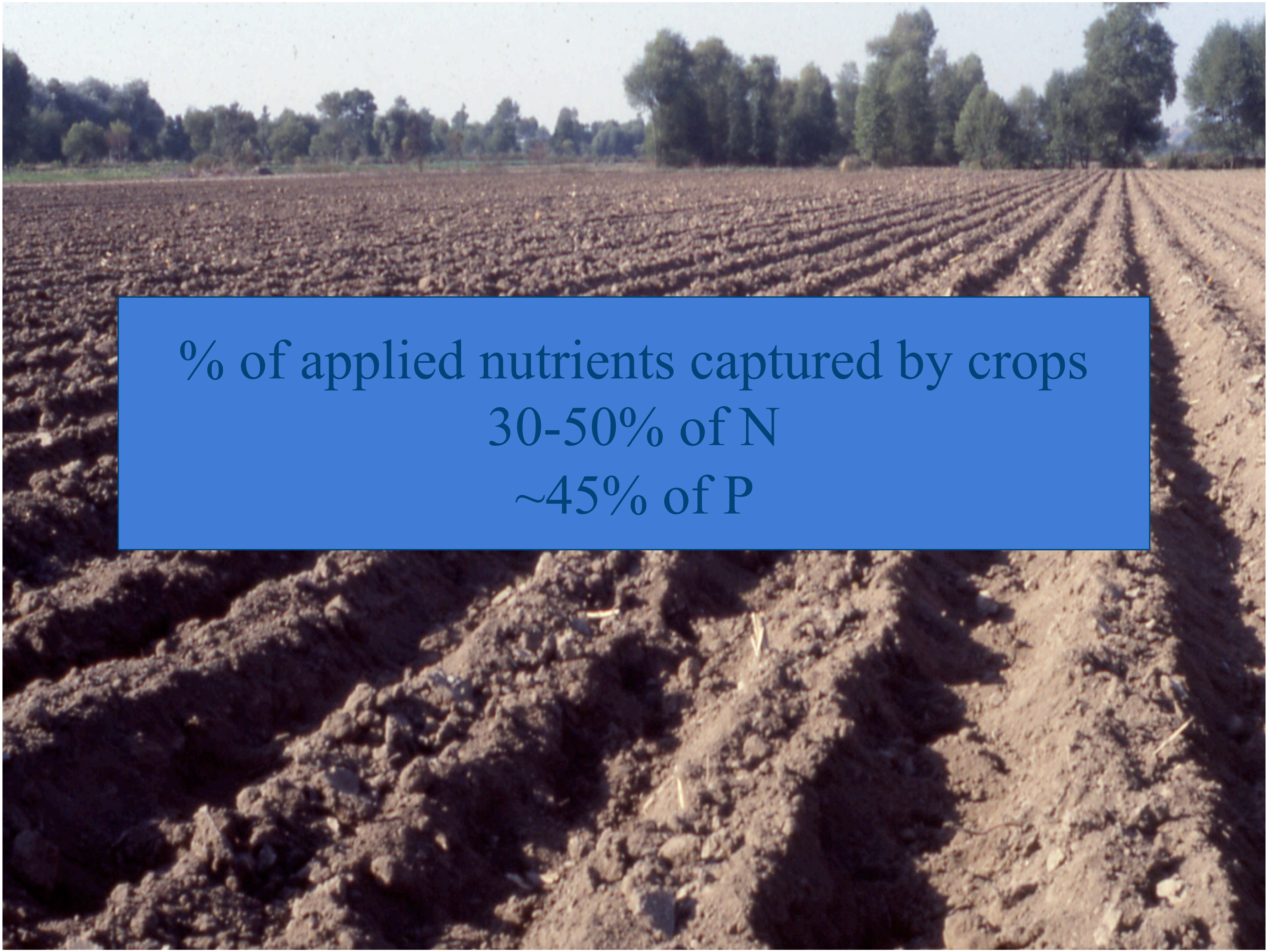
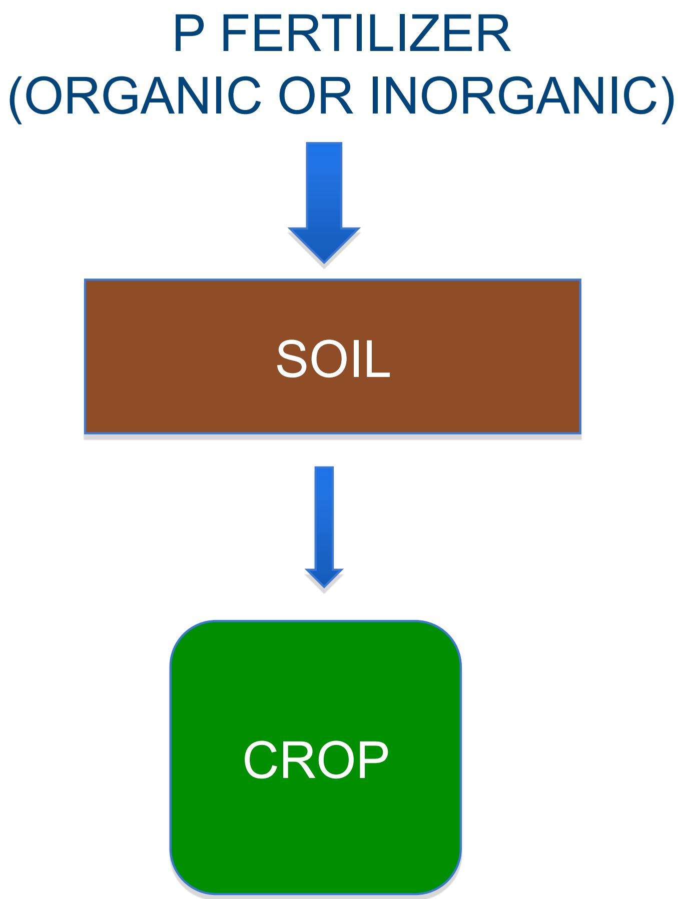


