Lecture IV: Phosphorus transfers and cycles

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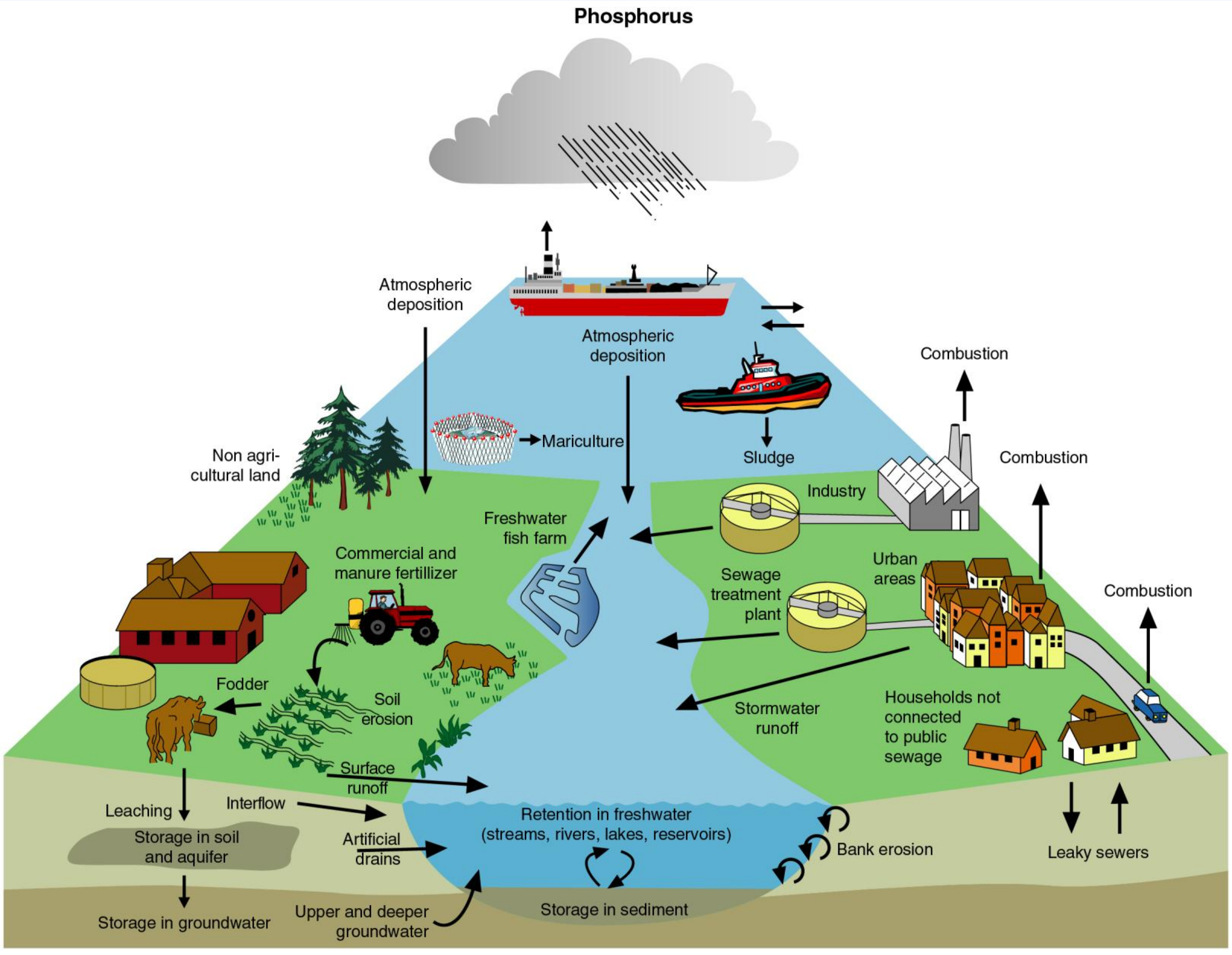
Learning Aims of this first 60 minutes lecture

- Sources of P to terrestrial and aquatic systems
- What is phosphorus for a kind of substance?
- Where is phosphorus coming from?
- What functions does P have in natural and managed systems?



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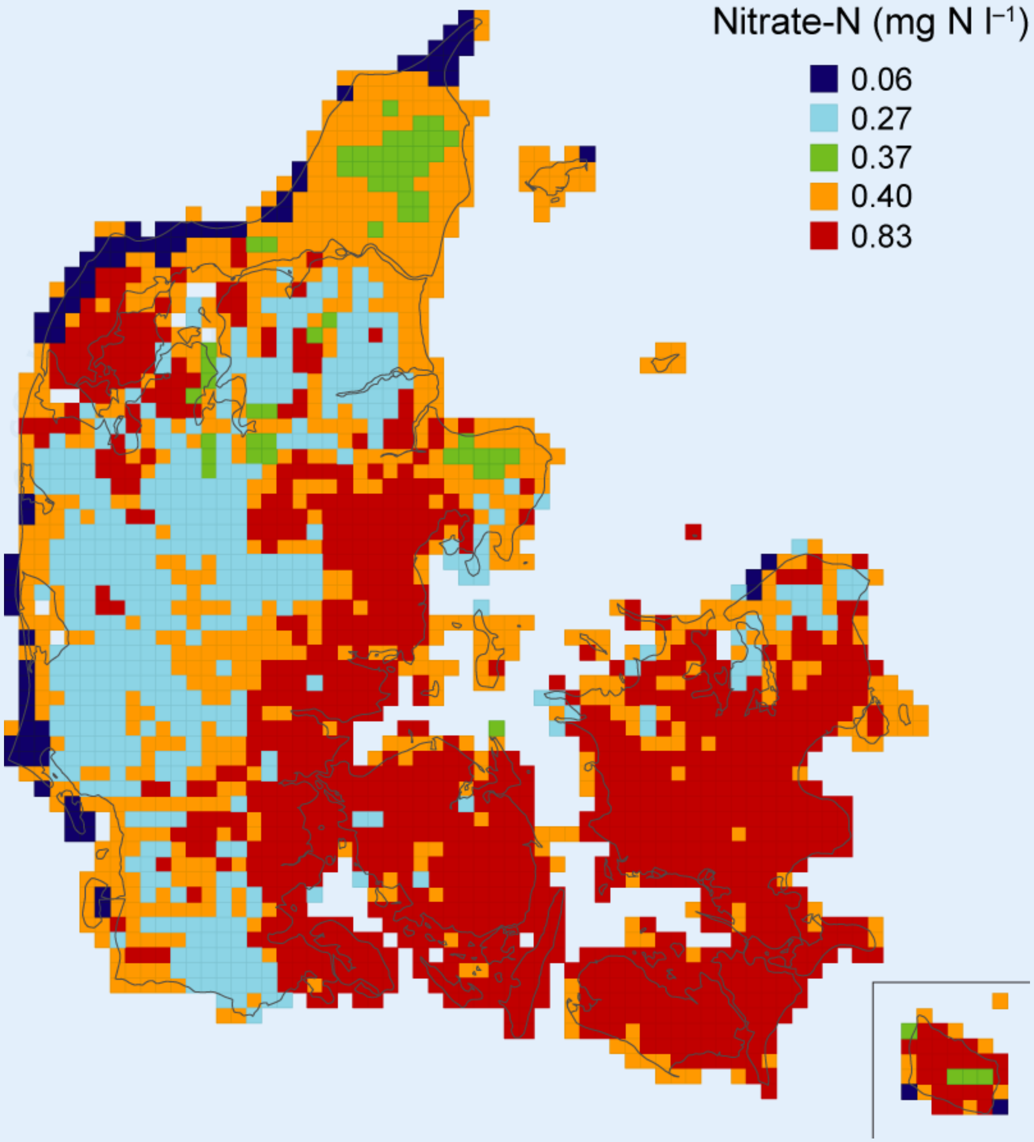
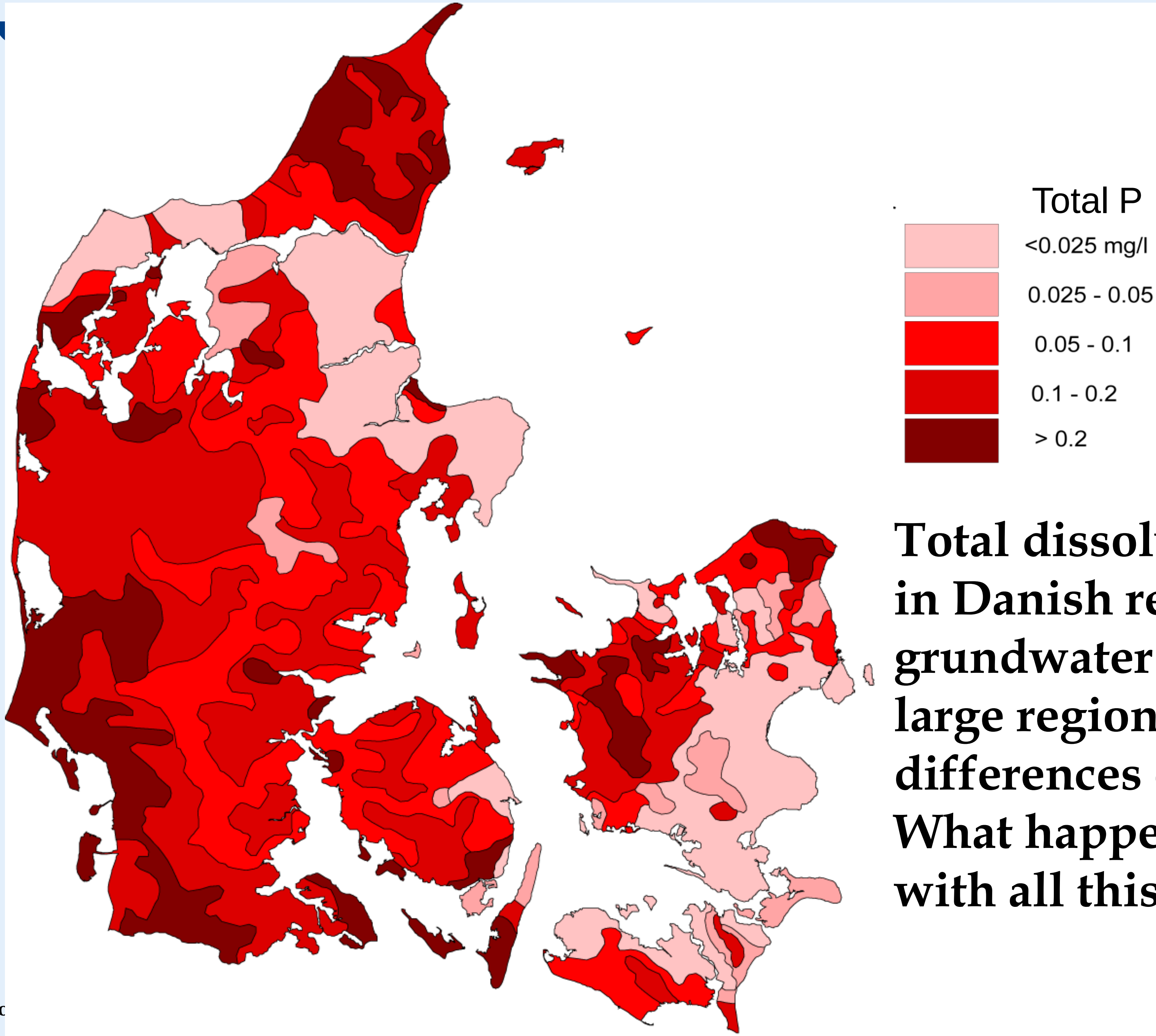
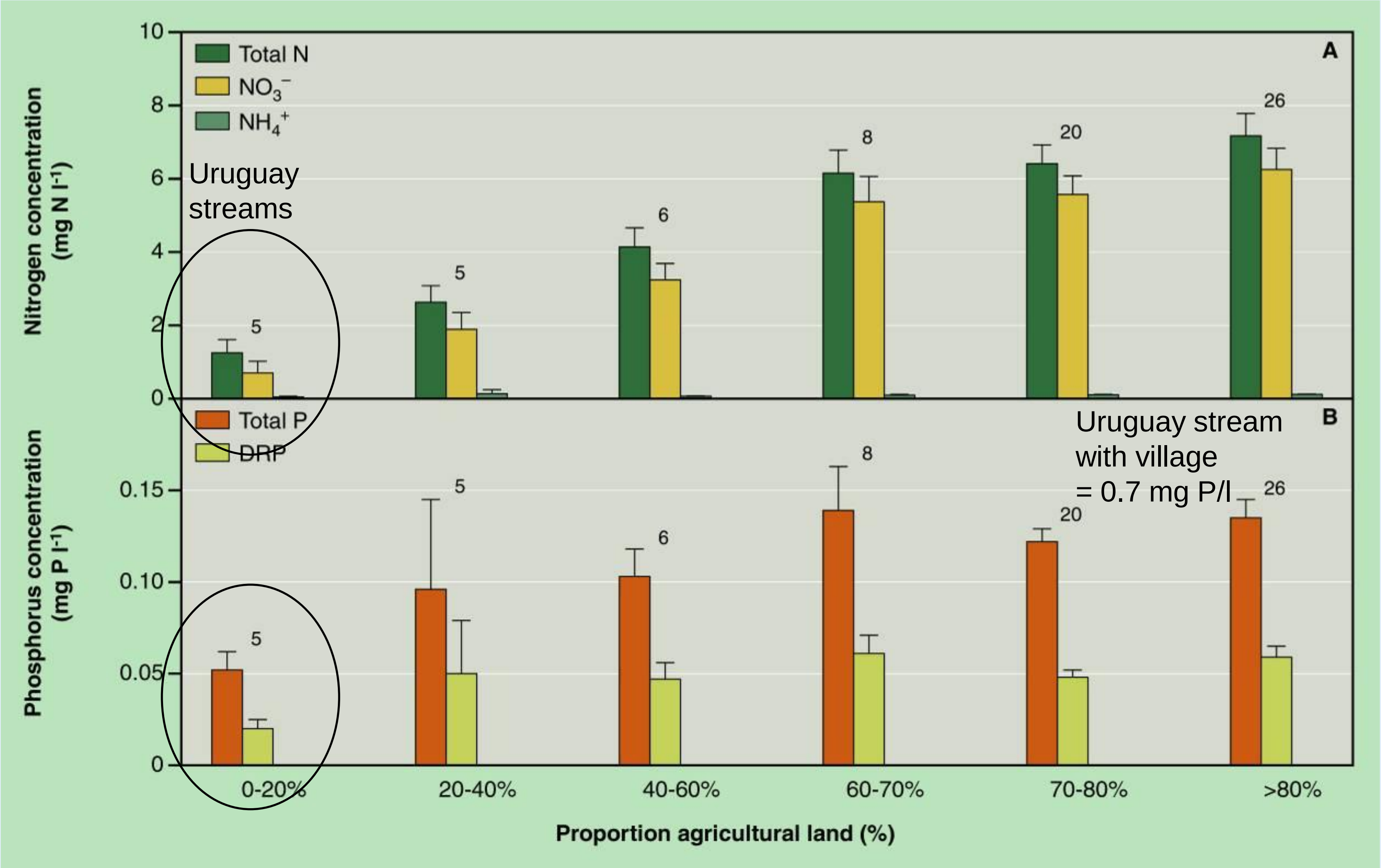
What is the background (baseline) concentrations of nitrate in Danish surface waters?





Total dissolved P in Danish reduced grundwater – large regional differences exists. What happens with all this P?

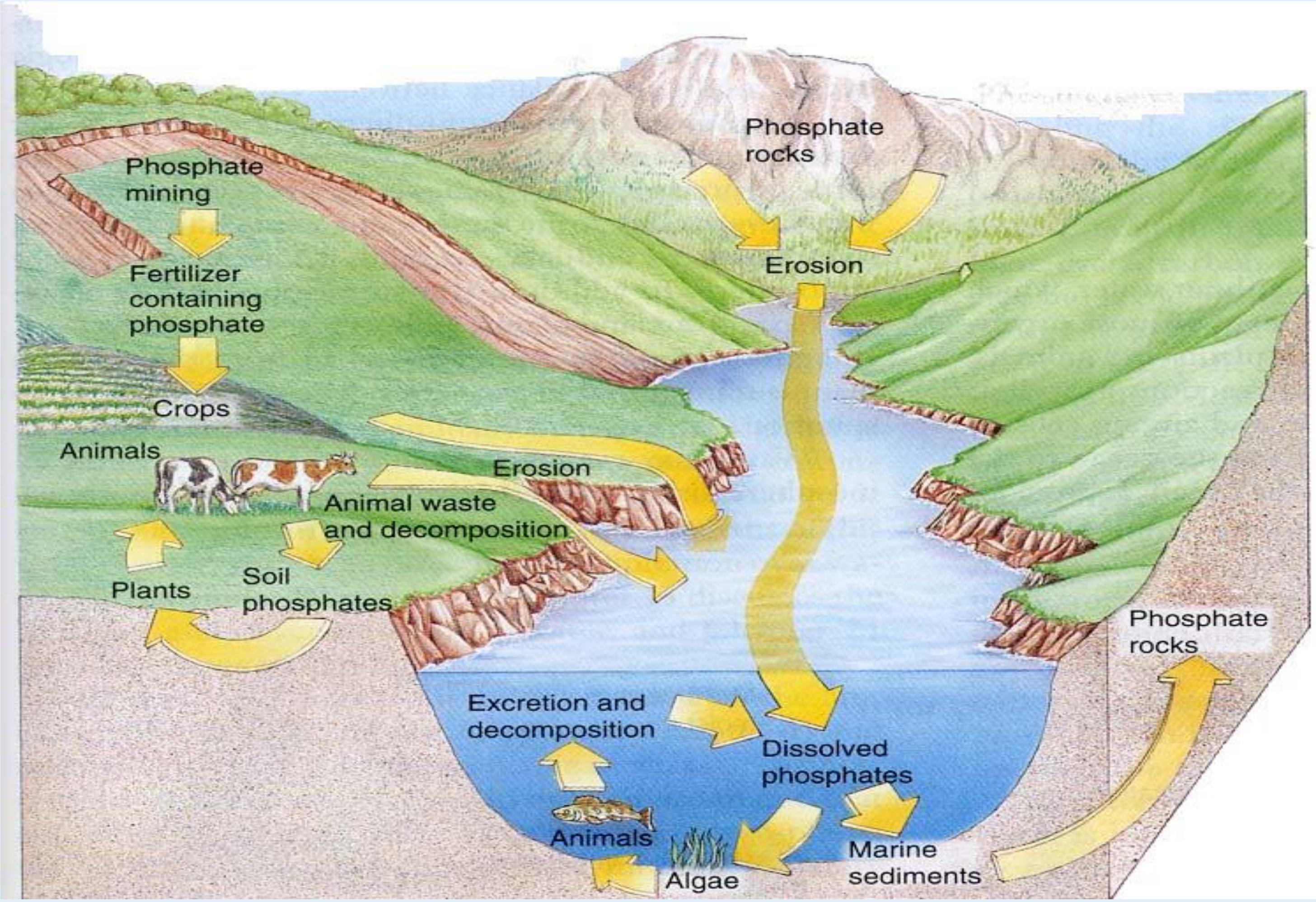
Nitrogen and phosphorus concentrations



Phosphorus (P) .

- Phosphorus (P) is the 11th most abundant element in the lithosphere.
- Phosphorus (P) is number 16 element in the Periodic Table and has atomic number 15.
- Atomic weight = 30.9737.
- Phosphorus is the limiting nutrient controlling biological production in many terrestrial and aquatic environments. When in excess dissolved phosphate leads to uncontrolled biological growth and water quality problems through a process called ’eutrophication’.

The Global P transfers and cycles



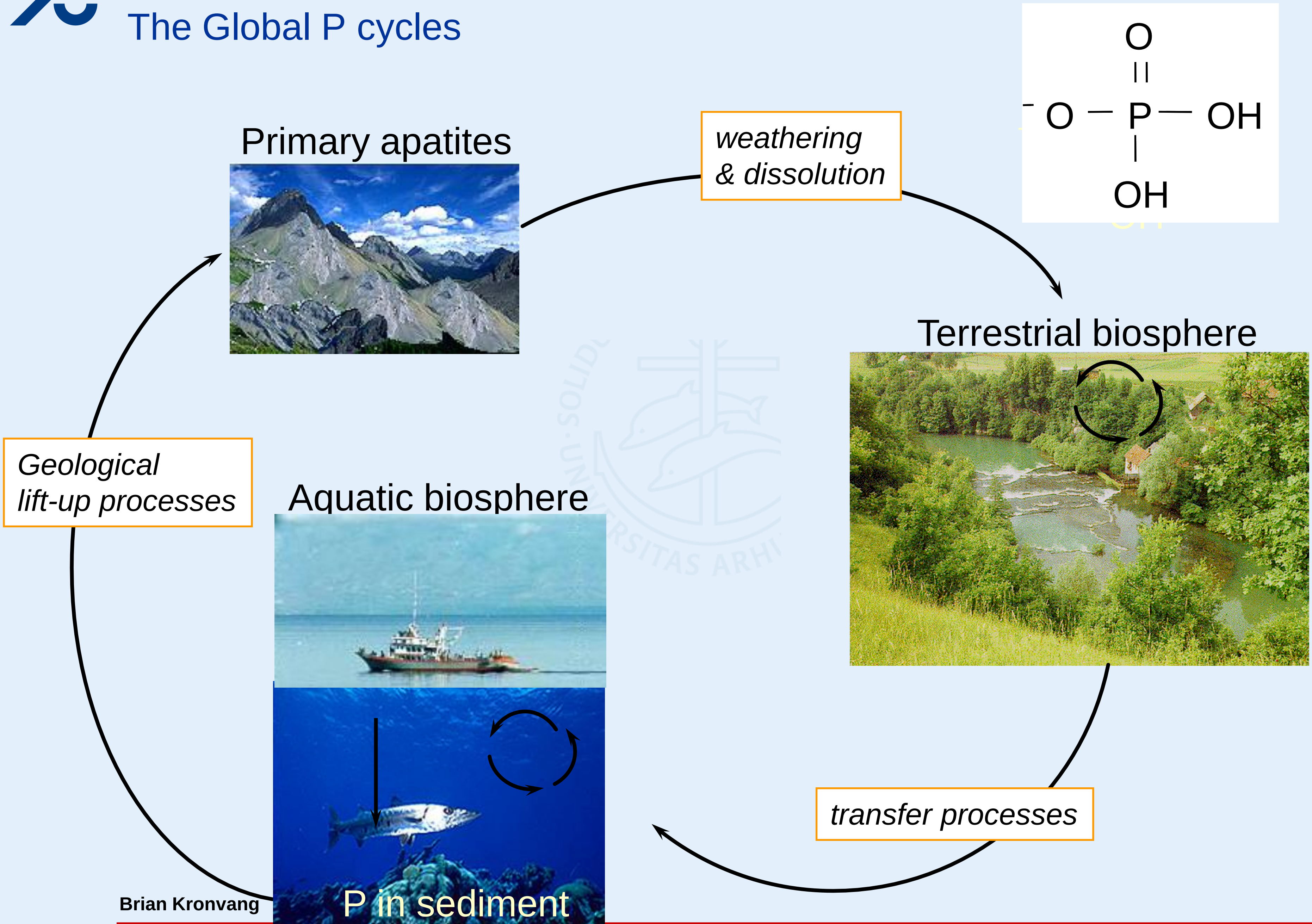
Some selected phosphate minerals

Table 1 SELECTED PHOSPHATE MINERALS

Mineral	Chemical Formula[1]
Apatite (fluorapatite)	$Ca_5(PO_4)_3F$
Autunite	$Ca(UO_2)_2(PO_4)_2 \cdot 10\text{-}12H_2O$
Chlorapatite	$Ca_5(PO_4)_3Cl$
Hydroxylapatite	$Ca_5(PO_4)_3OH$
Monazite	$(REE,U,Th)PO_4$
Pyromorphite	$Pb_5(PO_4)_3Cl$
Rhabdophane	$(REE)PO_4 \cdot H_2O$
Strengite	$FePO_4 \cdot 2H_2O$
Turquoise	$CuAl_6(PO_4)_4(OH)_8 \cdot 4H_2O$
Variscite	$AlPO_4 \cdot 2H_2O$
Vivianite	$Fe_3(PO_4)_2 \cdot 8H_2O$
Wavellite	$Al_3(PO_4)_2(OH)_3 \cdot 5H_2O$
Xenotime	$(Y,REE)PO_4$

1 REE stands for rare earth elements

The Global P cycles



Phosphorus is a limited global resource – though necessary in agricultural production to feed a growing population

- Economic phosphorus supplies may be severely depleted over the next 100 years.

TABLE 2 PHOSPHATE ROCK PRODUCTION AND RESOURCES FOR 2005 (Jasinski 2006)

Country	Production (thousands of metric tons P_2O_5)	Resources (millions of metric tons of phosphate rock)
Australia	550	1200
Brazil	2200	370
Canada	380	200
China	9130	13,000
Egypt	800	760
Israel	880	800
Jordan	2060	1700
Morocco	8300	21,000
Russia	4000	1000
South Africa	1000	2500
Syria	1050	800
Togo	368	60
Tunisia	2400	600
United States	10,500	3400
Other countries	2482	2610
Total	**46,100**	**50,000**

Trends in Global phosphate rock production

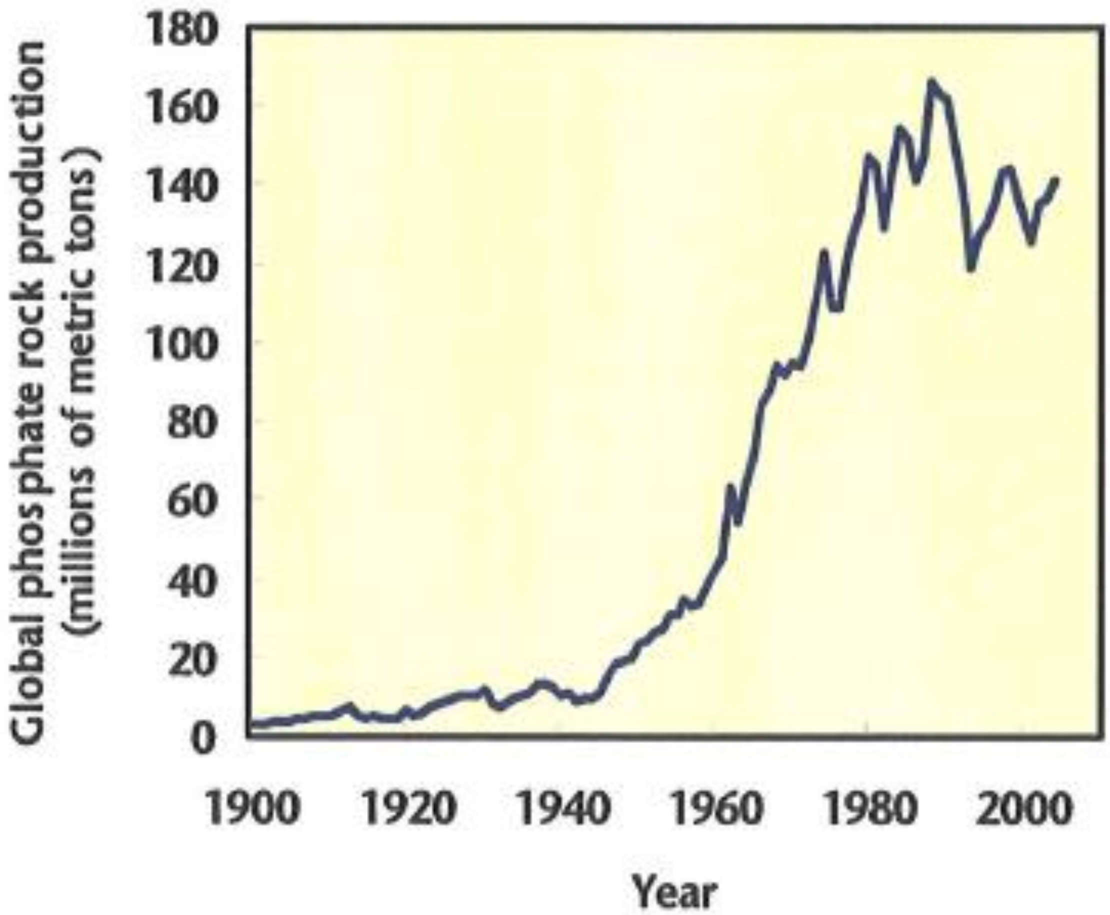


FIGURE 4 Global phosphate production (U.S. Geological Survey 2007)