Figure 8. The pools and flows of phosphorus in the CENTURY model


P FERTILIZER
(ORGANIC OR INORGANIC)
SOIL
CROP


% of applied nutrients captured by crops
30-50% of N
~45% of P

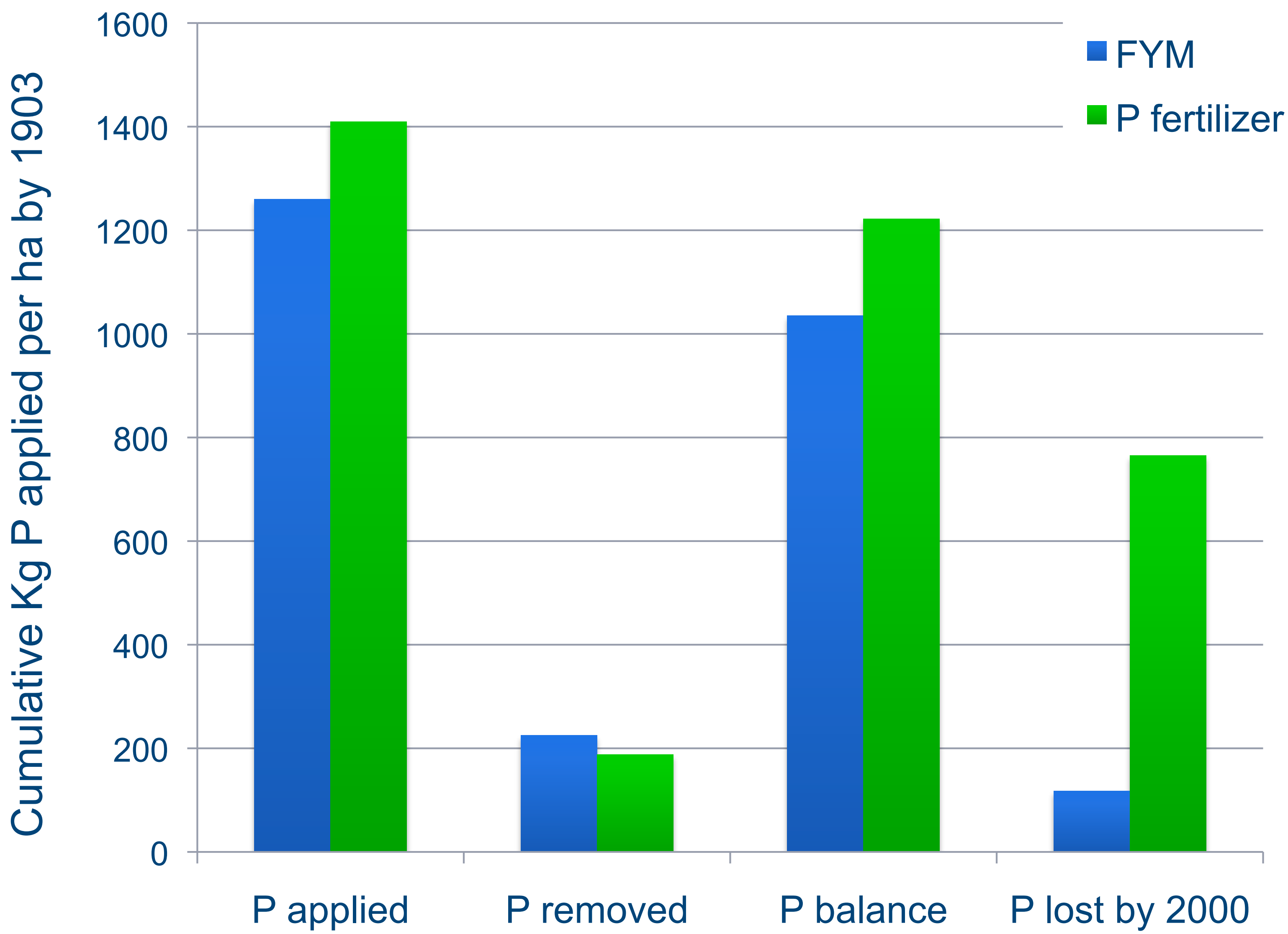


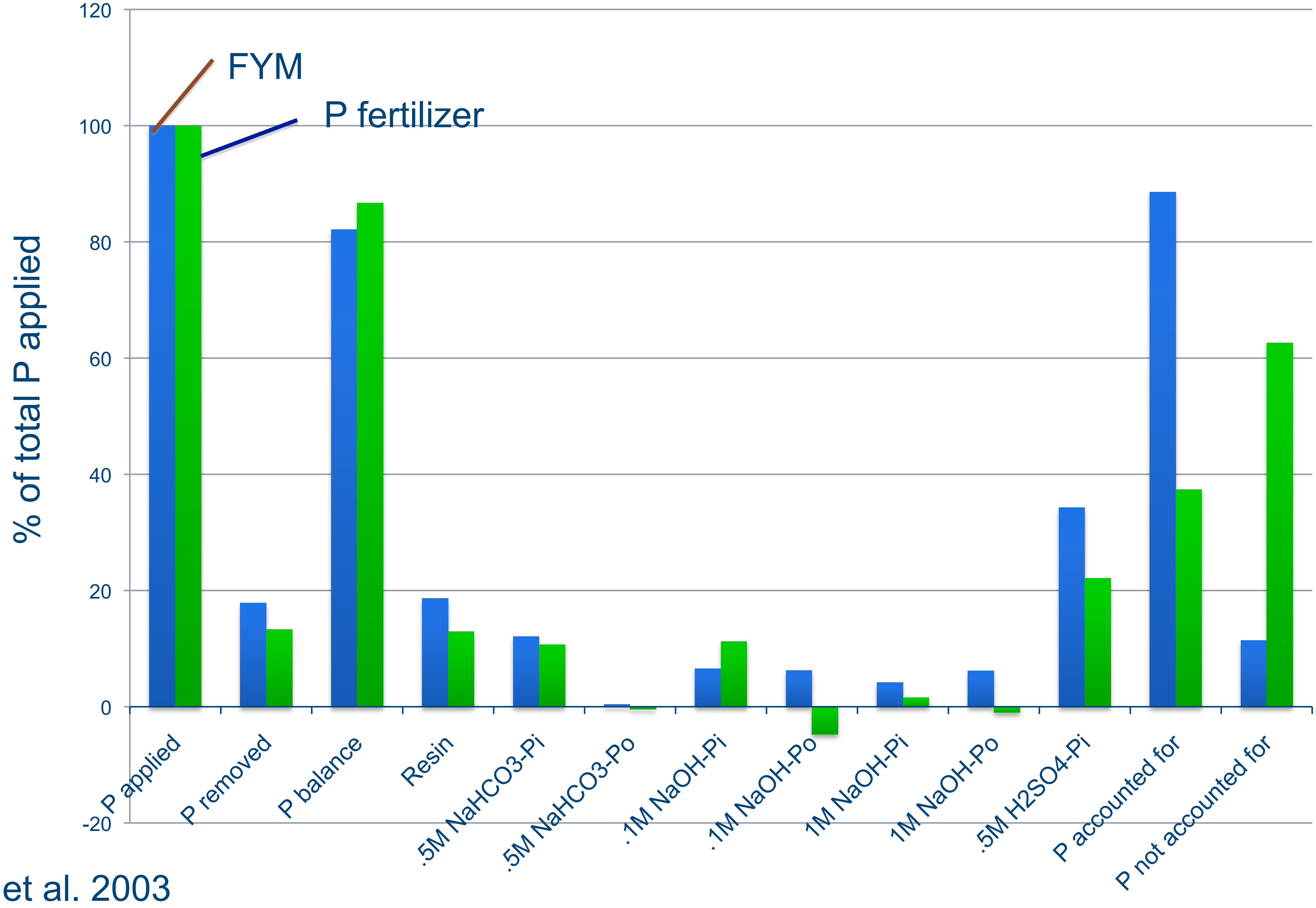
Clay mineralogy

<u>High sorption capacity:</u>
Amorphous alluminosilicates
Fe oxides
Al oxides

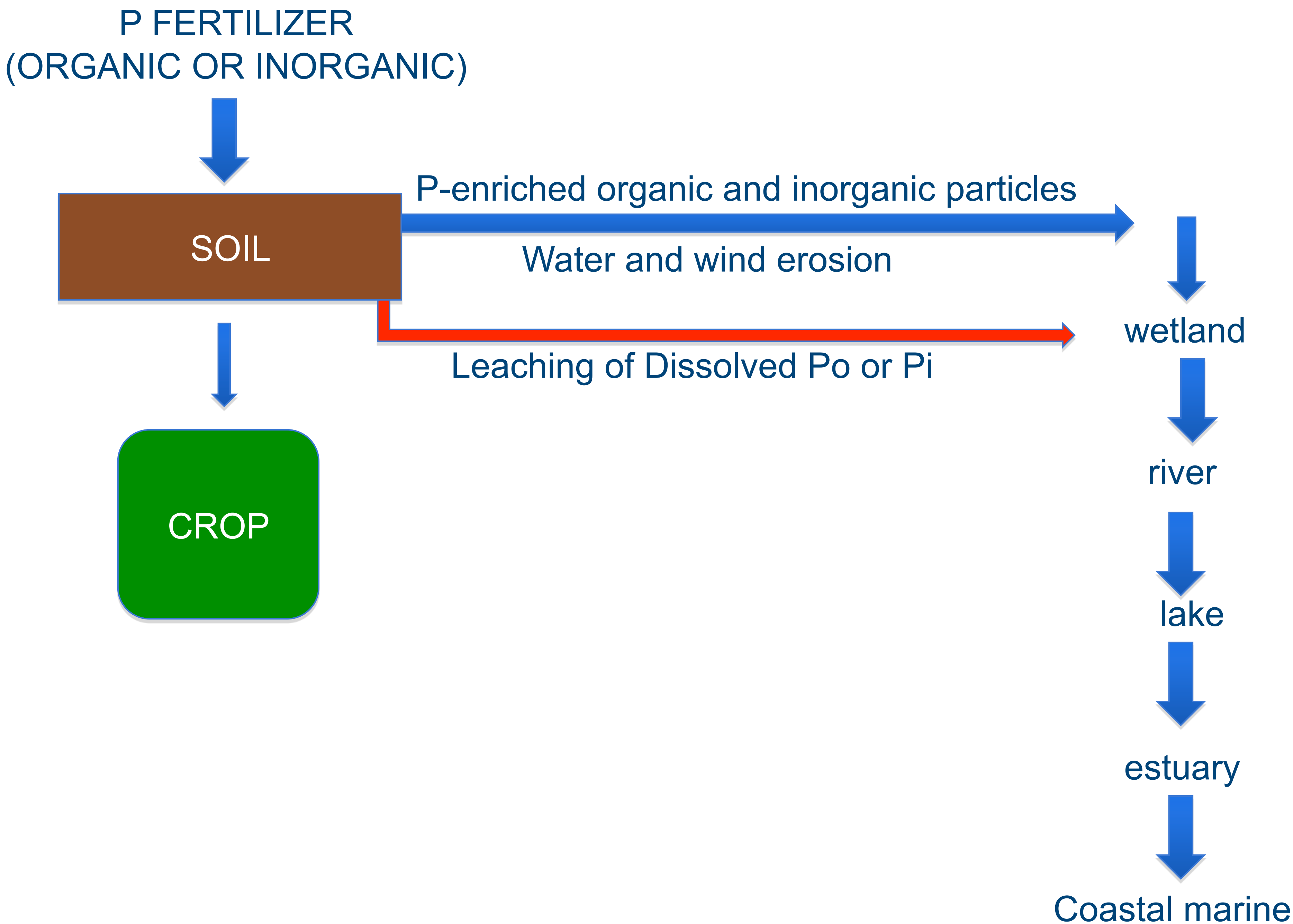
<u>Moderate sorption capacity:</u>
Crystalline aluminosilicates
Humic compounds

Cumulative P additions as Farm Yard Manure (FYM) or P fertilizer by 1903
And P removal in wheat, potato and barley harvests to present at Exhaustion
Land Plots—Rothamsted Research, U.K. (Blake et al. 2003)





Blake et al. 2003


P FERTILIZER
(ORGANIC OR INORGANIC)
SOIL
P-enriched organic and inorganic particles
Water and wind erosion
Leaching of Dissolved Po or Pi
CROP
wetland
river
lake
estuary
Coastal marine

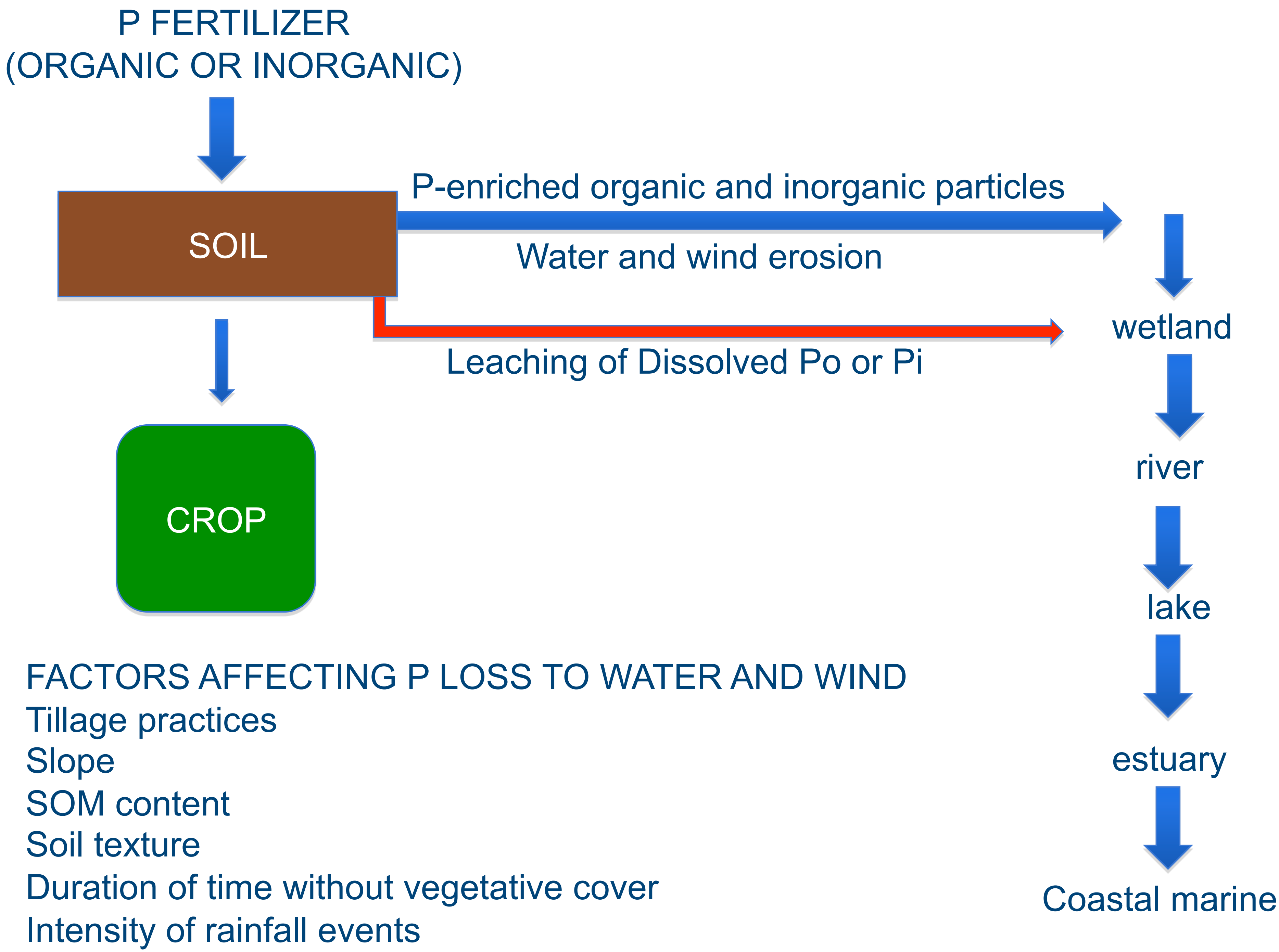
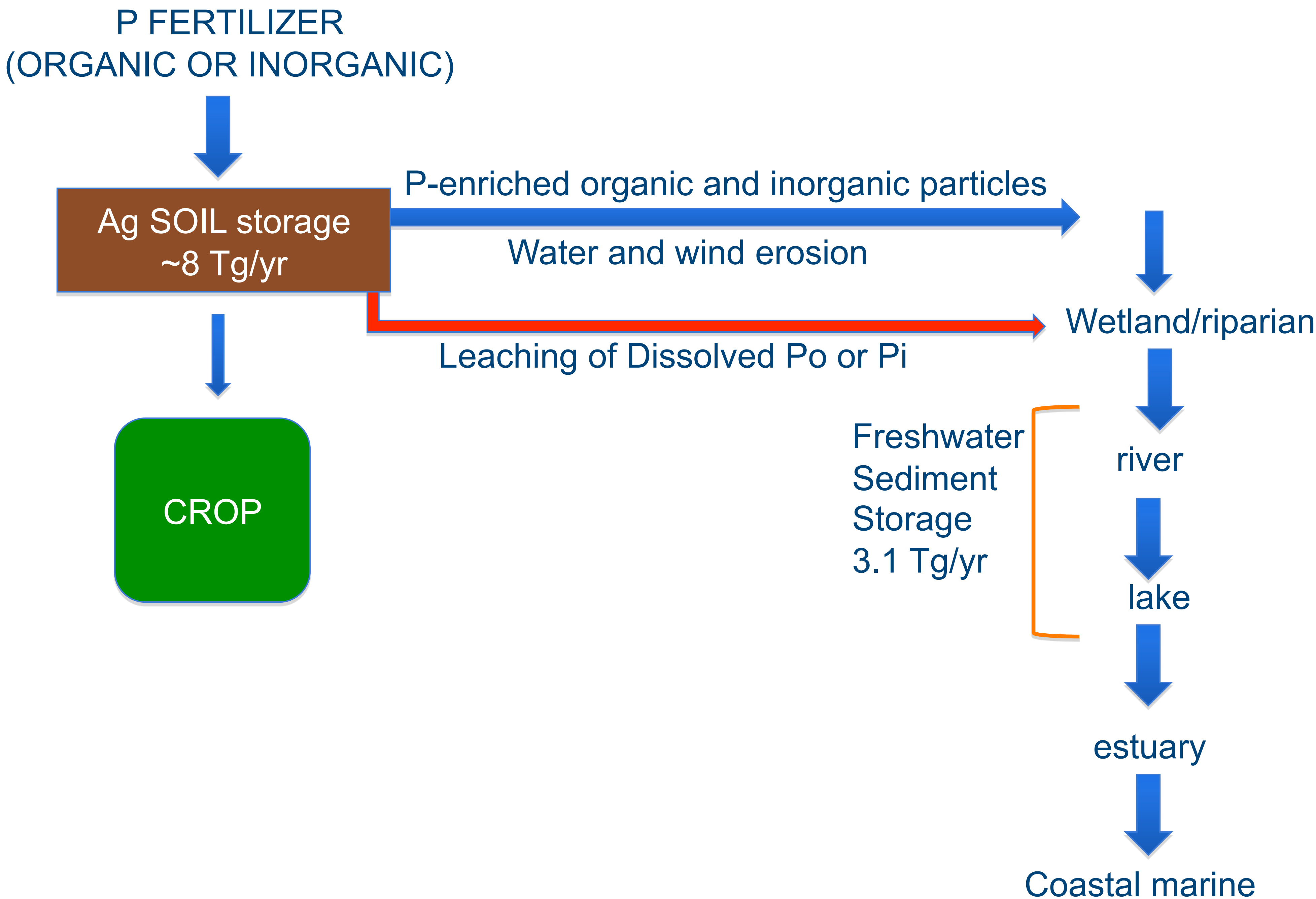

P FERTILIZER
(ORGANIC OR INORGANIC)
SOIL
P-enriched organic and inorganic particles
Water and wind erosion
Leaching of Dissolved Po or Pi
CROP
wetland
river
lake
estuary
Coastal marine
FACTORS AFFECTING P LOSS TO WATER AND WIND
Tillage practices
Slope
SOM content
Soil texture
Duration of time without vegetative cover
Intensity of rainfall events

Table 5. Effect of fertilizer P application on the loss of P in surface runoff.

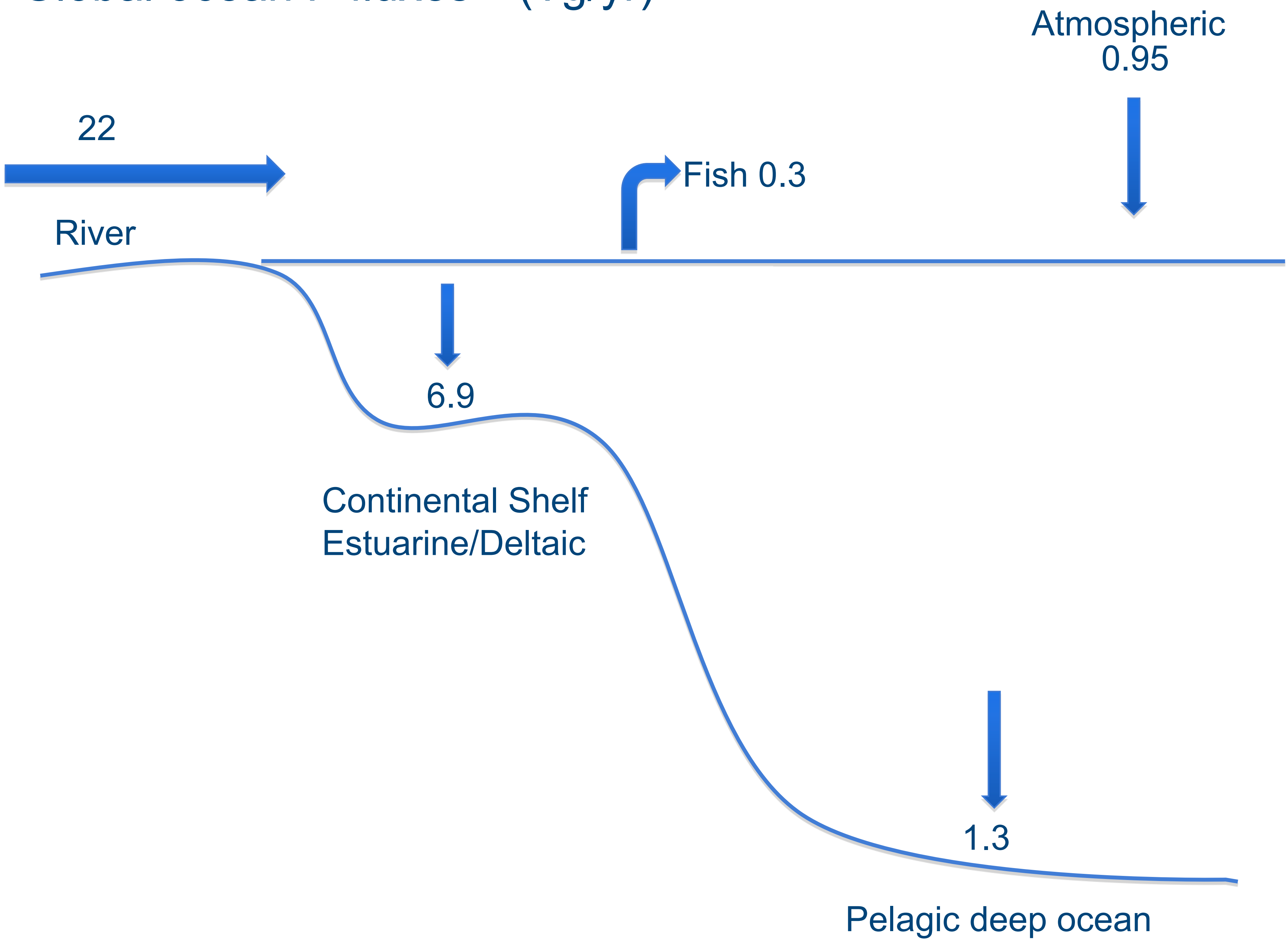
Land use	Fert. Appld.	P losses Solub.	P losses Partic.	P losses Solub.	P losses Partic.	Fert. loss Solub.	Fert. loss Partic.
		------ kg ha-1 y-1 ------		------ mg l-1 ------		------ % ------	
Contour corn [1]	40	0.12	0.45	0.19	0.71		
	66	0.15	0.76	0.25	1.27	0.1	1.2
Grass [2]	0	0.01	0.20	0.01	0.06		
	75	0.04	0.29	0.03	0.14	0.04	0.1
No till corn	0	0.70	1.30	0.23	0.43		
for silage [3]	30	0.80	1.00	0.39	0.49	0.3	+23.1+
No till corn	0	1.10	2.20	0.23	0.46		
for grain [3]	30	1.80	1.60	0.57	0.51	2.3	+27.3+
Conventional	15	0.30	15.10	0.07	3.57		
corn [3]	30	0.20	17.50	0.11	9.71	+3.3+	16.0
Wheat/fallow [4]	0	0.20	1.40	0.30	1.80		
	54	1.20	2.90	3.70	7.40	1.9	2.8
Grass [5]	0	0.50	0.67	0.18	0.24		
	50	2.80	2.74	0.98	0.96	4.6	4.1

+ Percent decrease in P loss from fertilised compared to check treatment
[1] Burwell et al. (1977) Minnesota; [2] McColl et al. (1977) New Zealand; [3] McDowell and McGregor (1984) Mississippi; [4] Nicholaichuk and Read (1978) Western Canada; [5] Sharpley and Syers (1979) New Zealand

Sharpley et al. 1995

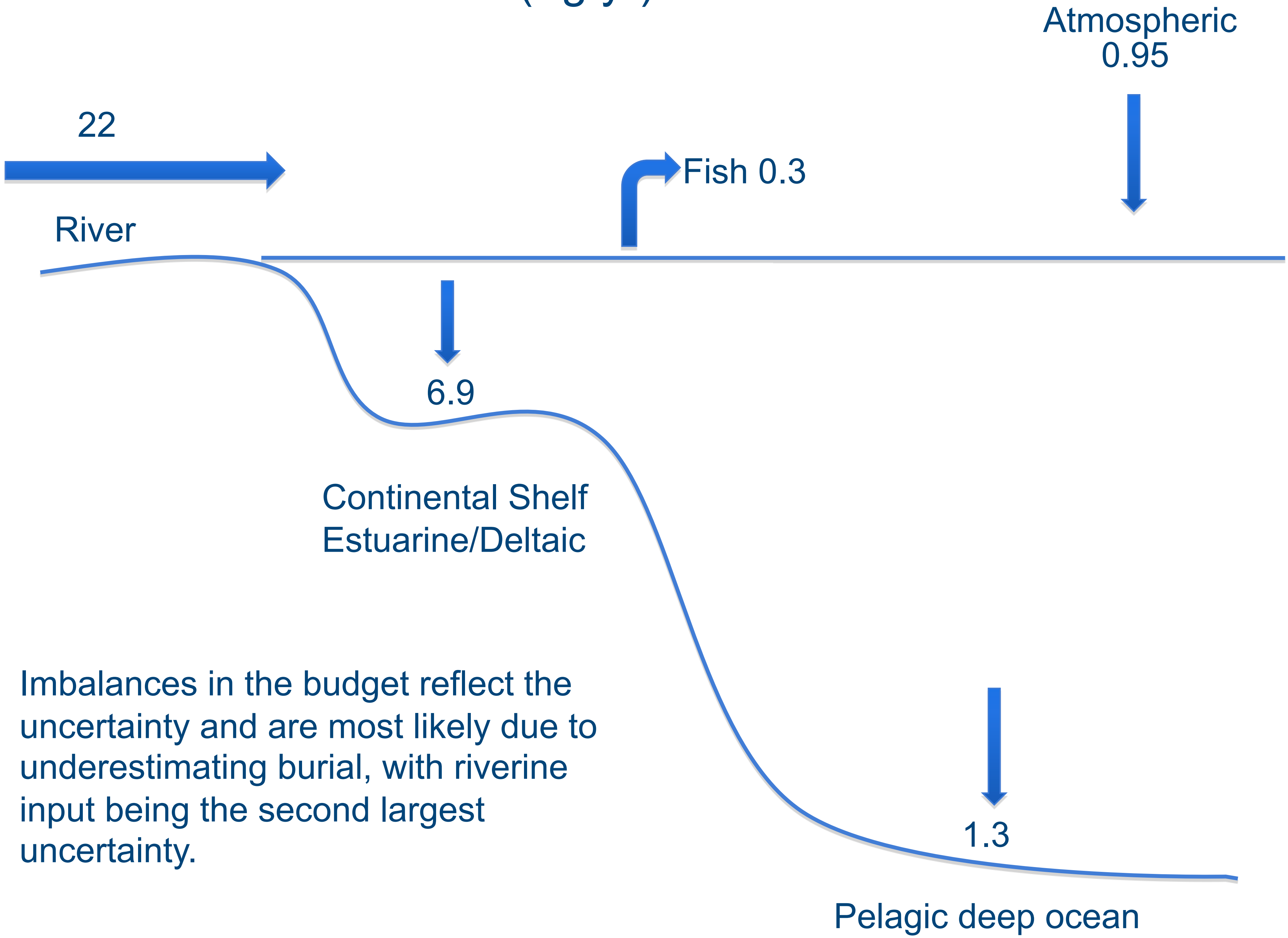

P FERTILIZER
(ORGANIC OR INORGANIC)
Ag SOIL storage
~8 Tg/yr
P-enriched organic and inorganic particles
Water and wind erosion
Leaching of Dissolved Po or Pi
CROP
Wetland/riparian
Freshwater
Sediment
Storage
3.1 Tg/yr
river
lake
estuary
Coastal marine

Global ocean P fluxes—(Tg/yr)



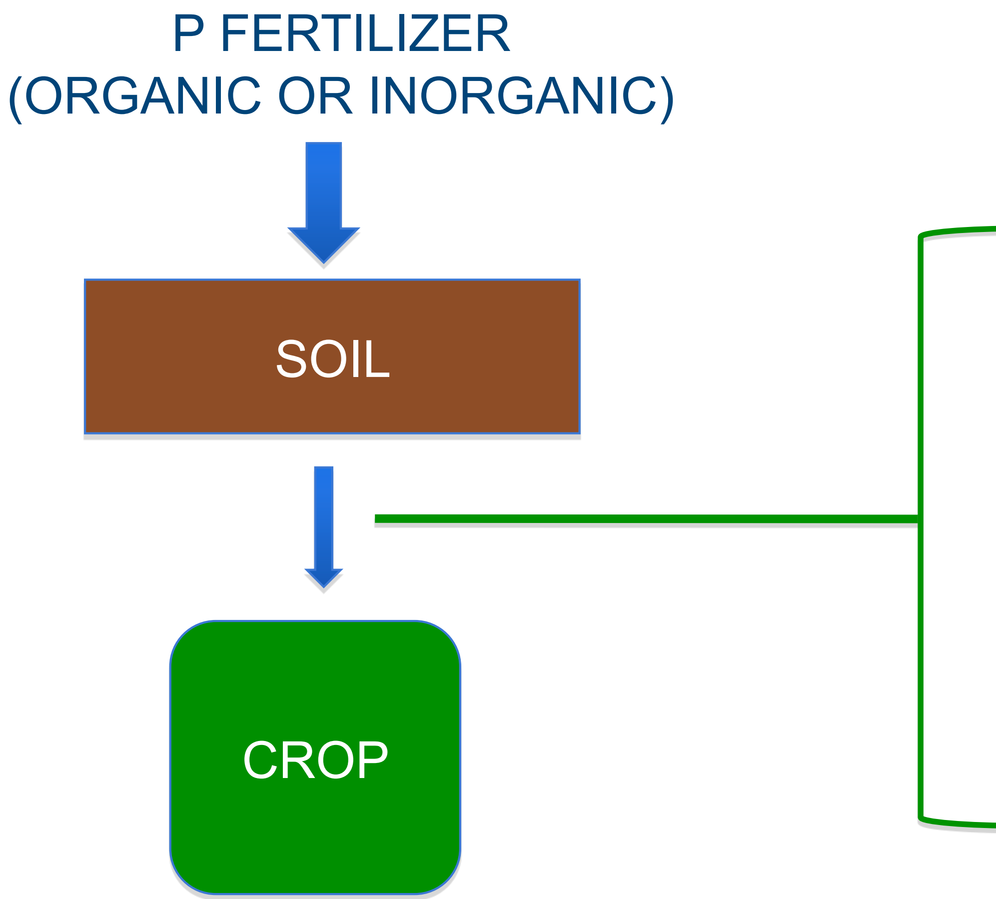
(Howarth et al. 1995)

Global ocean P fluxes—(Tg/yr)



Imbalances in the budget reflect the uncertainty and are most likely due to underestimating burial, with riverine input being the second largest uncertainty.