Costs of producing one ton of P fertilizer fixed to 1998 US$ level

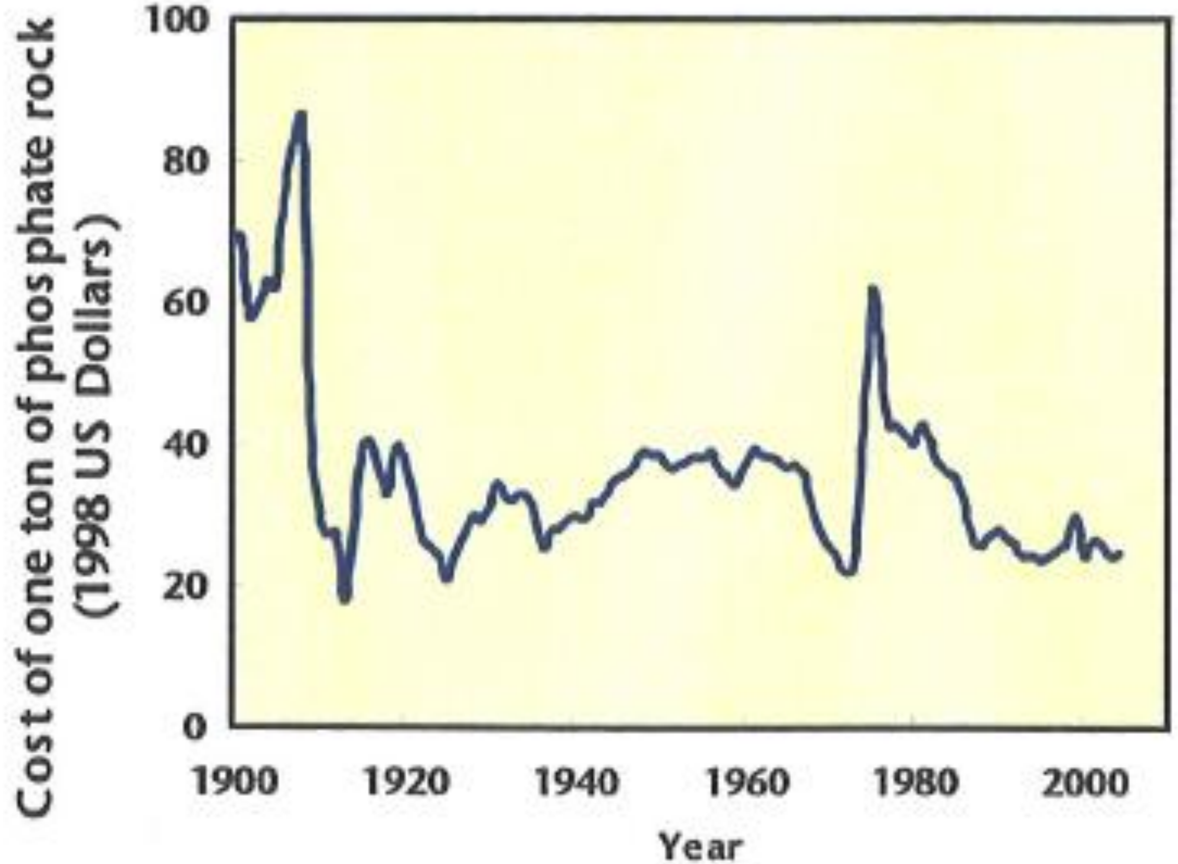


FIGURE 5 Cost of phosphate rock from 1900 to 2005 in constant 1998 US dollars (U.S. Geological Survey 2007)

P is an essential nutrient for organisms

- P-forms in plants:
  - ATP etc
  - Fatty acids
  - DNA/RNA
  - Phytic acid
- P forms in animals:
  - ATP
  - Fatty acids
  - DNA/RNA
  - Proteins
  - Calcium phosphates (bones)

P in Aquatic systems –where especially is it harmful?:

- Streams ? Normally not
- Rivers? Yes
- Lakes? Yes
- Estuaries? Yes
- Oceans? No

US EPA has set the following regulations in phosphorus concentrations in surface waters

- Running waters entering lakes and reservoirs = 0.050 mg P/l = 50 µg P/l.
- In-lake and in-reservoir concentrations = 0.025 mg P/l = 25 µg P/l.
- Running waters not entering a lake or reservoir = 0.100 mg P/l = 100 µg P/l.


Eutrofication of surface waters
-Especially rivers, reservoirs, lakes
and estuaries

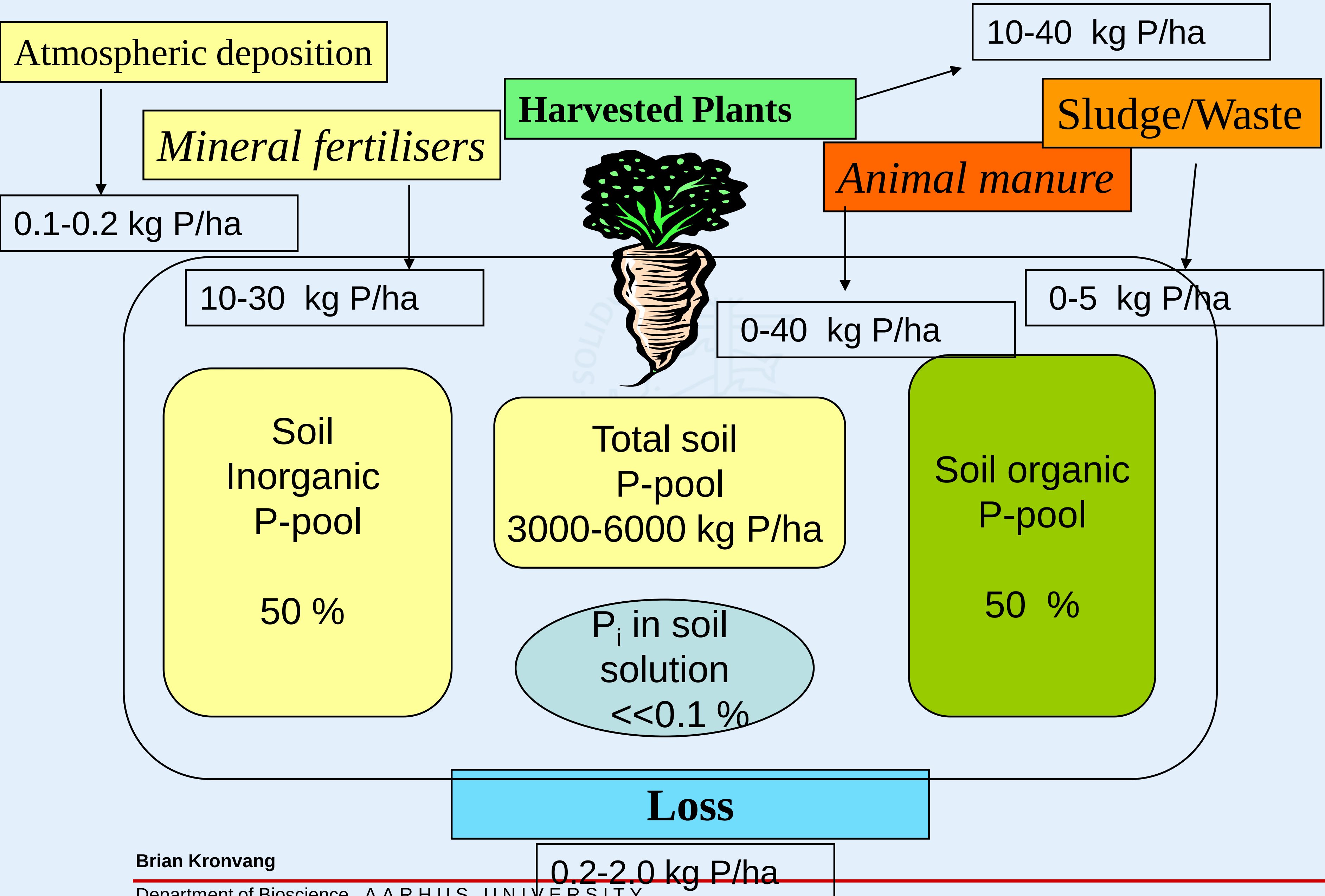
Redfield ratio - used in judging what is the limiting nutrient for algal growth

- **Redfield ratio** is the molecular ratio of nitrogen and phosphorus in deep sea phytoplakton. The stoichiometric ratio is N:P = 16:1.
- Thus, the Redfield N:P ratio is 16:1 at a molar basis.
- On a weight base the N:P ratio can be calculated knowing the molar weight of N (14.01 g) and P (30.97 g).
- N:P weight basis = ((16 · 14.01)/(1 · 30.97)) = 7.23.
- If Redfield ratio is > 7.23 (weight) or 16 (molar) then phosphorus is limiting algal growth.
- If Redfield Ratio is < 7.23 (weight) or 16 (molar) then nitrogen is limiting algal growth.

- Exercise 1:
- This figure shows the important P inputs, pools and outputs in managed agricultural systems, but all the boxes indicating the numbers of P (kg P/ha) or (Percentage of soil pool) are empty.

- Put your best judgement on the numbers into the boxes as fixed values or range’s.
- Compare the numbers between the inputs, pools and outputs.
    - Where do you believe it is possible to regulate in order to lower P-losses from soil?
    - What kind of P is lost from the soil?

P inputs, pools and outputs in agricultural systems (kg P per hectare per year)



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Learning Aims of this second 60 minutes lecture

- Importance of Phoshorus as a plant nutrient?
- P pools and balances in agricultural systems?
- P pathways from land to water?
- P forms?

Terrestrial P cycles

- P sources for plants in natural systems
  - Dissolution of primary minerals
  - Recycling of organic P
  - Release from secondary minerals retaining P
- Additional P sources in agricultural systems
  - Inorganic fertilisers
  - Animal manure
  - P rich waste products

Phosphate reacts willingly and fast with soil.

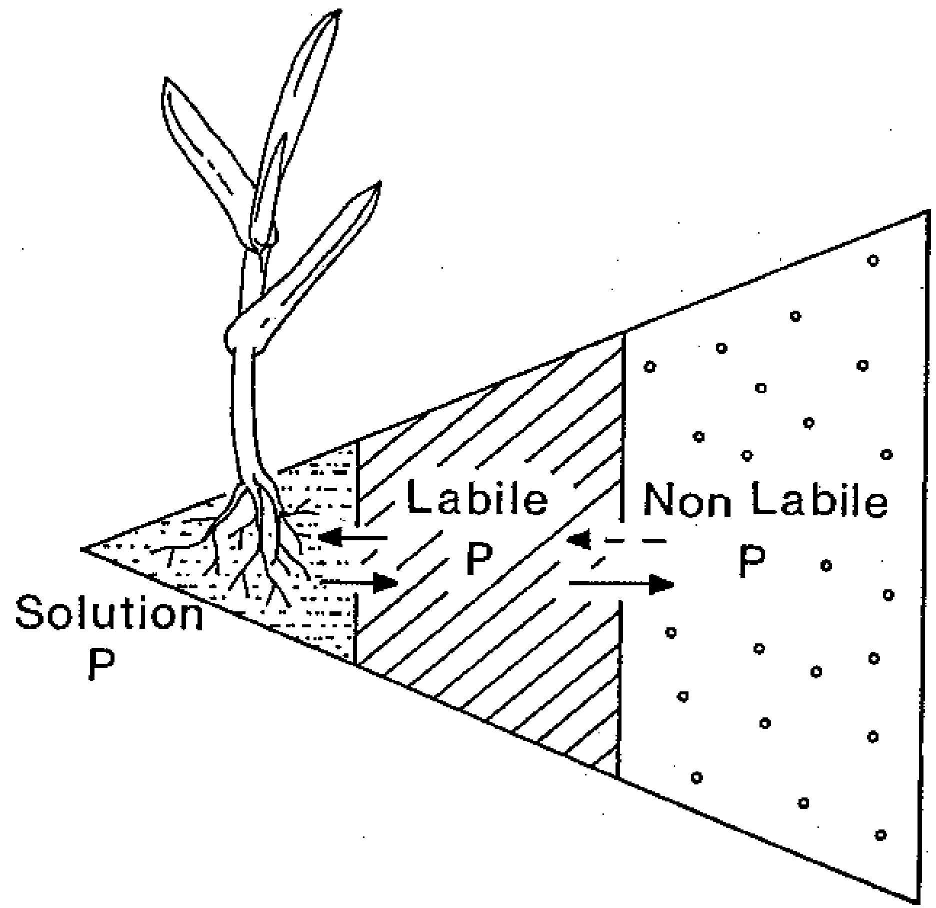
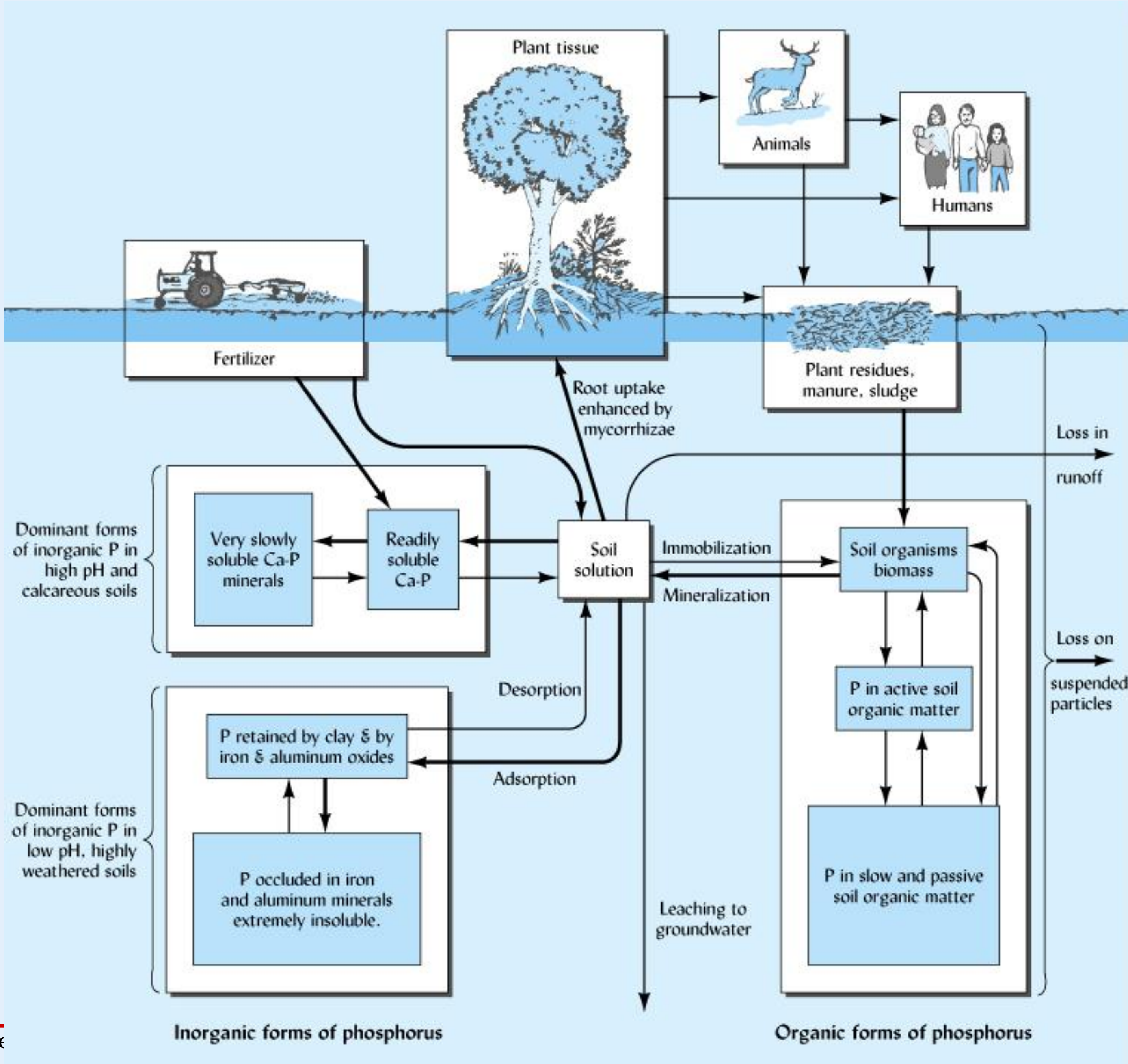


Fig.9.2 Schematic representation of the 3 important P soil fractions for plant nutrition.