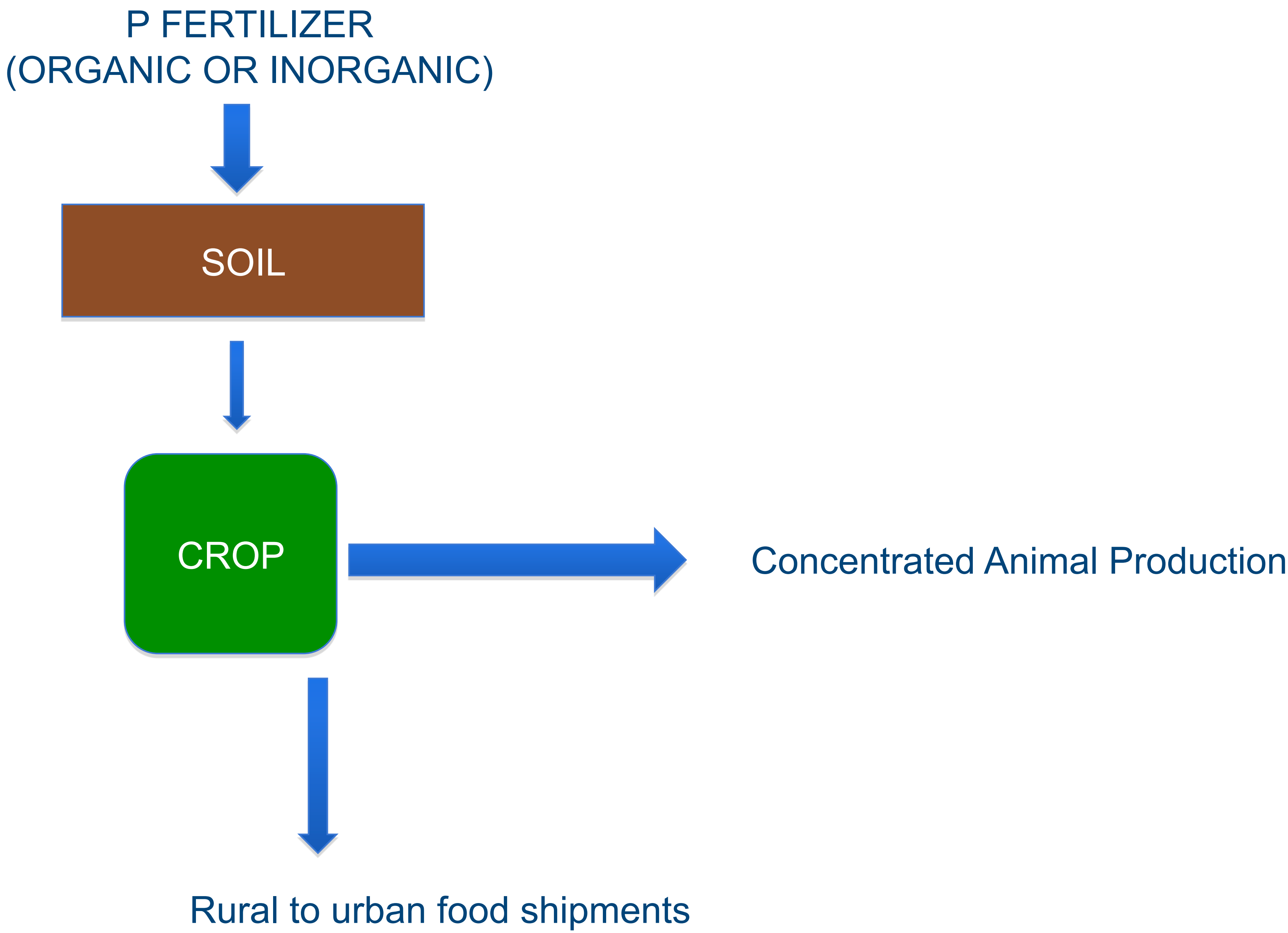
(Howarth et al. 1995)



10-90 % of applied P might be taken
Up by the crop

Average ~45%

MANAGEMENT FACTORS
Crop selection
Crop deployment in time and space
Soil pH management (lime)
Alleviation of other crop limiting factors
Mycorrhizal colonization (?)


P FERTILIZER
(ORGANIC OR INORGANIC)
SOIL
CROP
Concentrated Animal Production
Rural to urban food shipments

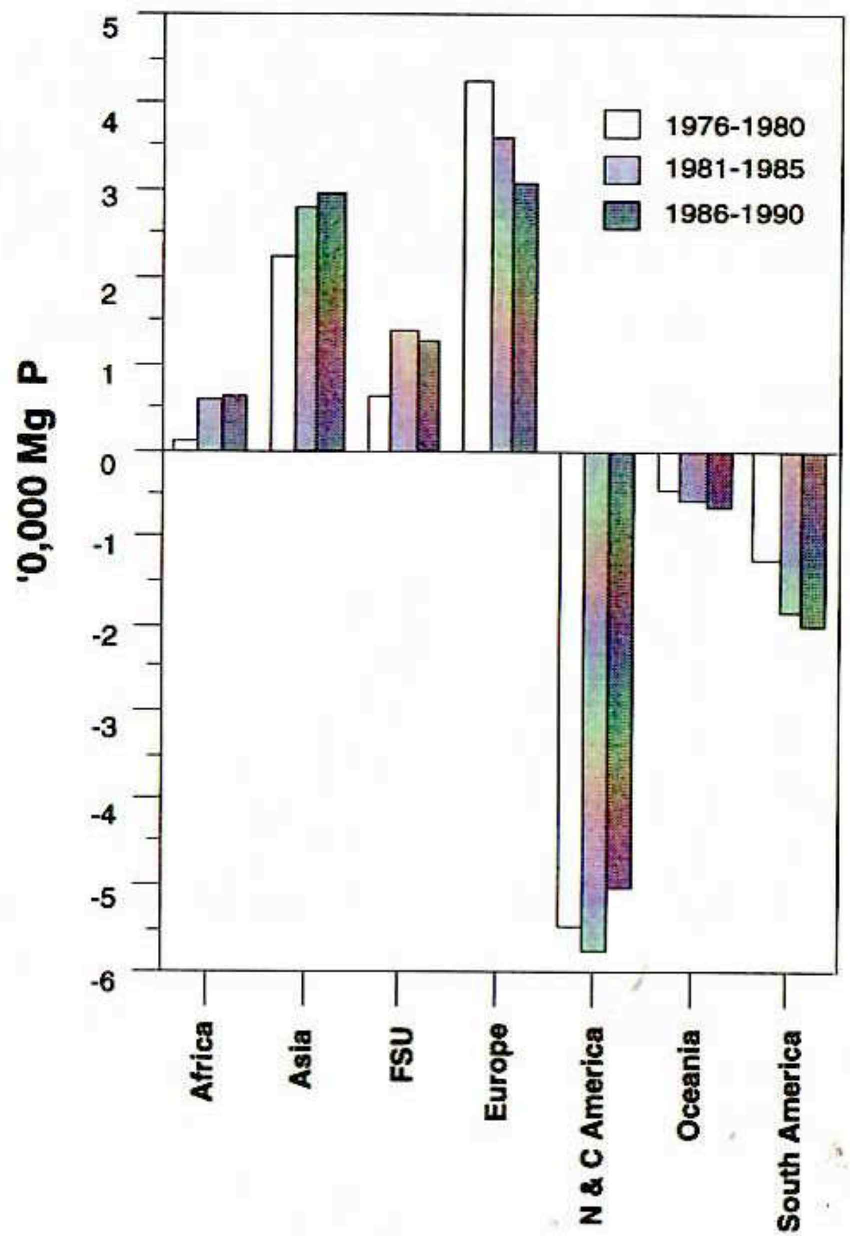
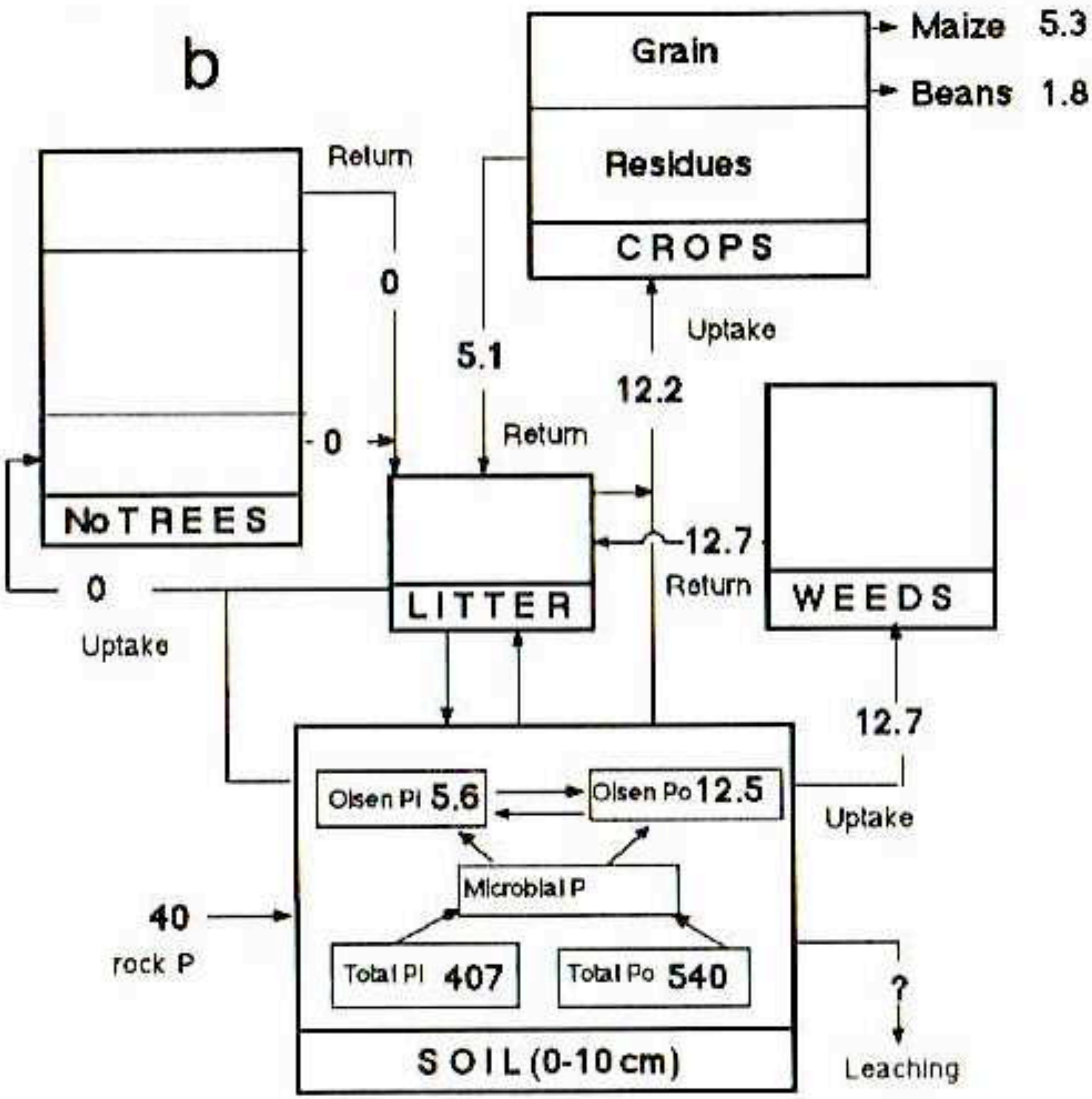


Figure 3. Regional net P balances (total P in imports - total P in exports) for crop commodities averaged over 1976-1980, 1981-1985, and 1986-1990.