Phosphate is mobile within the plant, but rather immobile in soil (compared to e.g. nitrate)

P cycling terrestrial systems

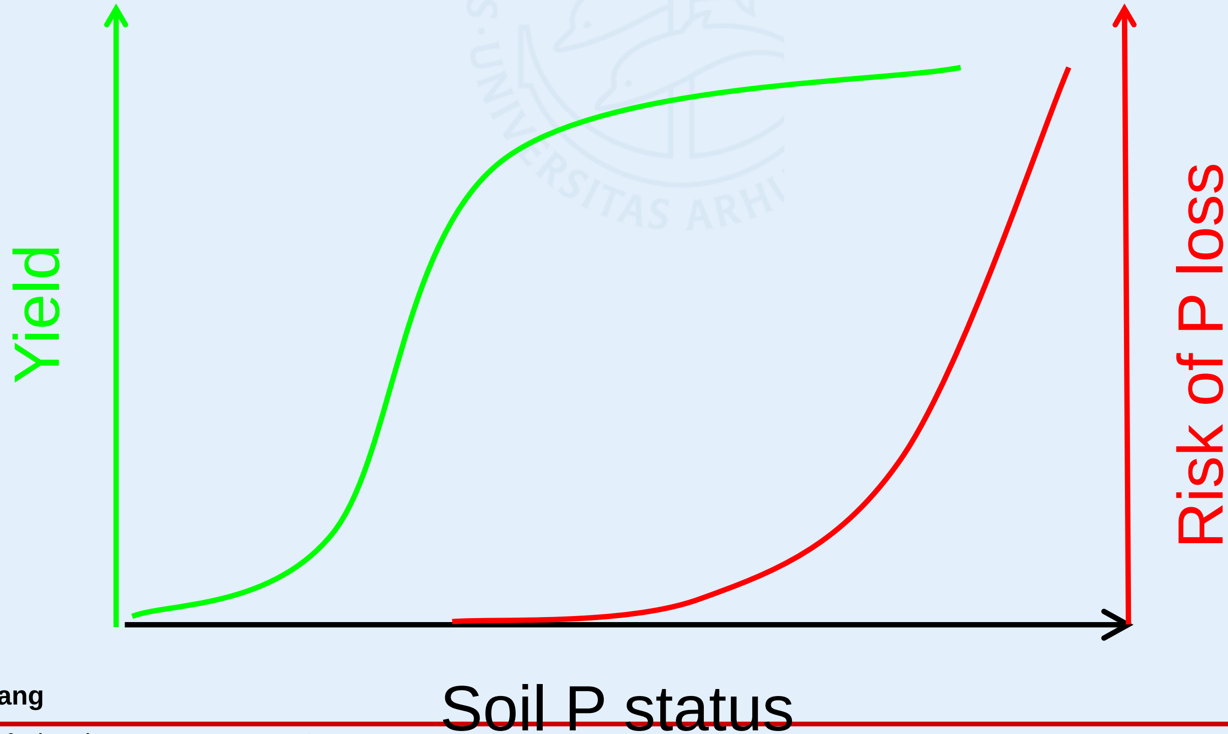
Brady and Weil, 2002.



For crop production a certain P level is needed, but….

Productivity

Environment



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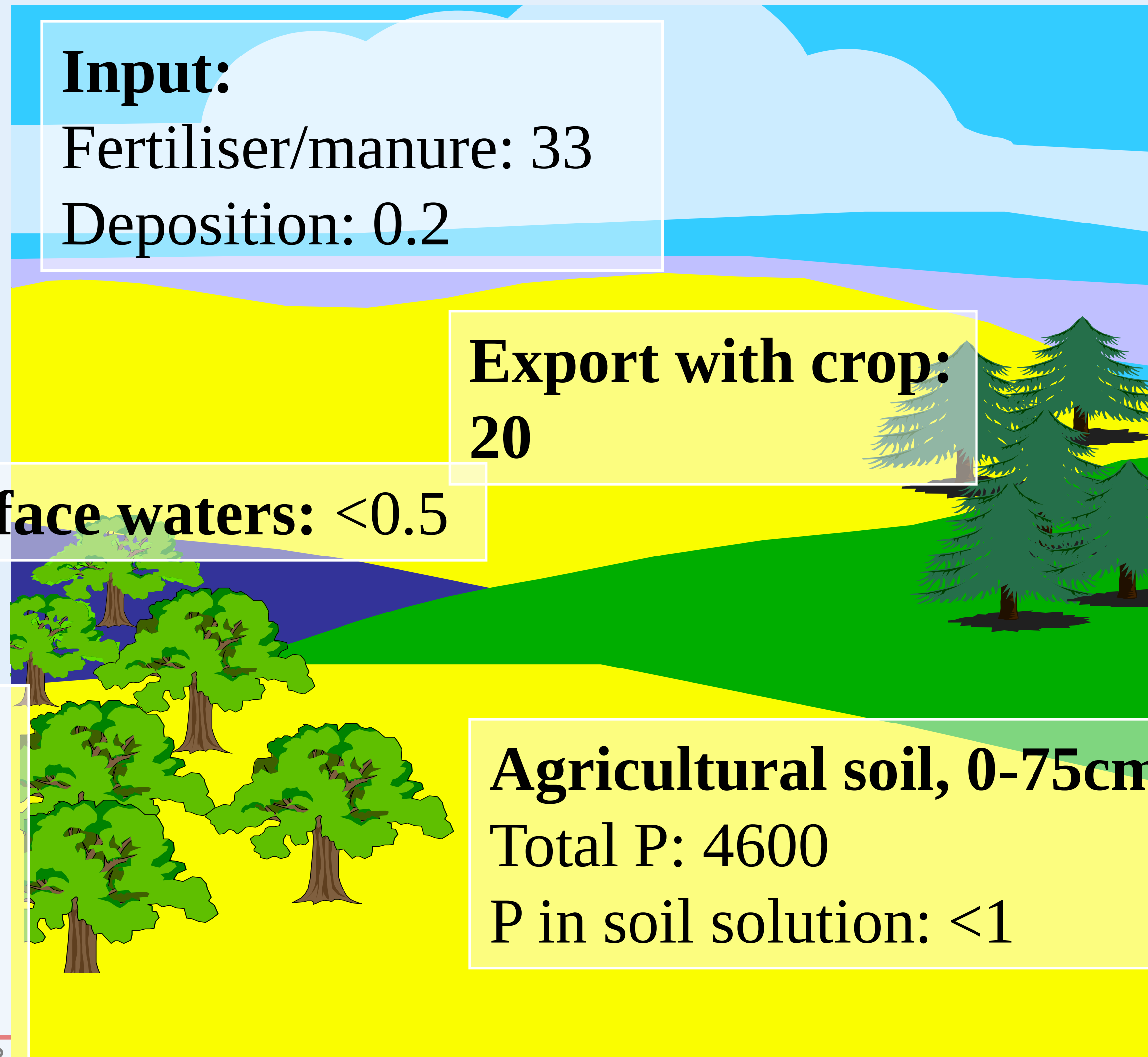
Phosphorus in Danish soils

[Kg Pha^{-1}]



Input:
Fertiliser/manure: 33
Deposition: 0.2

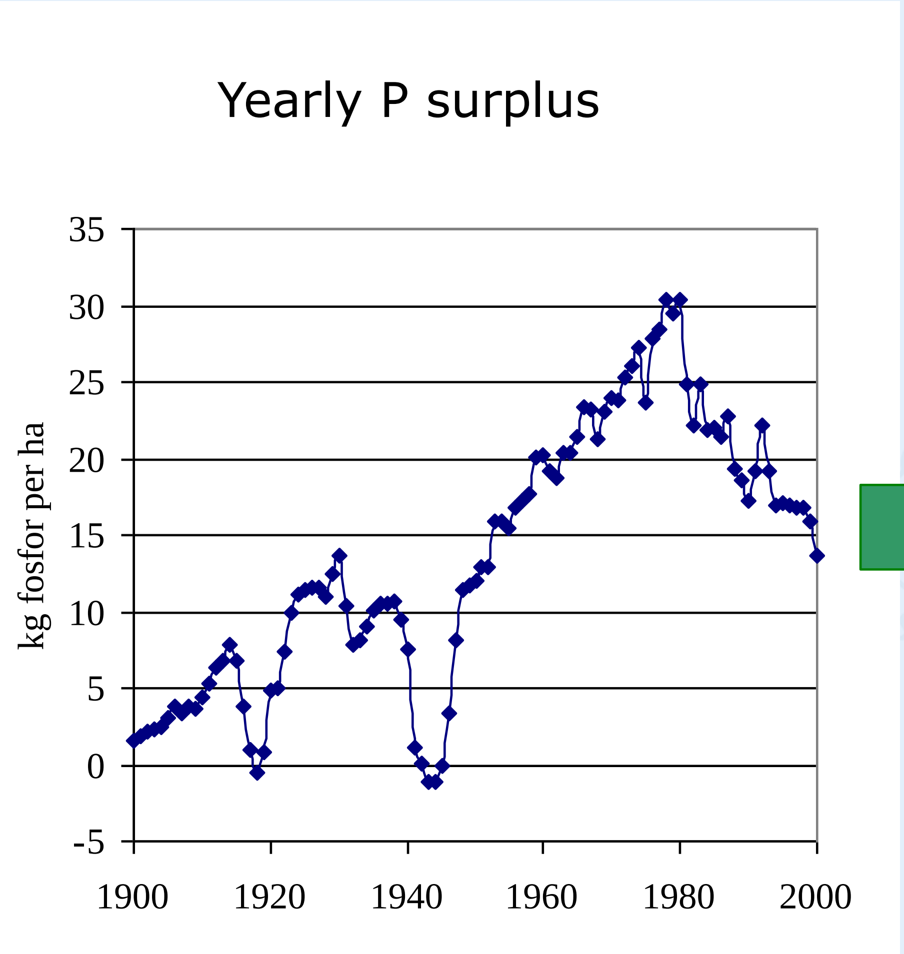
Export with crop: 20

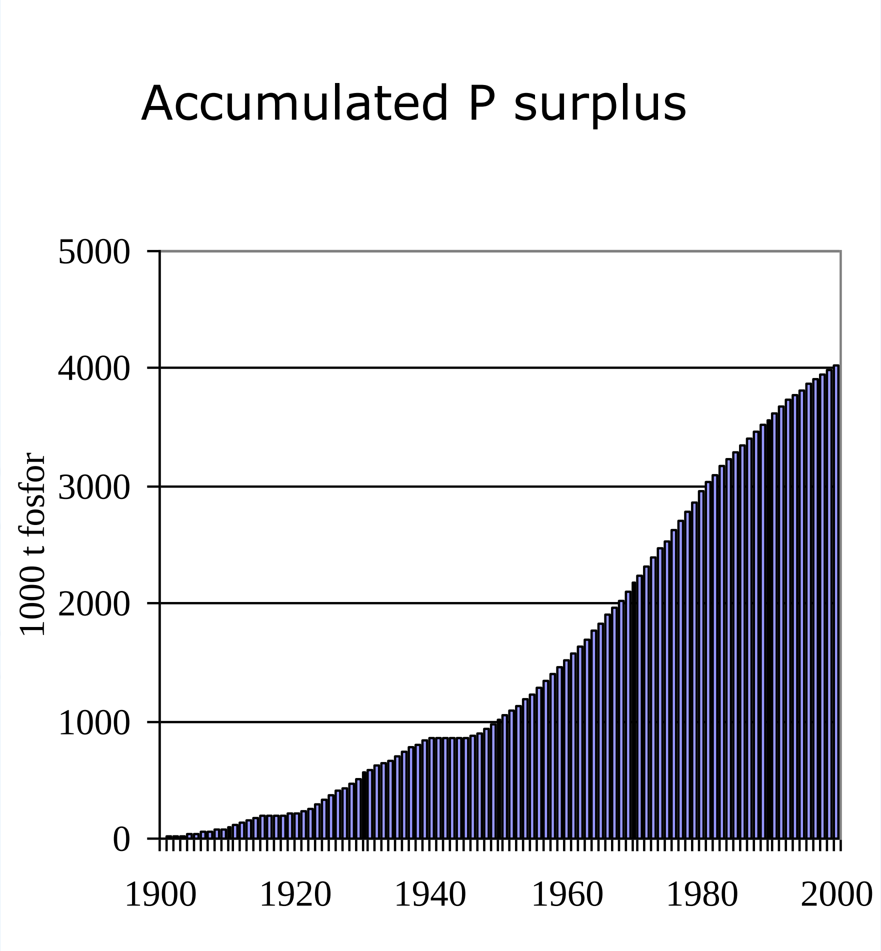
Loss to surface waters: <0.5

Deciduous forest soil, 0-75 cm:
Totalfosfor: 2700

Agricultural soil, 0-75cm
Total P: 4600
P in soil solution: <1

The yearly P surplus in Denmark





More than 1,4 tons P/ha

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Farming system and P balance, a US-example

Table 1. Farming system and P balance

P	Farming system			
	Crop*	Dairy†	Poultry‡	Hogs§
Input	- - - - - - - - - - - - - - - - - lb P/acre/yr - - - - - - - - - - - - - - - -			
Fertilizer	20	10	0	0
Feed	0	20	1,375	95
Output	–18	–13	– 365	-60
Balance	+2	+17	+1,010	+35

SOURCE: Lanyon and Thompson (1996) and Bacon et al. (1990).

$$\text{Kg ha}^{-1} = 1.12 \times \text{lb acre}^{-1}$$

N based nutrient management may lead to surplus P additions on farms with intensive animal production

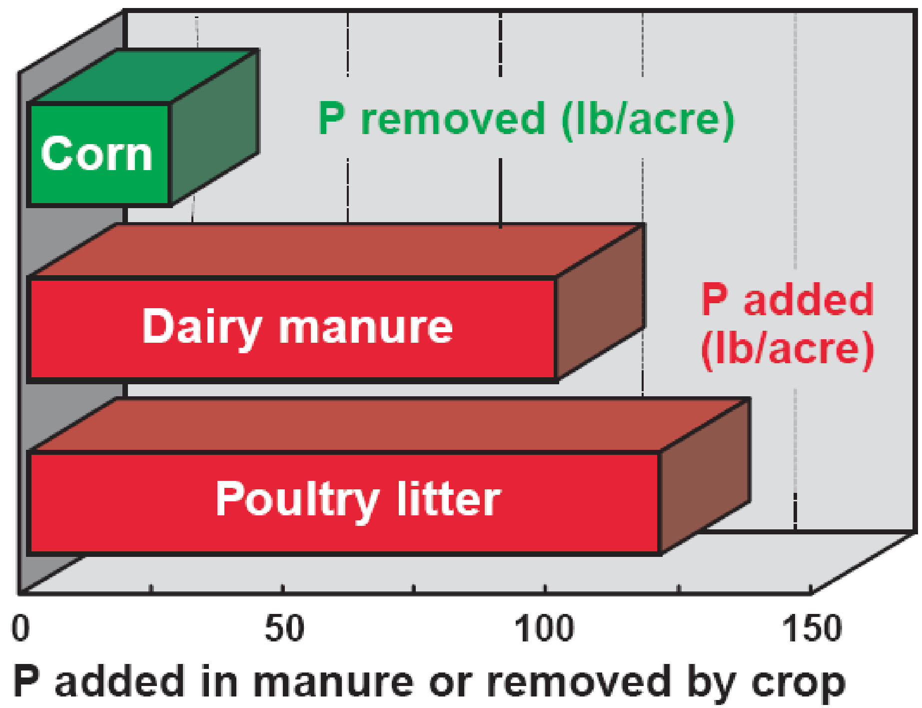

Figure 5. Applying manure to meet crop N needs (about 200 lb available N/acre) adds much more P than corn crop needs.

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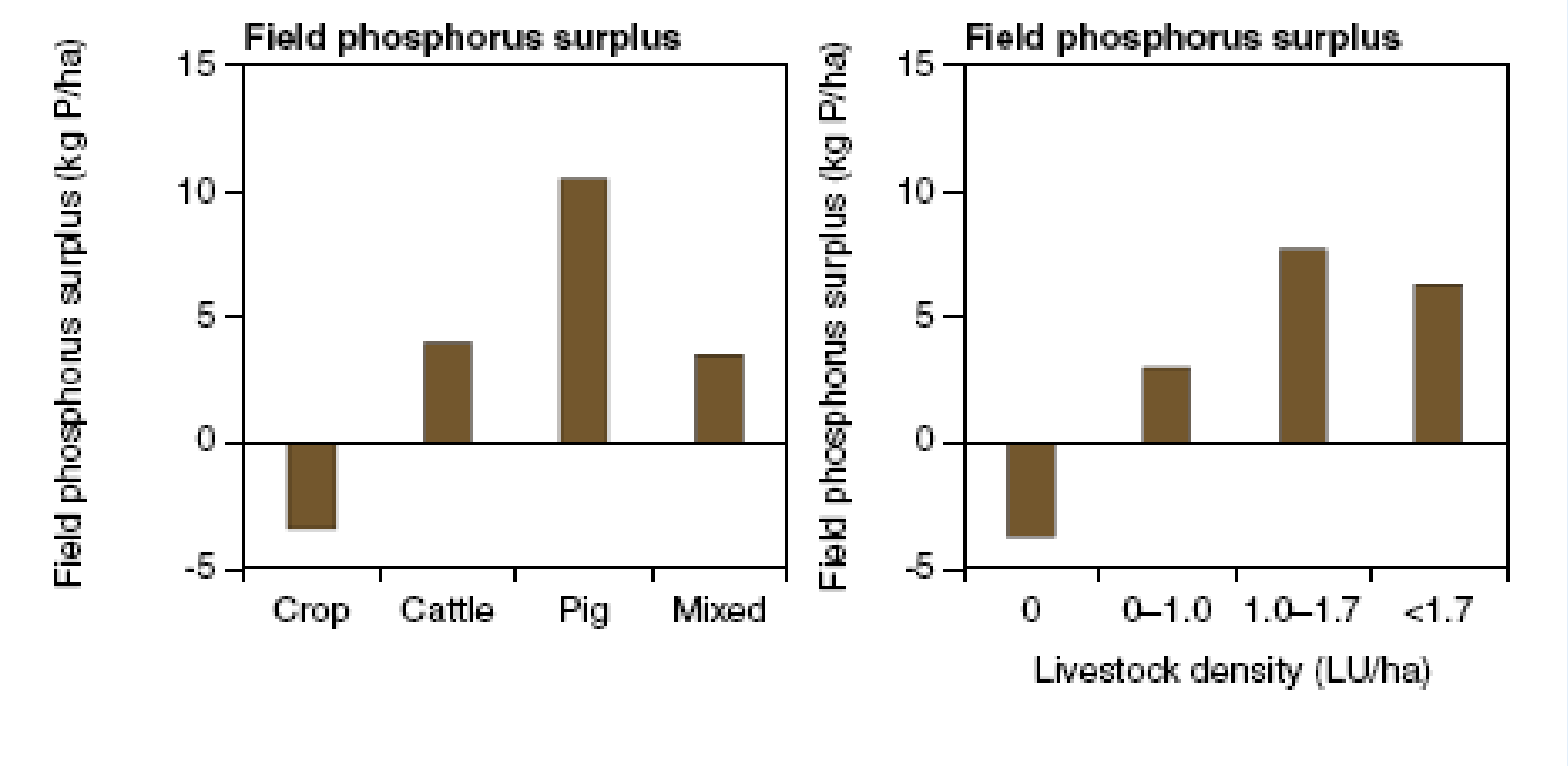
Field P-surplus dependency on type of animal farm and livestock density – Danish example from 2004



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P balances, DK examples

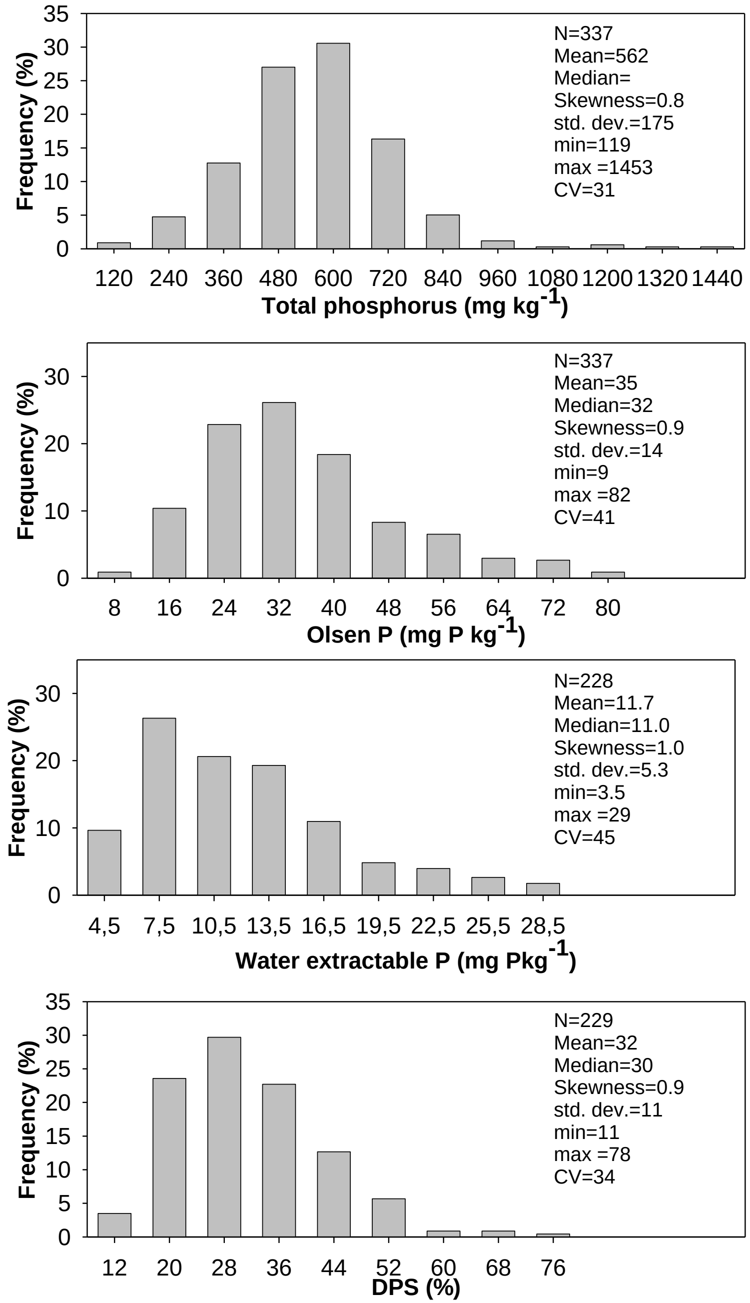
		Yearly P surplus kg ha^{-1}	
	Animal density	Sandy soil no irrigation	Sandy loam
Cattle	1.7	7	1
Cattle	2.3	18	12
Sows	1.4	22	14
Pigs	1.4	14	6
Chicken	1.4	25	17
Hens	1.4	33	25
Mink	1.4	45	37

From ”Pas på fosfor” Dansk landbrugsrådgivning 2004


Time for a break?
MAC

Soil P content in Danish agricultural fields shows a great variability.

So, it is vital to have information from single fields when deciding among mitigation options!



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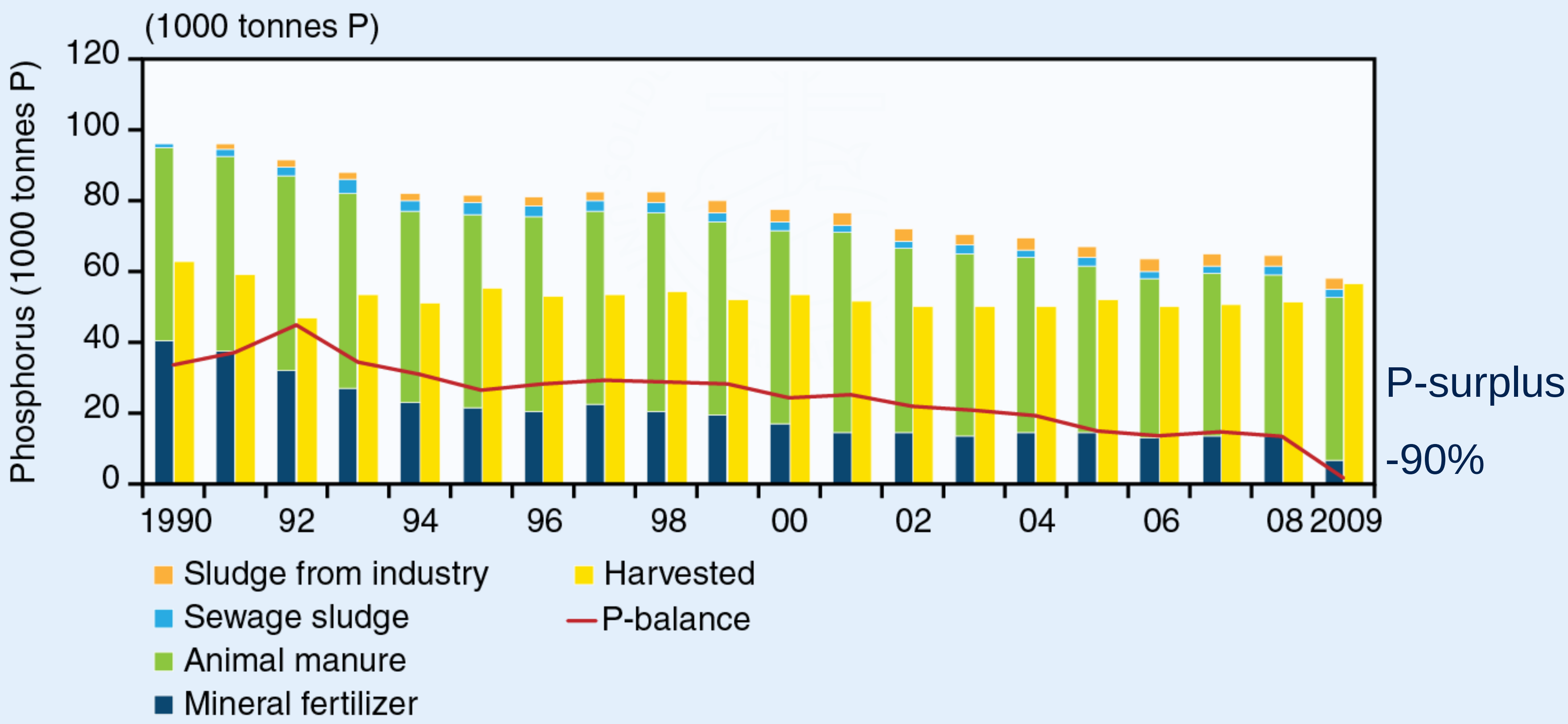
Also the national field P balance has improved due to reductions in use of mineral fertilizer – last year really low (harvest was high)