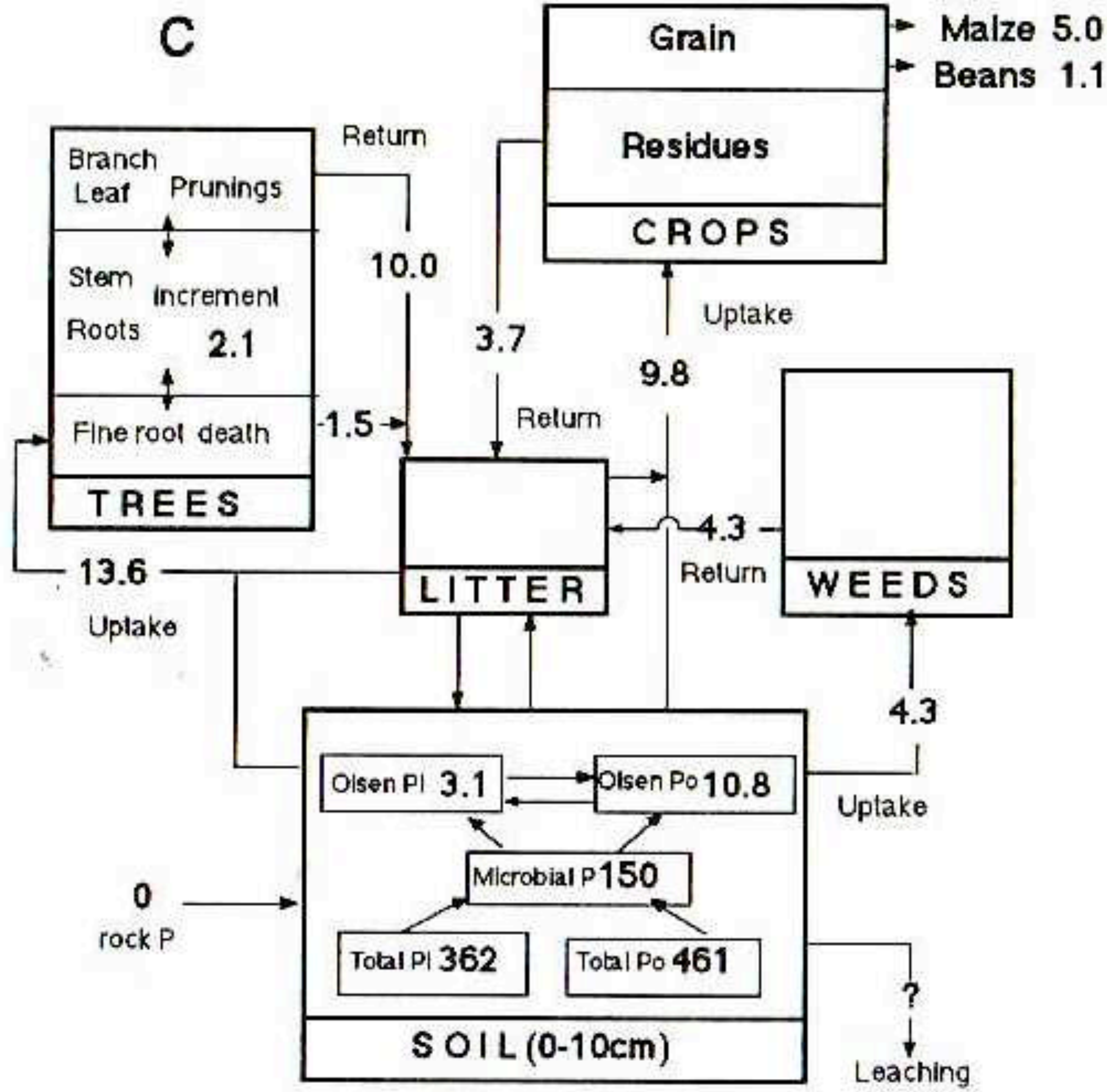
Beaton et al. 1995

Optimize the utility of P fertilizers, a scarce, non-renewable, non-substitutable and Highly valuable resource, rather than simply try to find the most effective sinks.

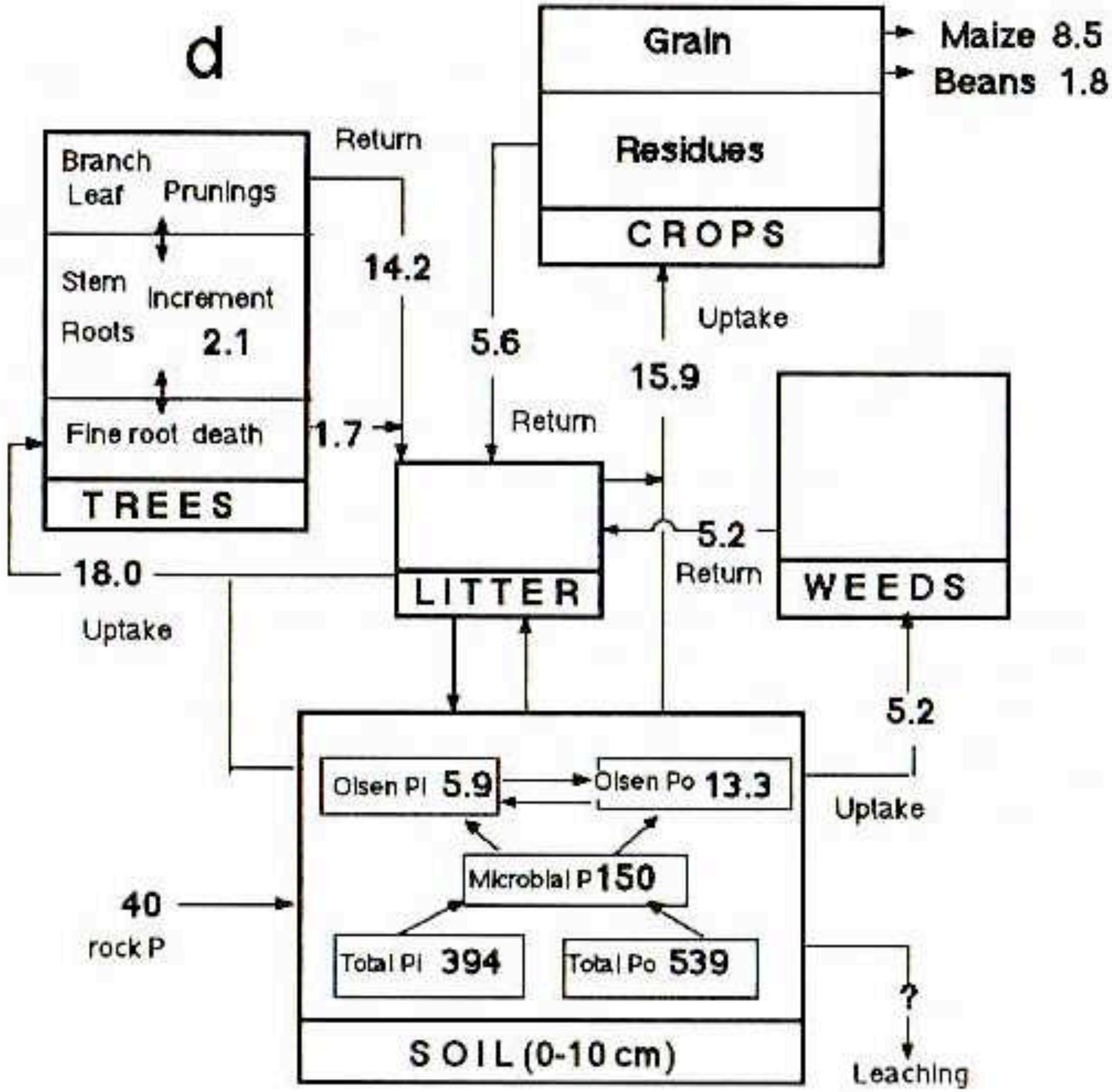
N ____________



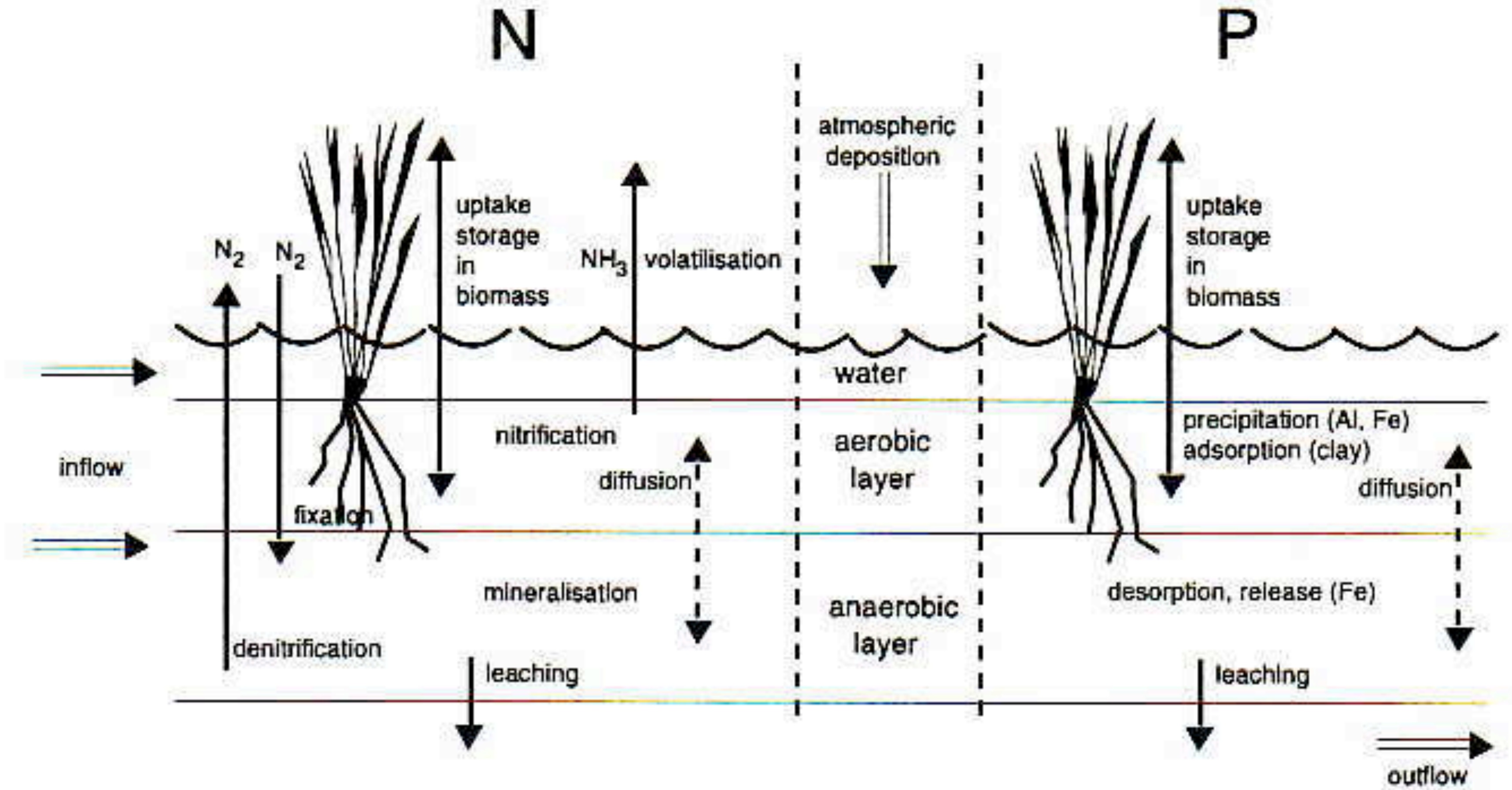
b
Grain
Residues
CROPS
Maize 5.3
Beans 1.8
Return
0
5.1
Uptake
12.2
Return
0
No TREES
LITTER
12.7
Return
WEEDS
0
Uptake
12.7
Olsen Pi 5.6
Olsen Po 12.5
Uptake
Microbial P
40
rock P
Total Pi 407
Total Po 540
?
SOIL (0-10 cm)
Leaching



C
Grain
Maize 5.0
Beans 1.1
Residues
CROPS
Branch
Leaf
Prunings
Return
Stem
Increment
Roots
2.1
Fine root death
TREES
10.0
3.7
Uptake
9.8
Return
1.5
LITTER
4.3
Return
WEEDS
13.6
Uptake
4.3
Olsen Pi 3.1
Olsen Po 10.8
Uptake
Microbial P 150
0
rock P
Total Pi 362
Total Po 461
?
Leaching
SOIL (0-10cm)



d
Grain
Maize 8.5
Beans 1.8
Residues
CROPS
Branch
Leaf
Prunings
Stem
Increment
Roots
2.1
Fine root death
TREES
Return
14.2
5.6
1.7
Uptake
15.9
Return
LITTER
5.2
Return
WEEDS
18.0
Uptake
5.2
Olsen Pi 5.9
Olsen Po 13.3
Uptake
Microbial P 150
40
rock P
Total Pi 394
Total Po 539
?
Leaching
SOIL (0-10 cm)