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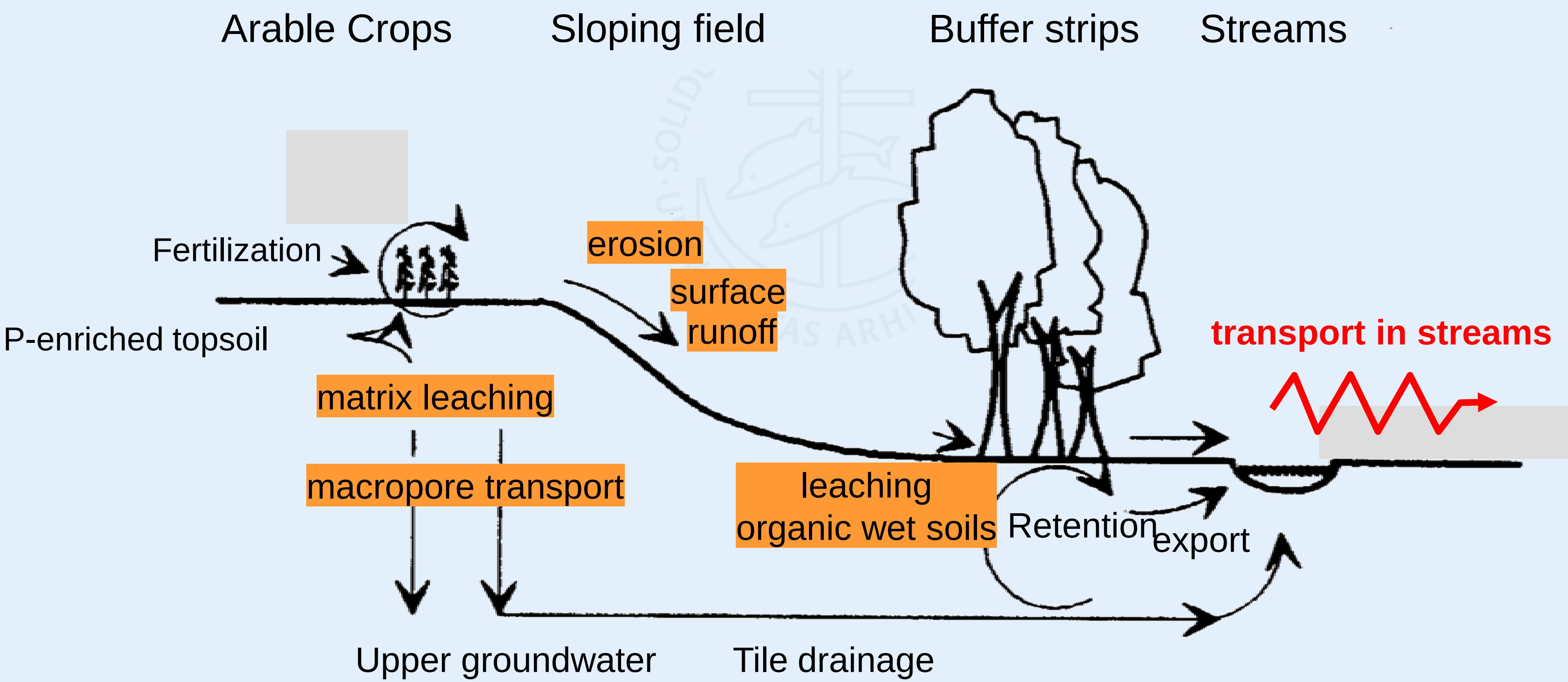
P losses is a result of many complex processes and pathways



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Question

- When and where will soil erosion occur on fields?
- What kind of fields are most prone/vulnerable for soil erosion?

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P-loss from agriculture is very complex

Natural factors

- climate
- topography
- soil types
- geology

source factors

- soil type
- P status
- land use
- fertilisation

transport factors

- runoff
- leaching
- erosion
- tile drainage

P-loss varies greatly from field to field and from year to year

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Phosphorus forms lost from soil –”conceptually” defined:

- Dissolved inorganic P: (H_xPO4^{3-x})
- Dissolved organic P (many types)
- Particulate or collodial inorganic P (many forms and sizes)
- Particulate or collodial organic P (many forms and sizes)

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Phosphorus forms lost from soil – operationally defined

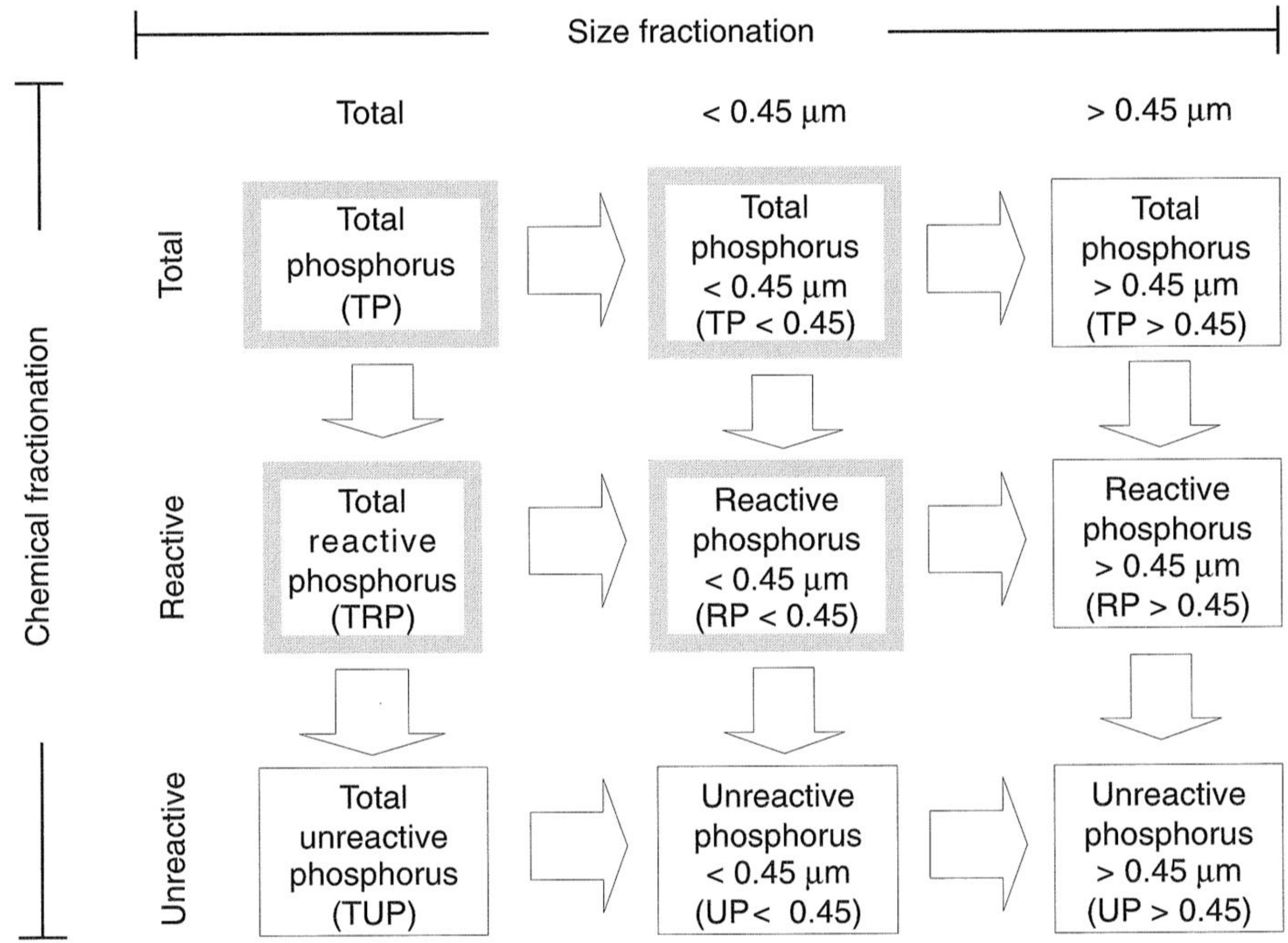

Fig. 2.4. Operationally defined phosphorus fractions determined in water, showing the directly determined fractions (in boxes with shaded borders) and fractions determined by difference.

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Haygarth and Jarvis, 2002

Conceptual interpretation of P loss

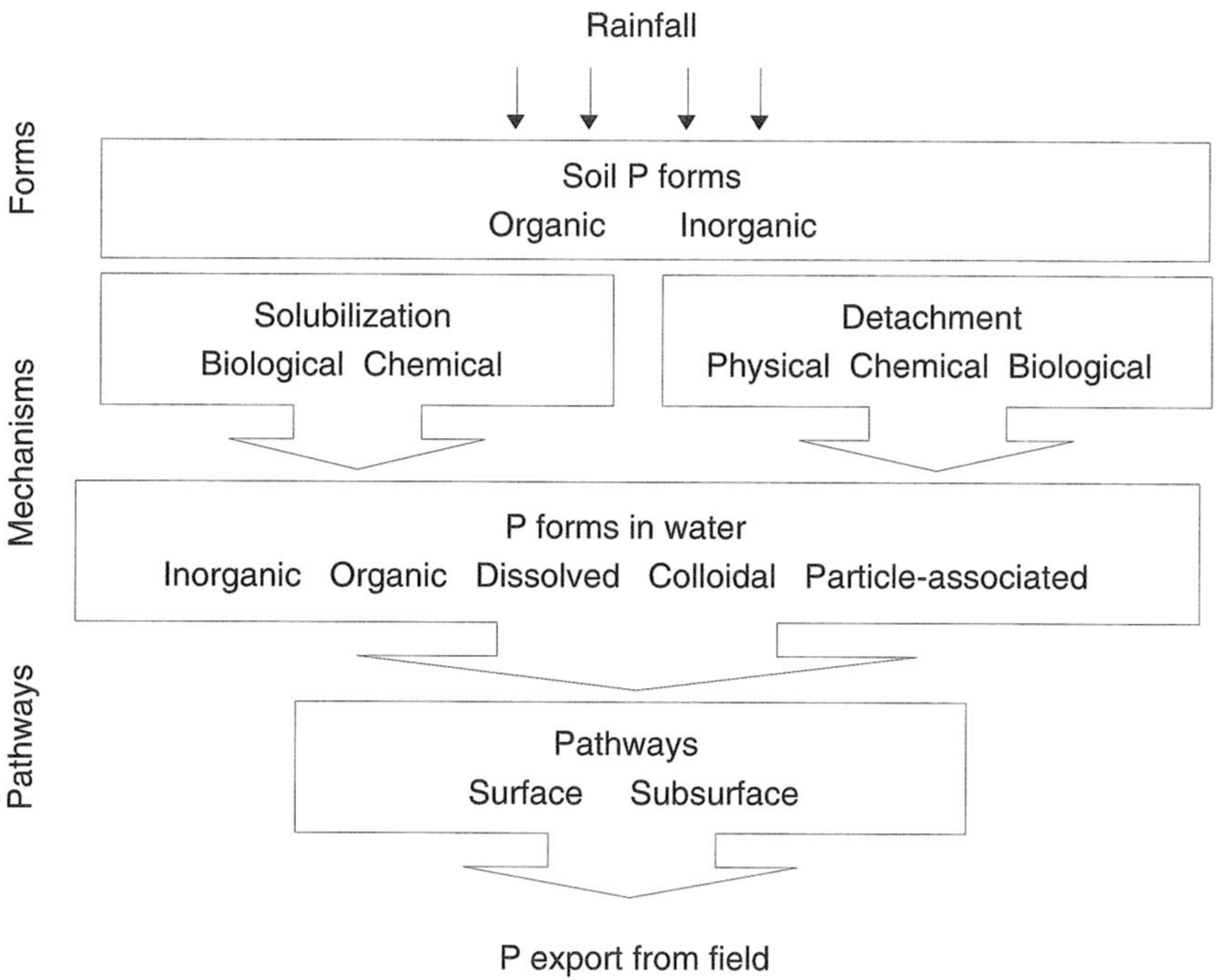
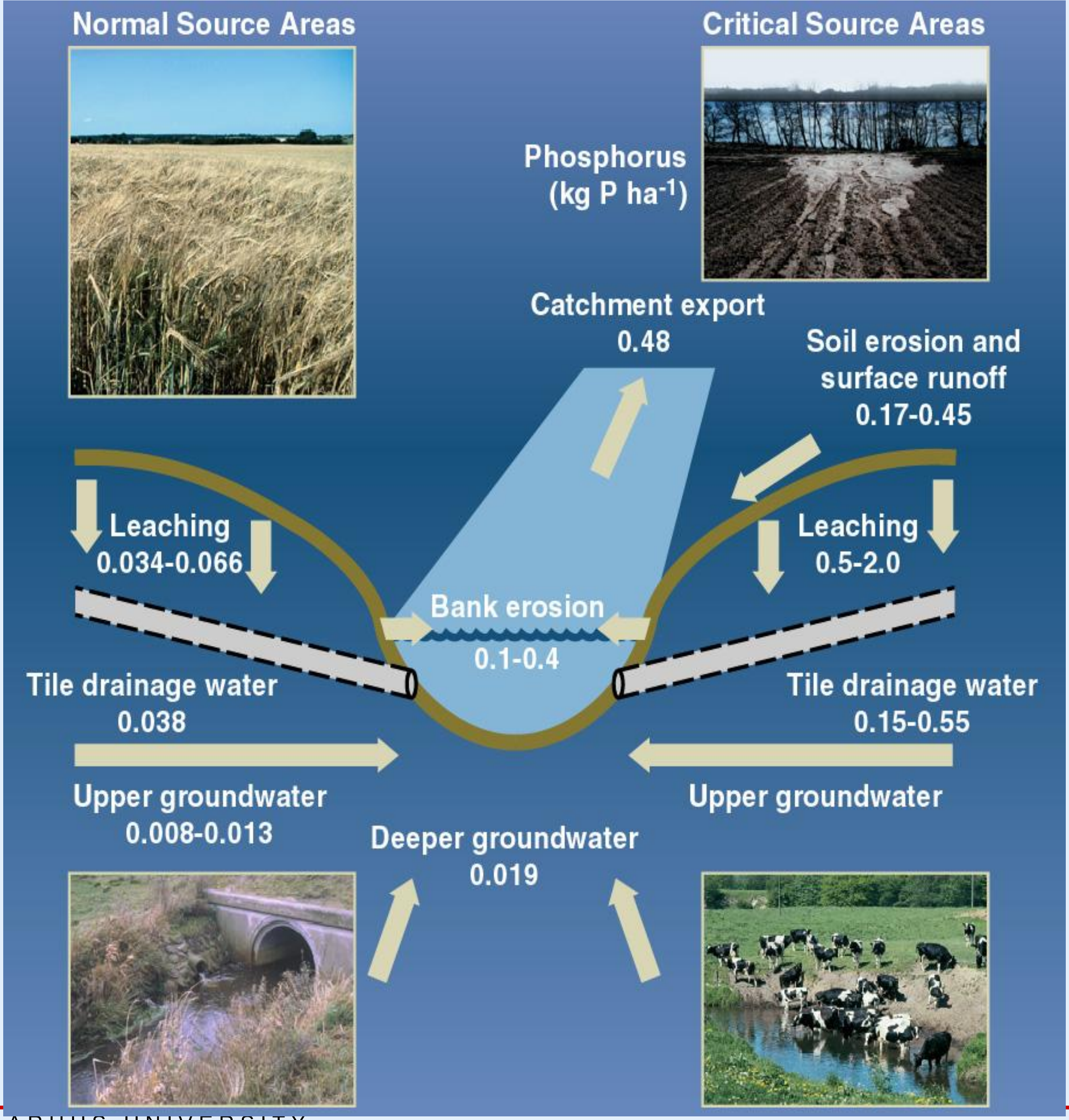


Fig. 2.5. A conceptual illustration of the transfer process (adapted from Haygarth and Jarvis, 1999).