N
P
atmospheric deposition
uptake storage in biomass
N_2
N_2
NH_3
volatilisation
uptake storage in biomass
water
nitrification
aerobic layer
precipitation (Al, Fe)
adsorption (clay)
inflow
diffusion
diffusion
fixation
mineralisation
anaerobic layer
desorption, release (Fe)
denitrification
leaching
leaching
outflow

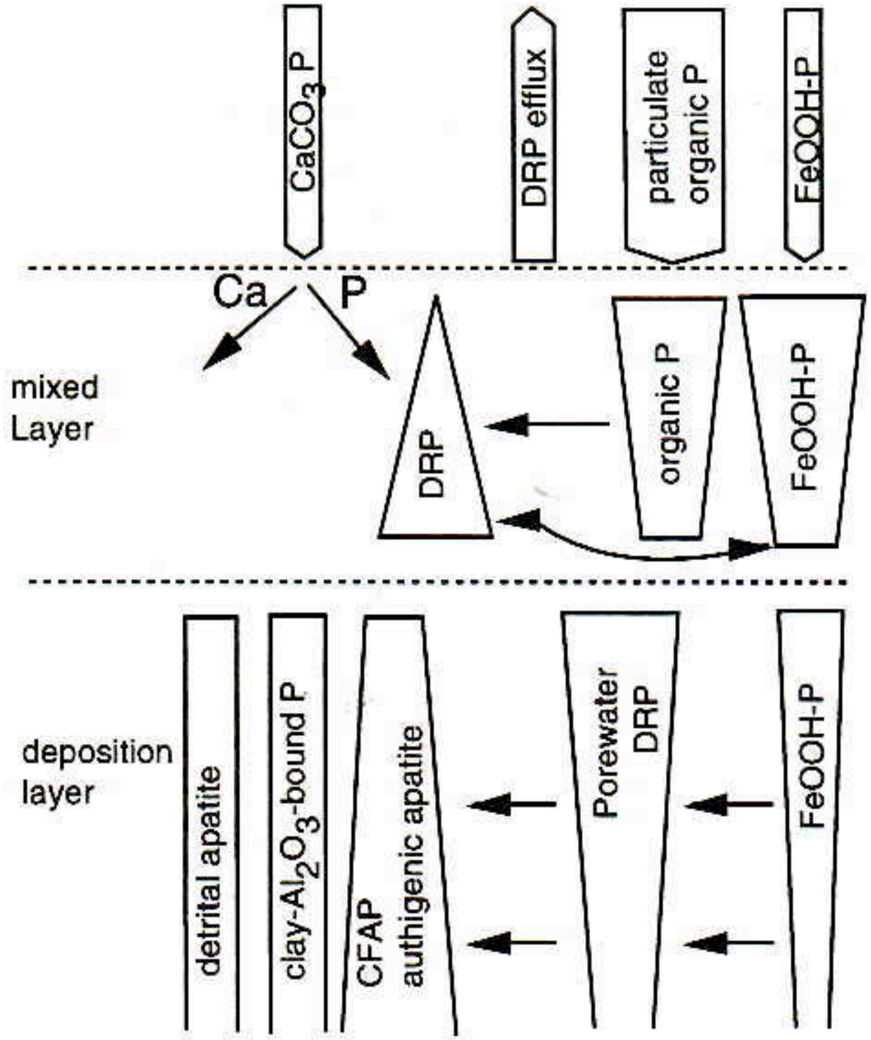


Figure 2. Schematic, general model of P diagenesis in sediments of temperate estuaries and deltaic coastlines. Phosphorus enters sediments primarily in particulate form bound to carbonates and Fe (III) hydroxides and as organic P. Some P also enters sediments as detrital apatite or bound to clays. Some P leaves as dissolved reactive phosphorus (DRP). In the surface mixed layer of the sediments, P is converted into DRP, authigenic apatite, and clay-bound forms; Fe-bound and organic P decrease. Note, however, that the Fe-bound P is important in regulating the flux of DRP to overlying waters (see text). In deeper sediment layers, Fe-bound and organic P further decrease and are converted to apatite.

Table 5. P removed in crops (harvested or grazed), net P fertilisation (all fertilizer P minus P removed in crops), and P in fodder. Net import or export of P in fodder is the difference between P amounts in total fodder used, and potential fodder available from crop removal, 1989.

Country	Crop removal	Net fertilisation	P in fodder Total	P in fodder Net import	P in fodder Net export
	kg P ha^{-1} y^{-1}				
Iceland	0.9	0.7	0.6		0.3
Norway	15.0	15.9	19.2	4.2	
Sweden	15.0	2.3	11.0		4.1
Finland	11.9	20.6	10.7		1.2
Denmark	21.7	15.5	28.3	6.6	
Ireland	12.2	8.4	11.8	0.4	
United Kingdom	14.1	5.4	11.9		2.2
Netherlands	21.8	57.2	81.0	59.2	
Belgium+Luxemb.	21.5	41.5	49.3	27.8	
France	16.6	14.6	12.0		4.6
W. Germany	20.2	24.4	29.2	9.0	
E. Germany	17.7	25.5	22.1	4.4	
Poland	12.0	14.0	10.8		1.2
Czechoslovakia	16.5	26.6	15.3		1.2
Switzerland	13.1	10.6	19.7	6.6	
Austria	13.5	6.3	13.6	0.1	
Hungary	12.8	15.5	11.3		1.5
Portugal	7.8	7.5	7.5		0.3
Spain	7.3	6.5	5.7		1.6
Italy	12.1	17.0	13.3	1.2	
Yugoslavia	7.6	4.6	6.2		1.4
Romania	7.6	7.5	5.5		2.1
Bulgaria	9.5	12.6	7.5		1.9
Albania	7.9	7.5	6.1		1.8
Greece	5.7	7.3	3.7		2.0
Europe	12.3	12.6	12.3		0.1
EC - 12	13.2	12.8	13.7	0.5	

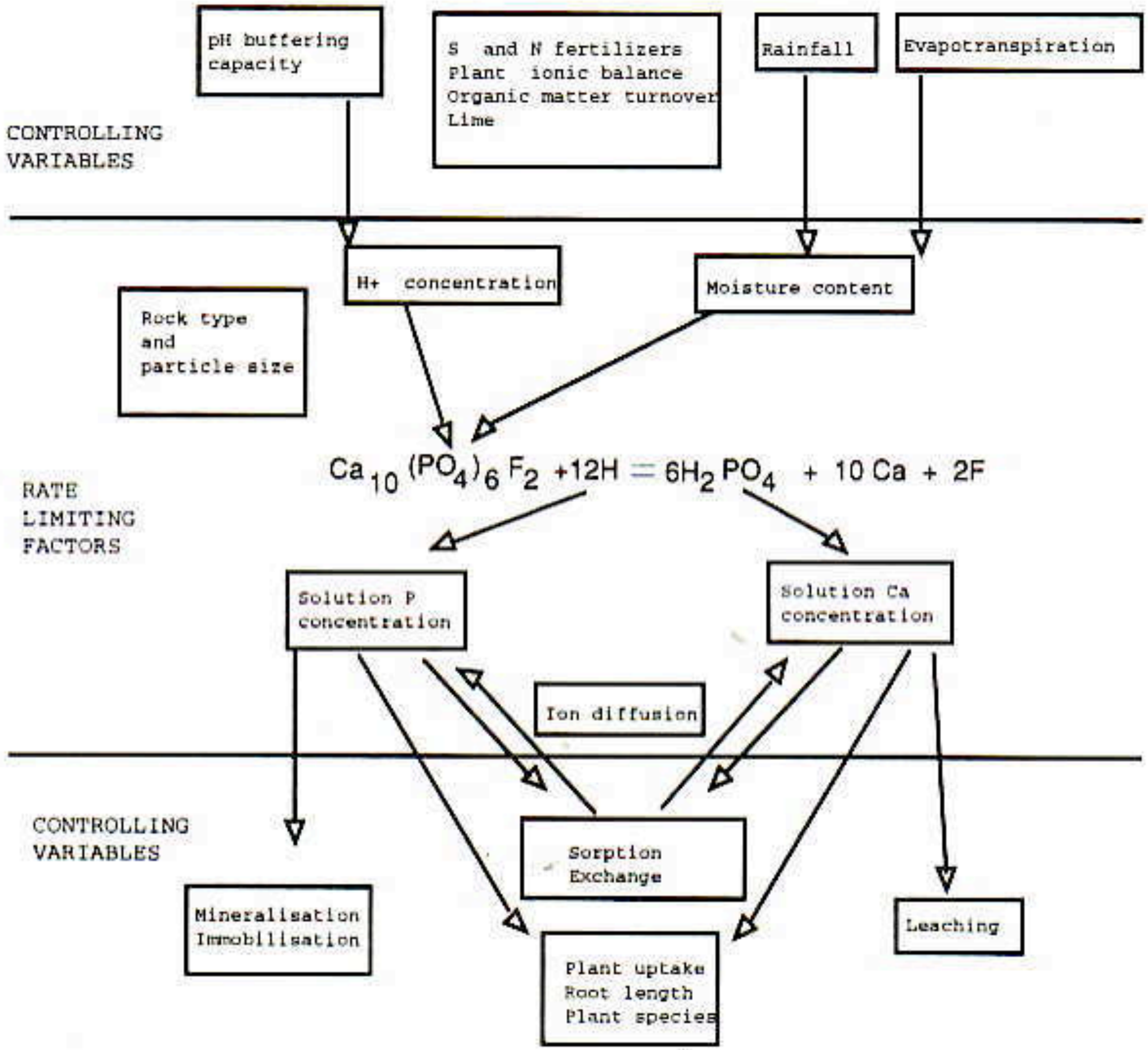


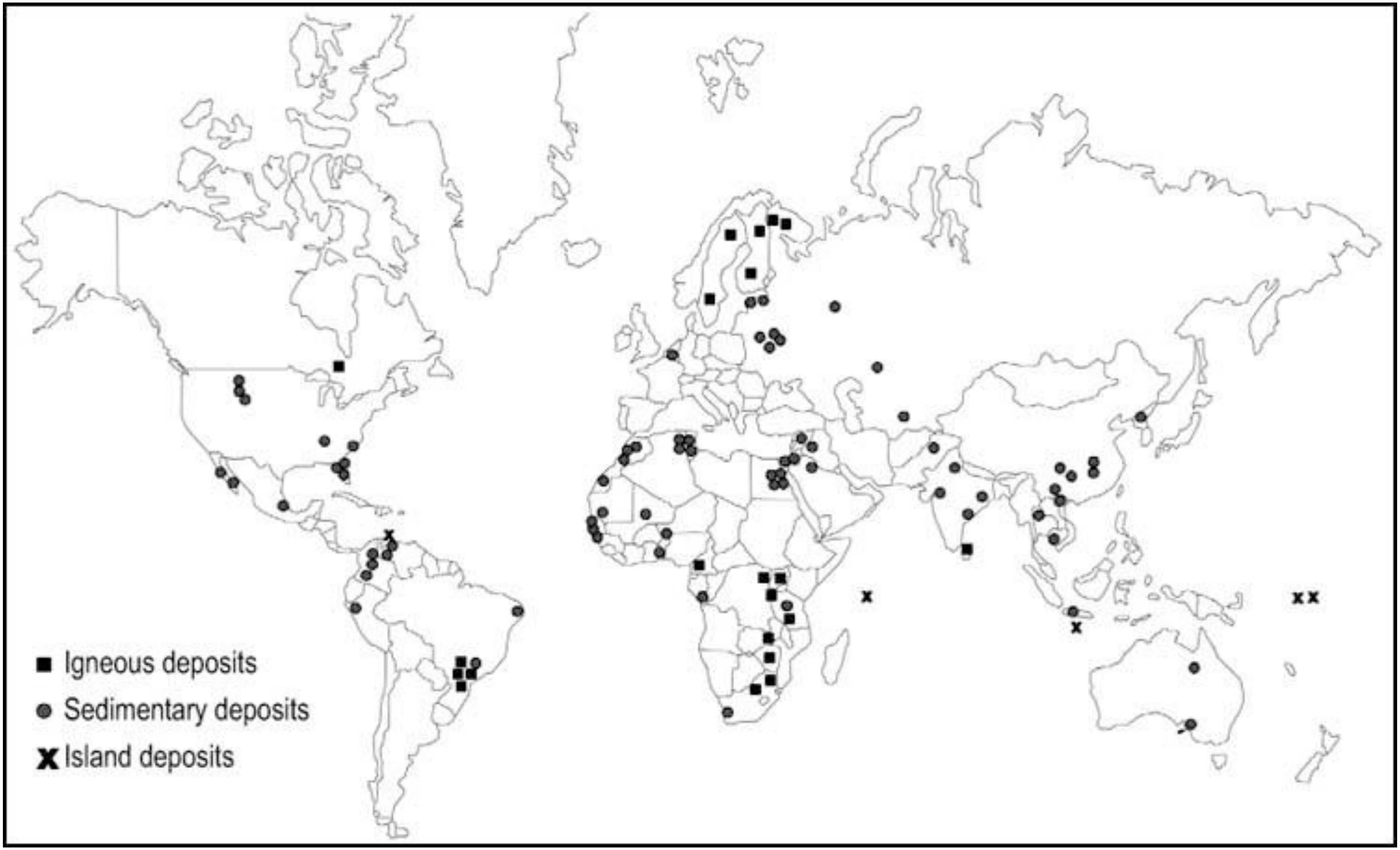
Figure 8. Schematic diagram showing the rate-limiting factors and variables determining phosphate rock dissolution

Table 4. P balances and changes in AL-soluble P content of soils between 1979 and 1982 on different slopes in the Zala River watershed (Debreczeni & Sisák, 1990).