Phosphorus source areas and pathways from agricultural areas in Denmark



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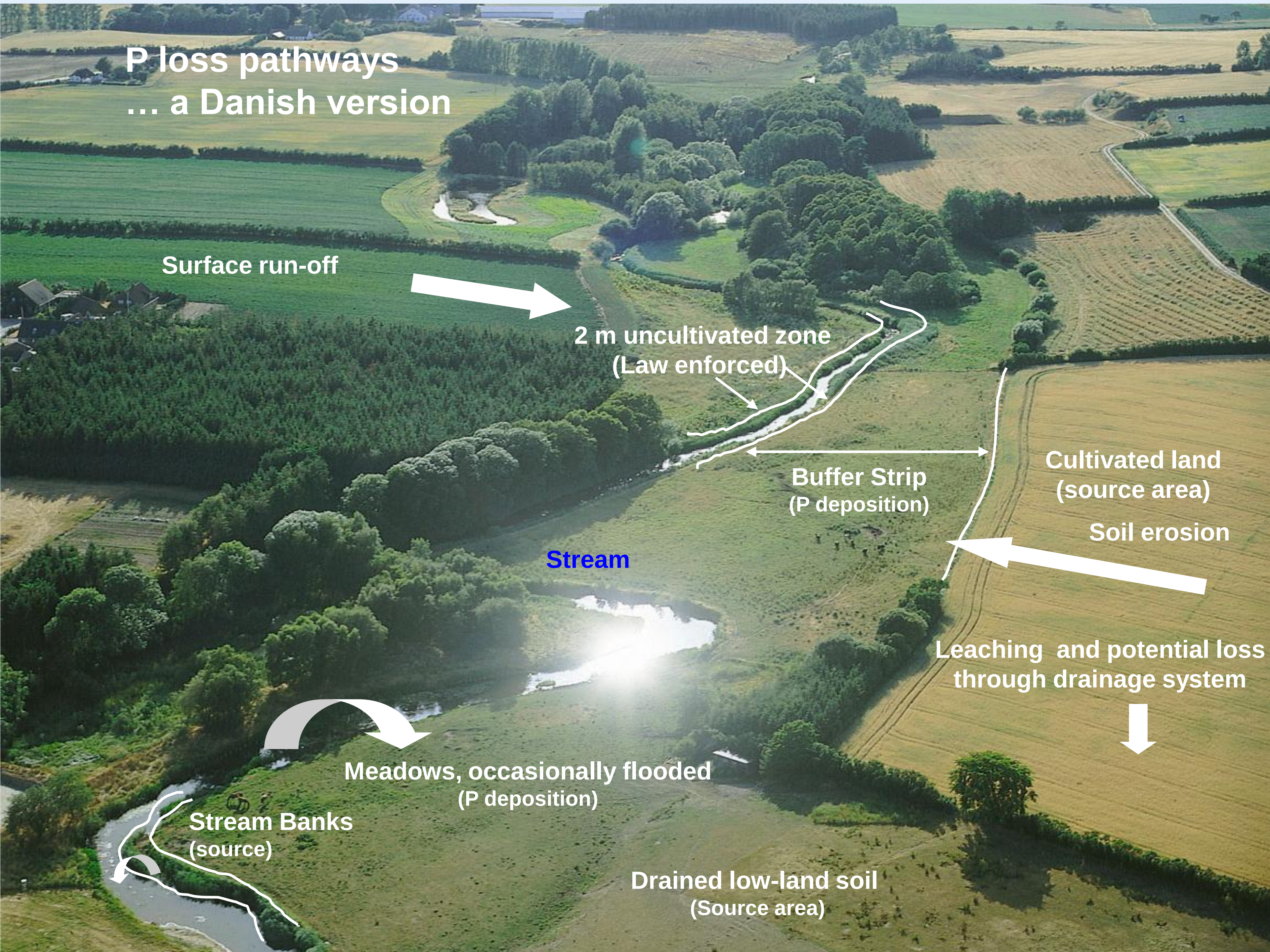
Estimated P discharges to the aquatic environment in Denmark

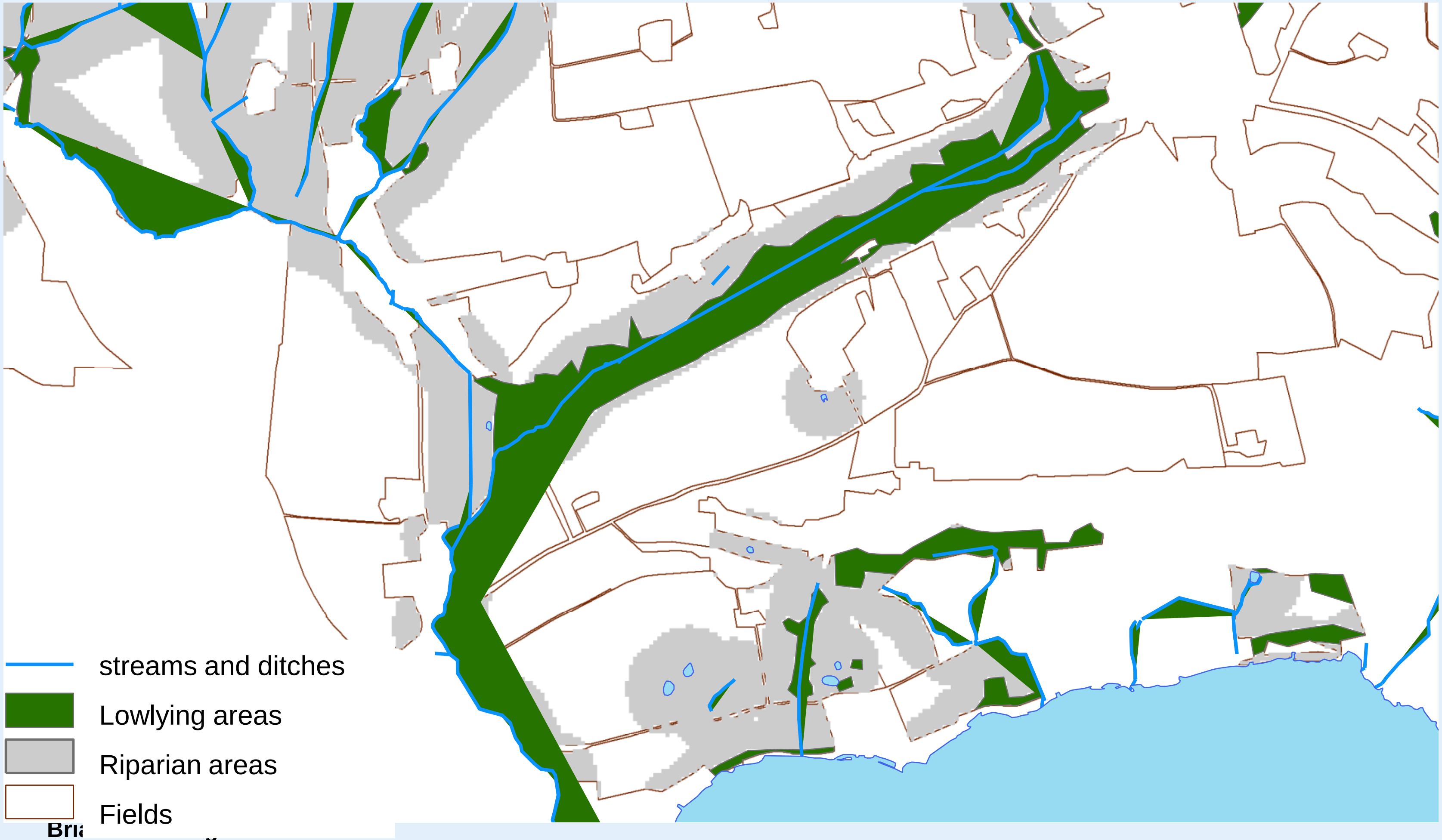
Contribution after upscaling	Mg P yr^{-1}
Soil erosion and surface runoff	7-35
Wind erosion	5-15
Bank erosion	275-645
Leaching to tile drains, mineral soil	55-200
Leaching to drains, organic soil	30-225
Upper ground water	<60
Sum	**432-1180**
Total via NOVA	***450-1050***

~ less than 0,5 kg P ha^{-1}

(Kronvang et al., 2005)

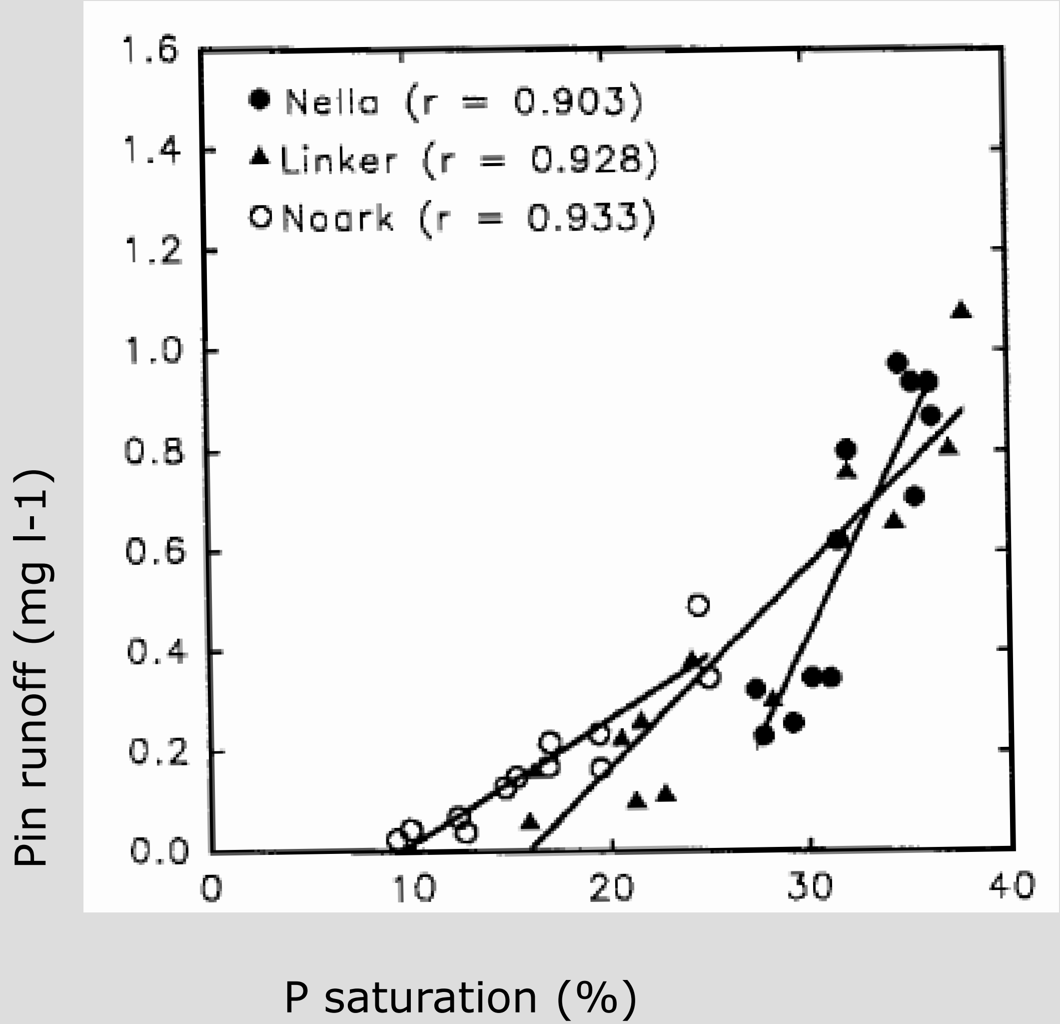

P loss pathways
… a Danish version
Surface run-off
2 m uncultivated zone
(Law enforced)
Buffer Strip
(P deposition)
Cultivated land
(source area)
Soil erosion
Stream
Leaching and potential loss
through drainage system
Meadows, occasionally flooded
(P deposition)
Stream Banks
(source)
Drained low-land soil
(Source area)

Landscape structure is important for P losses – connectivity between land and surface water important !