Slope	P balance	Changes in AL-P
%	kg $ha^{-1}y^{-1}$	mg kg^{-1}
0-5	44	18.2
5-10	40	10.2
10-15	37	9.5
15-20	35	6.5
20-30	31	5.3

52 percent of known unexploited global P reserves

Economic and potentially economic phosphate deposits of the world



FAO 2004

P inputs	**kg ha^{-1} yr^{-1}**
Soil mineral weathering	0.05 - 1.0 (5.0 possible)
Atmospheric deposition	0.07 - 1.7
Total	0.12 - 2.7

Other P inputs that may be significant in particular ecosystems include: pollen, volcanic ash, fossil fuel combustion (e.g., fly ash), forest fires, ocean spray

Newman (1995)

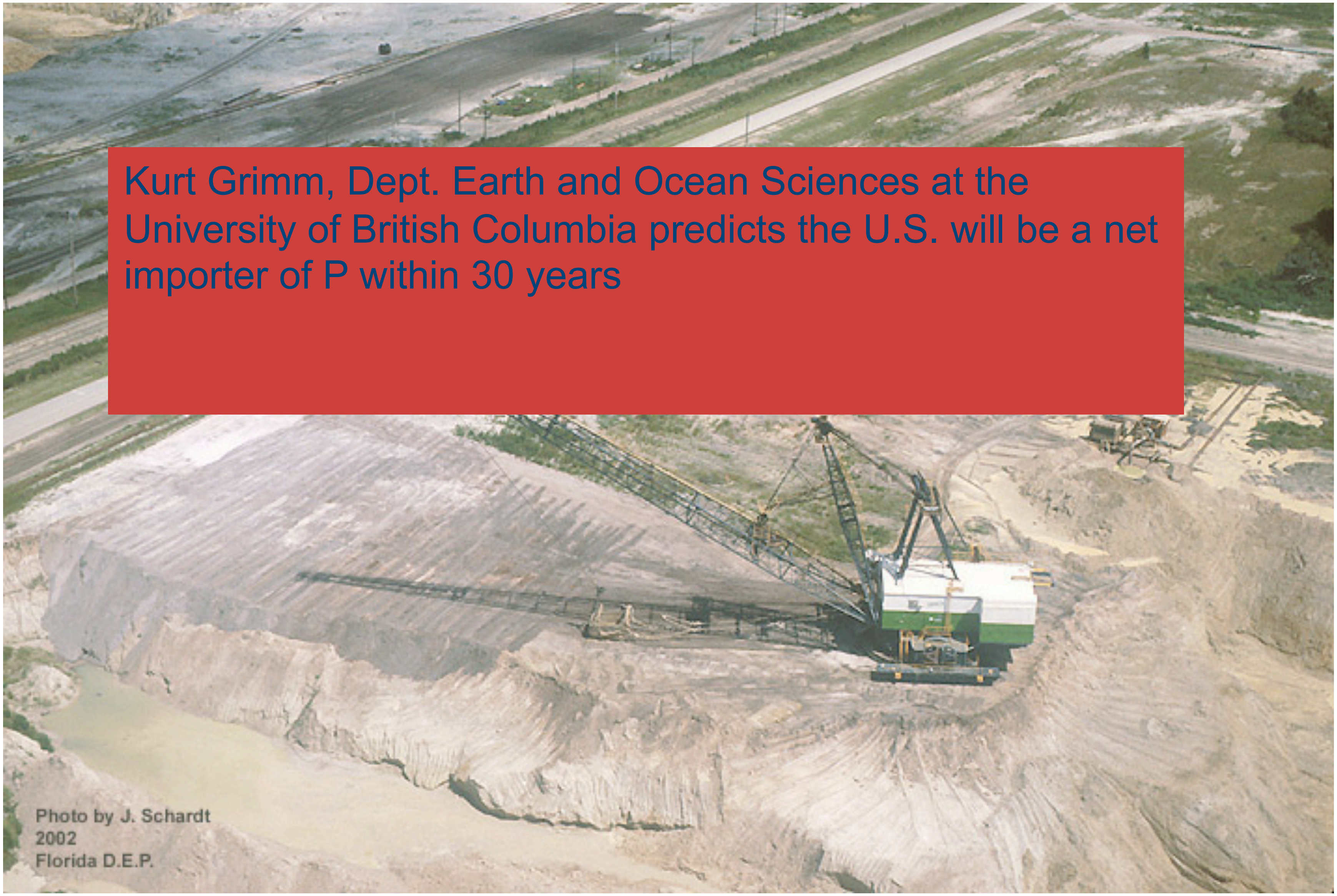
P balance for a typical modern wheat farm in Great Britain

P inputs	$kg\ ha^{-1}\ yr^{-1}$		
Soil mineral weathering	0.3		
Atmospheric deposition	net 0		
Fertilizer		25	
Total			25.3

P outputs	$kg\ ha^{-1}\ yr^{-1}$	
Leaching	0.4	
Soil erosion by water	0.5	
Soil erosion by wind	net 0	
Harvested grain	19	
Straw	3	
Total		22.9

Newman (1997)

The U.S. supplies between 38-50% of the world P market.
Florida alone supplies 75% of U.S. and 25% of the world's
P market.



Kurt Grimm, Dept. Earth and Ocean Sciences at the University of British Columbia predicts the U.S. will be a net importer of P within 30 years

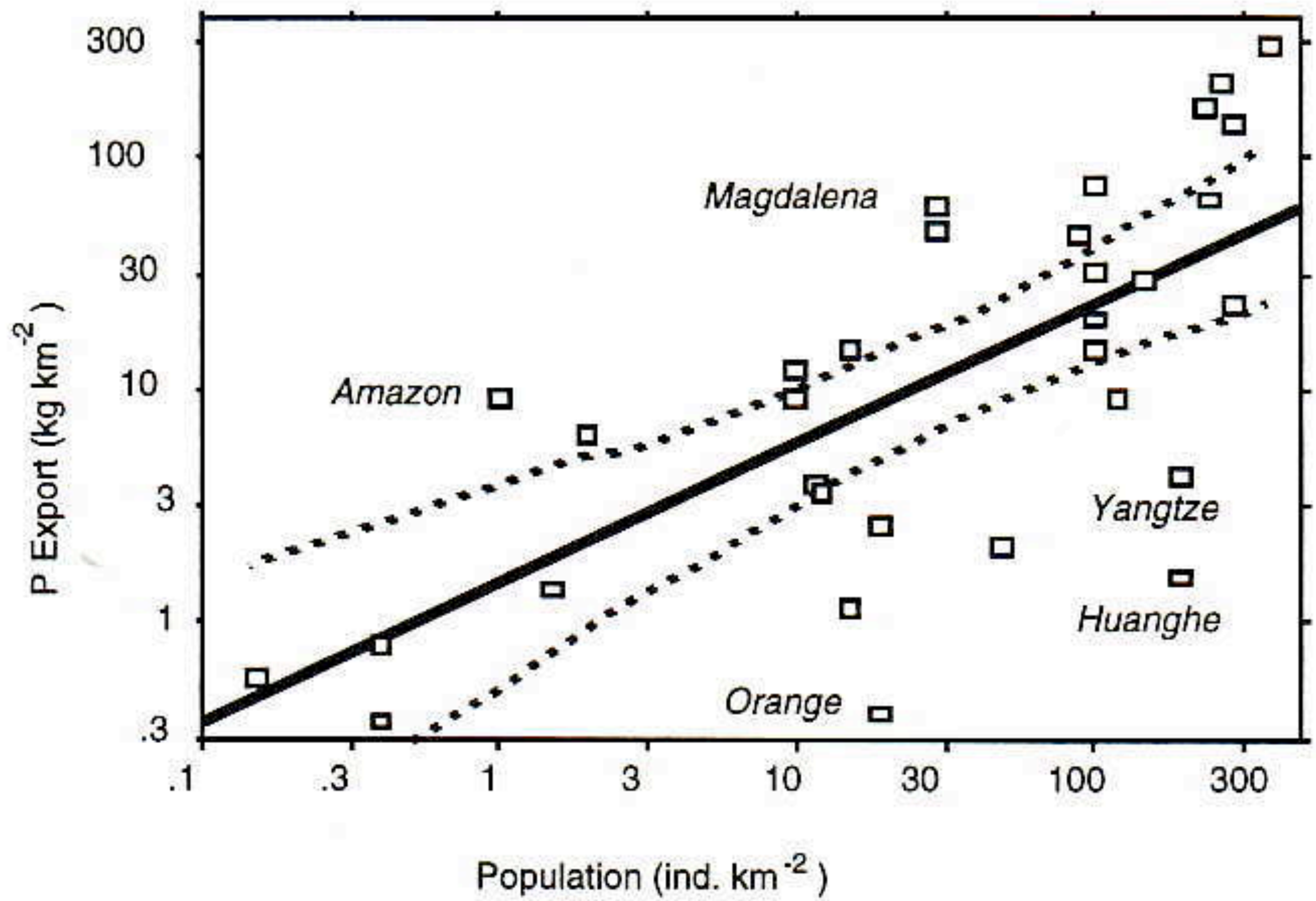
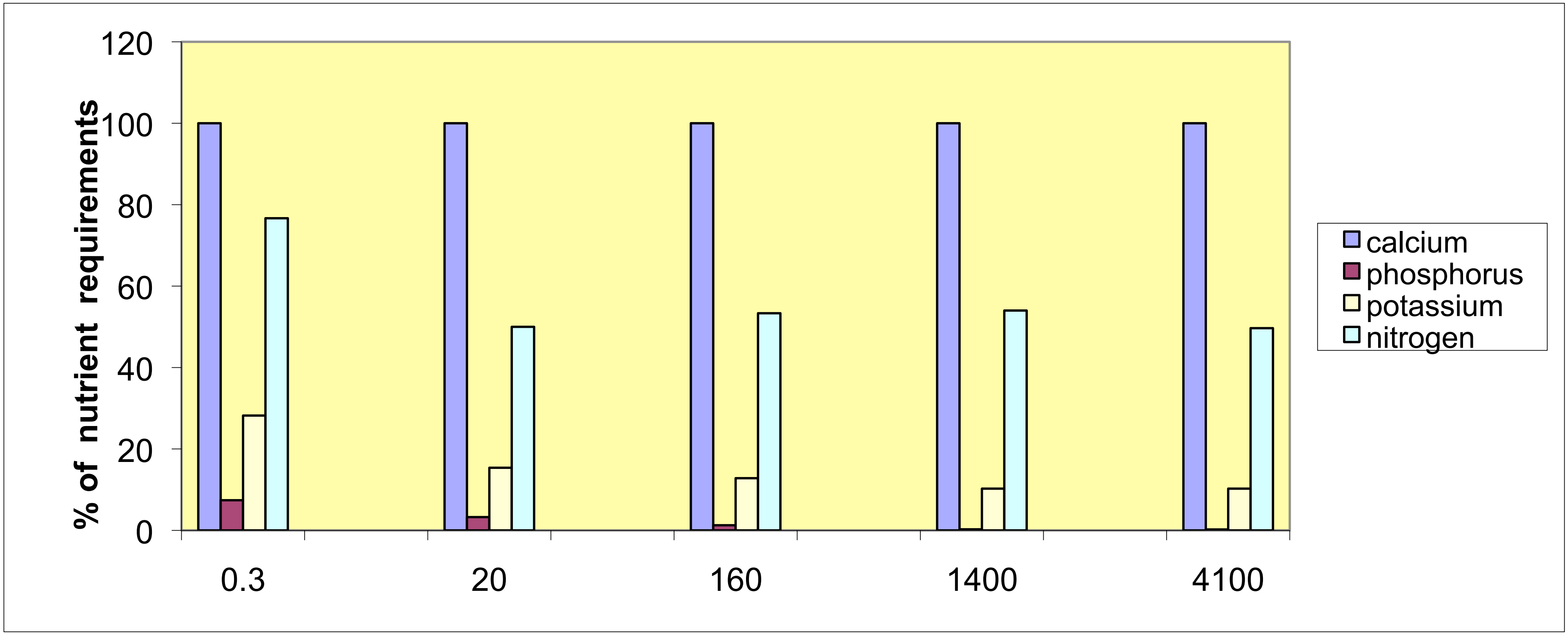


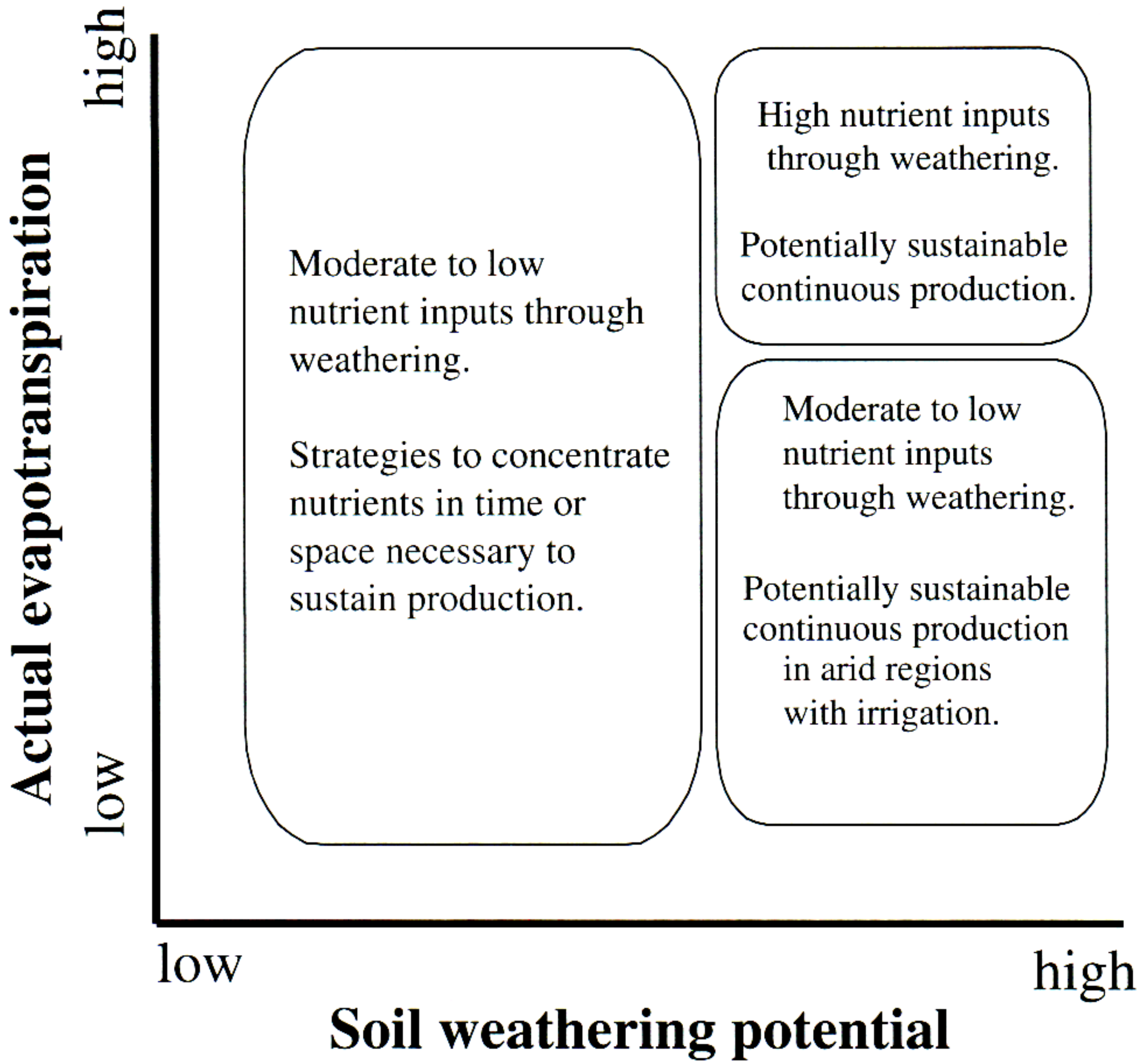
Figure 1. Relationship between population density in the watershed and export of SRP in river water. Data are for 32 major rivers (Table 1).

Percentage of sweet potato nutrient uptake[1] satisfied by endogenous nutrient supplies estimated by Vitousek (2004)



Site age (1000 years)

[1]Sweet potato crop yielding 9 Mg ha^{-1} (fresh yield) grown with no fertilizer inputs in Papua, New Guinea (Hartemink et al. 2000)



high
Actual evapotranspiration
low
Moderate to low nutrient inputs through weathering.
Strategies to concentrate nutrients in time or space necessary to sustain production.
High nutrient inputs through weathering.
Potentially sustainable continuous production.
Moderate to low nutrient inputs through weathering.
Potentially sustainable continuous production in arid regions with irrigation.
low
high
Soil weathering potential

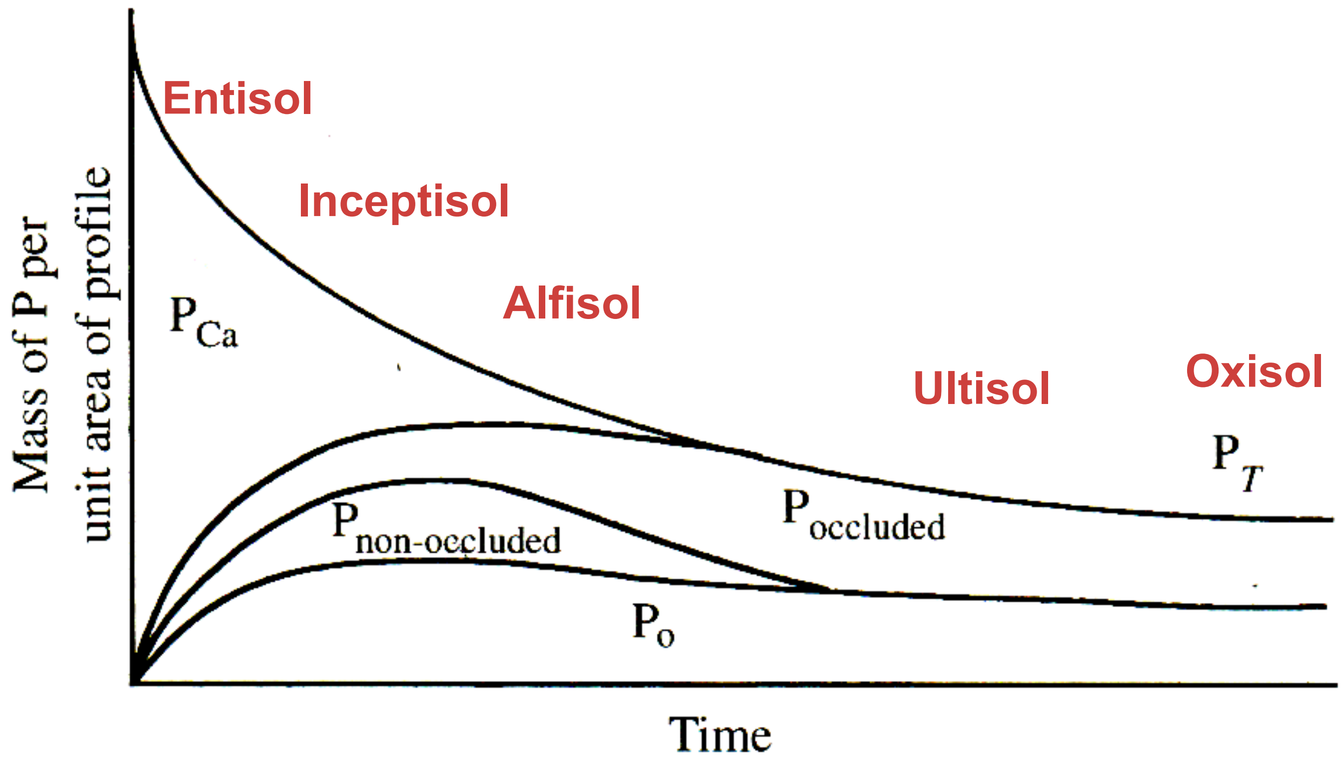
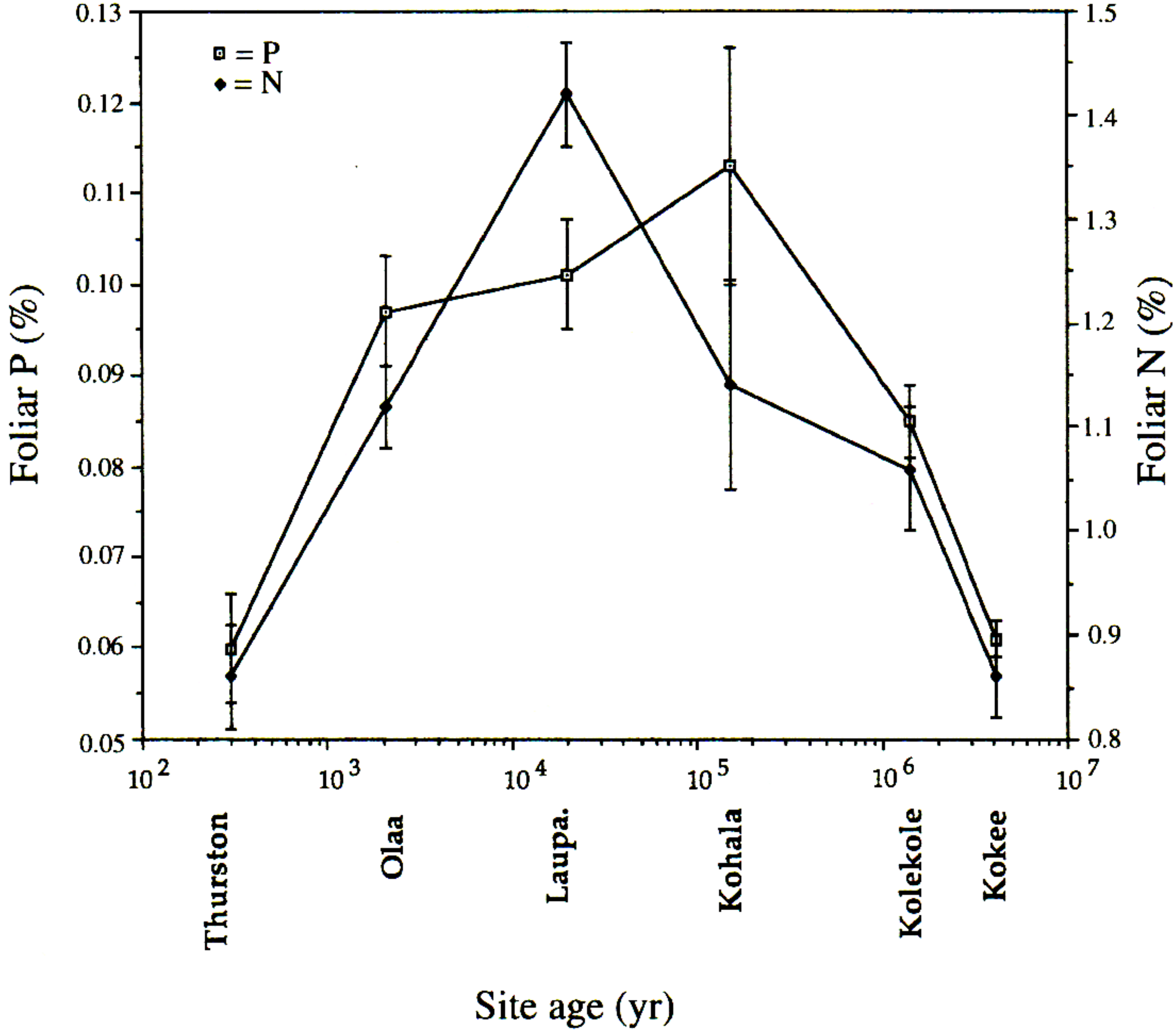


FIG. 1. Walker and Syers' (1976) diagram of P transformations with time. P_{Ca} = calcium phosphates, P_T = total phosphorus, P_o = P bound to organic matter.


0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
Foliar P (%)
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
Foliar N (%)
= P
= N
10^2
10^3
10^4
10^5
10^6
10^7
Thurston
Olaa
Laupa.
Kohala
Kolekole
Kokee
Site age (yr)

P balance for a typical modern wheat farm in Great Britain

P inputs	$kg\ ha^{-1}\ yr^{-1}$		
Soil mineral weathering	0.3		
Atmospheric deposition	net 0		
Fertilizer		25	
Total			25.3

P outputs		$kg\ ha^{-1}\ yr^{-1}$	
Leaching		0.4	
Soil erosion by water	0.5		
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Total			22.9

Newman (1997)