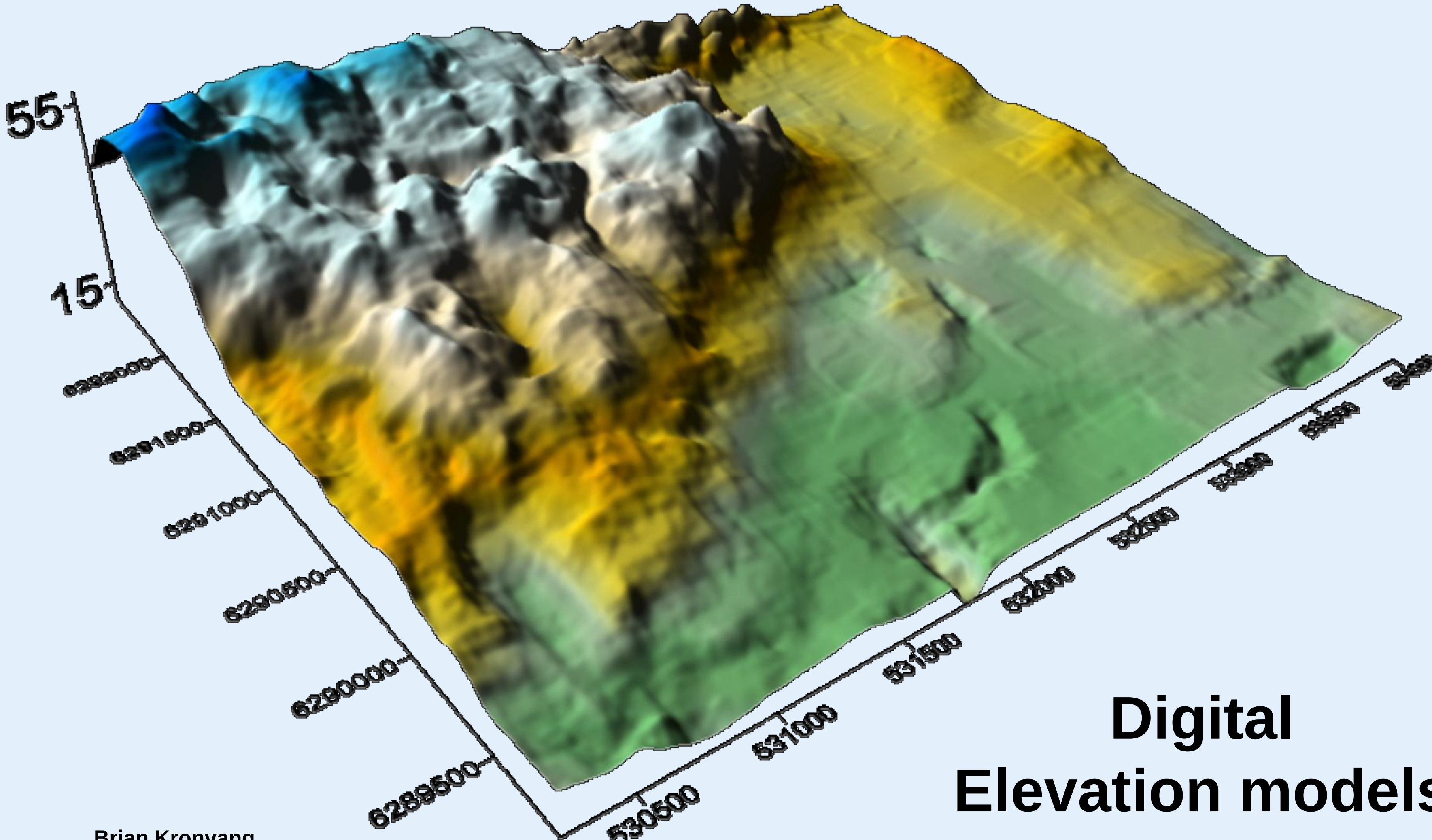
Erosion and surface runoff

P status and loss



3 soils in US trials

Differences in height is responsible for water transport in the landscape



Digital Elevation models

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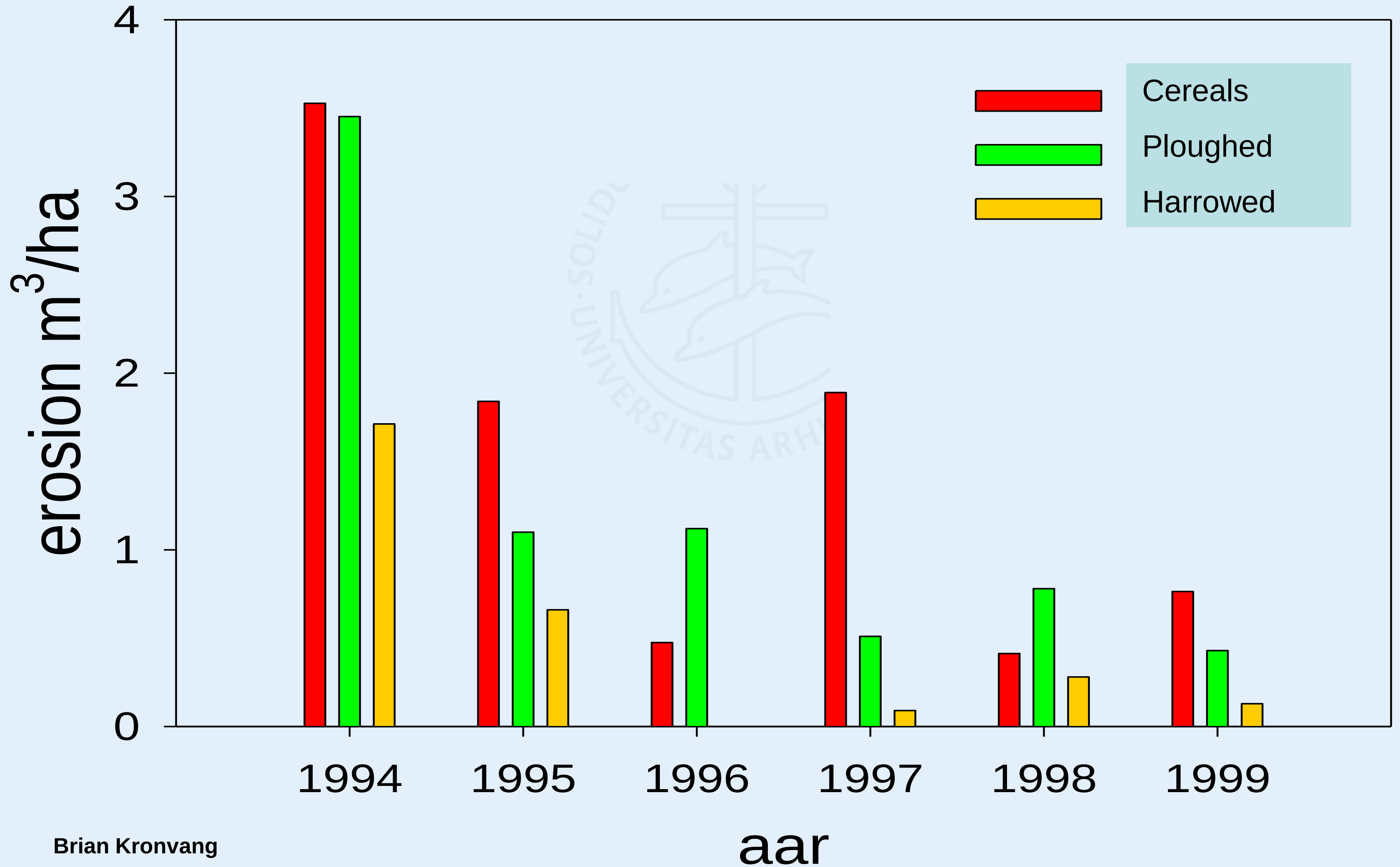
Soil erosion on sloping fields in Denmark - 130 fields studied with different crops/tillage



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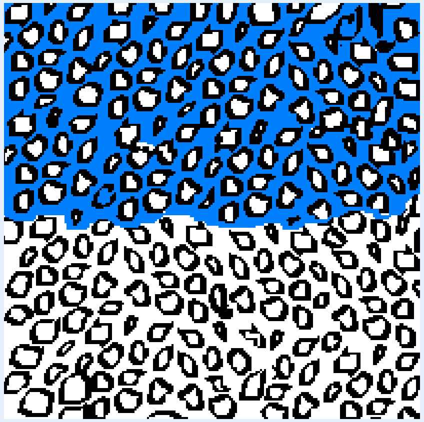
Flow processes in soils

Matrix

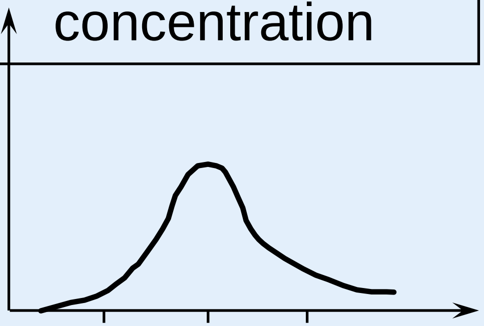


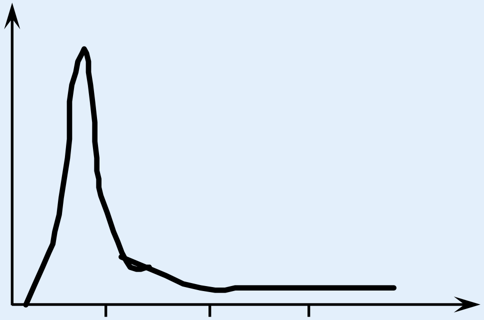
homogene soil

Macropore

heterogene soil

relative concentration





Flow volume

Elevator holes

Cracks

Biopores

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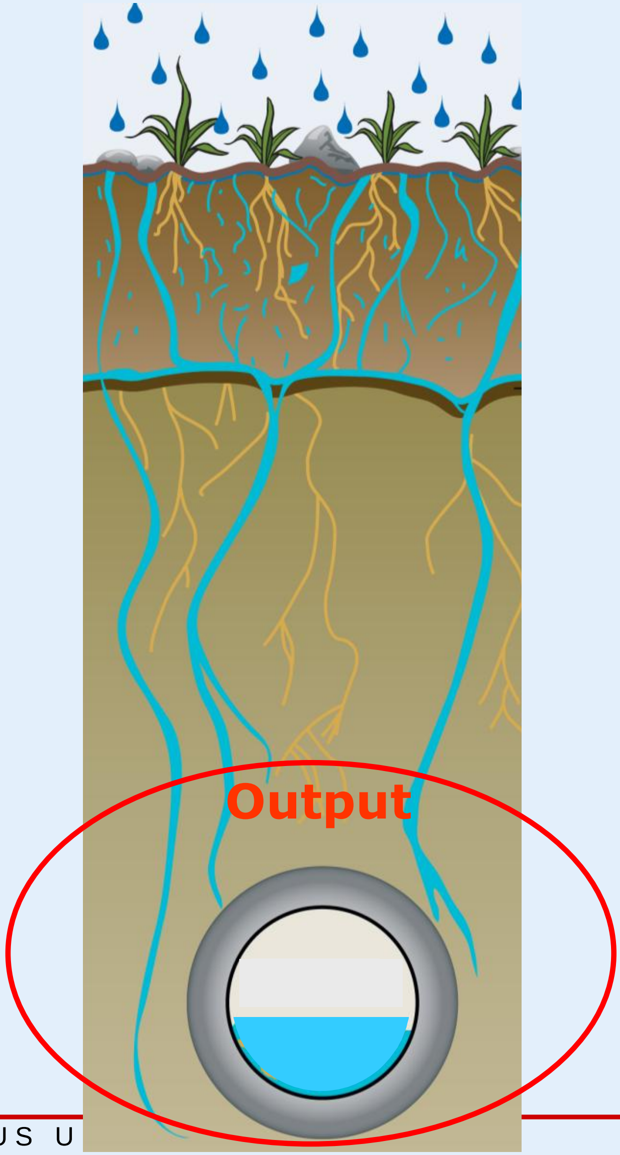
Leaching of colloids and P

Colloid mobilization

Macropore transport

Worm wholes

Root pores

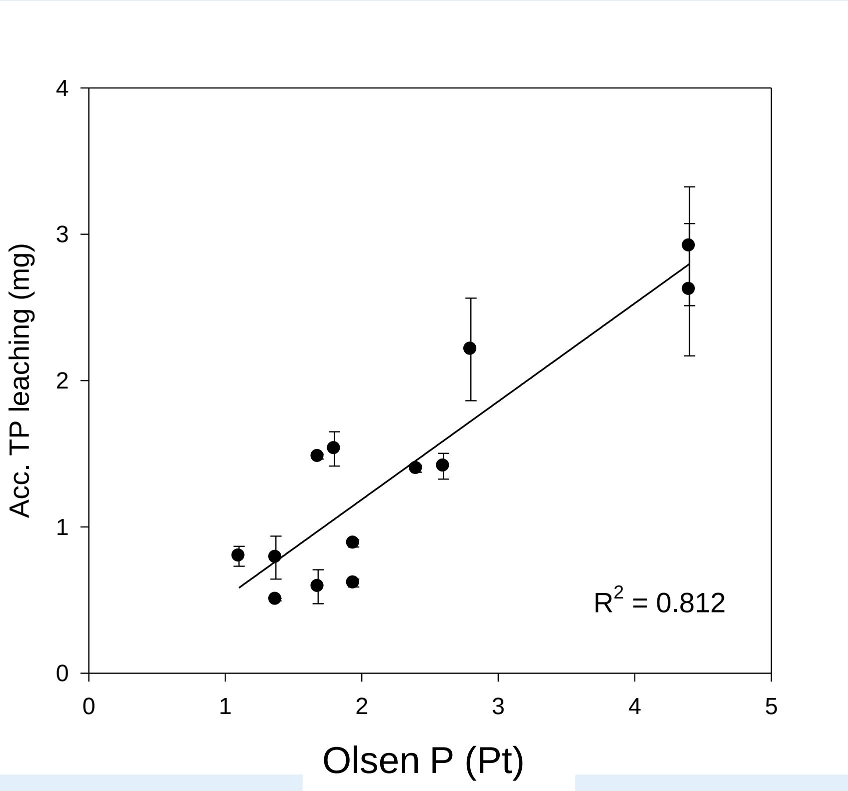


Topsoil

B- and C horizons

Tile drain

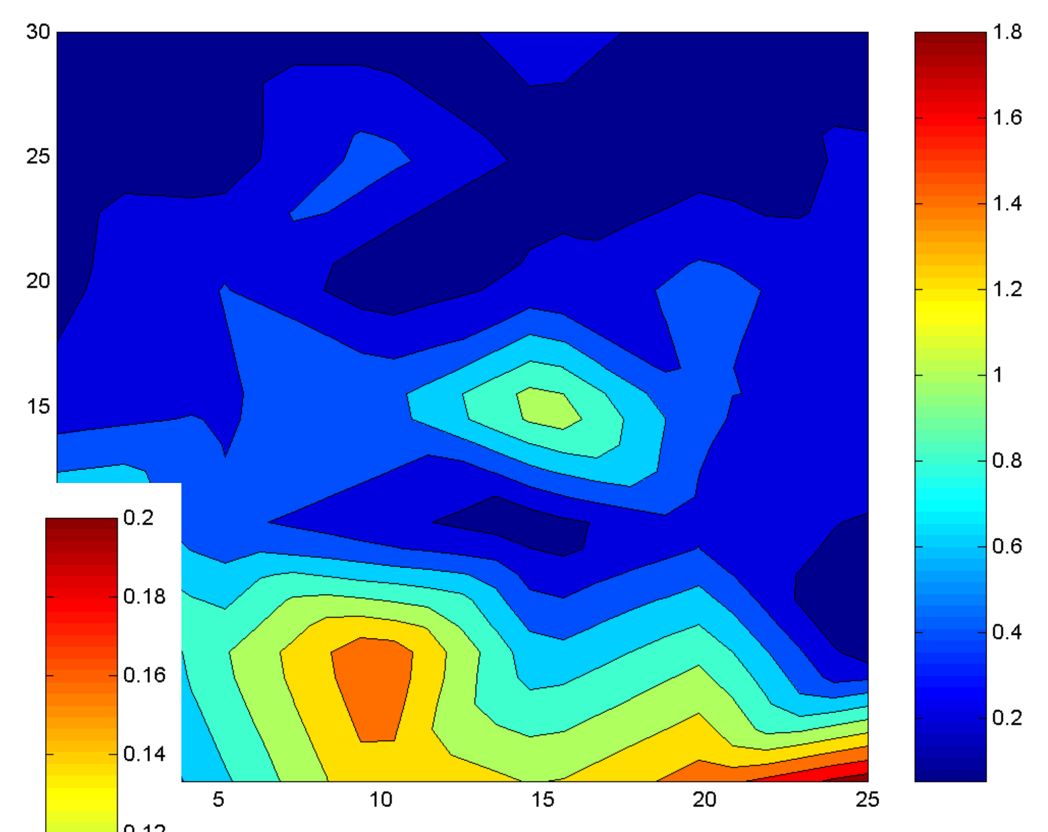
Soil P content (Olsen P) as indicator for P-loss – yes, a relationship can be established but with low precision



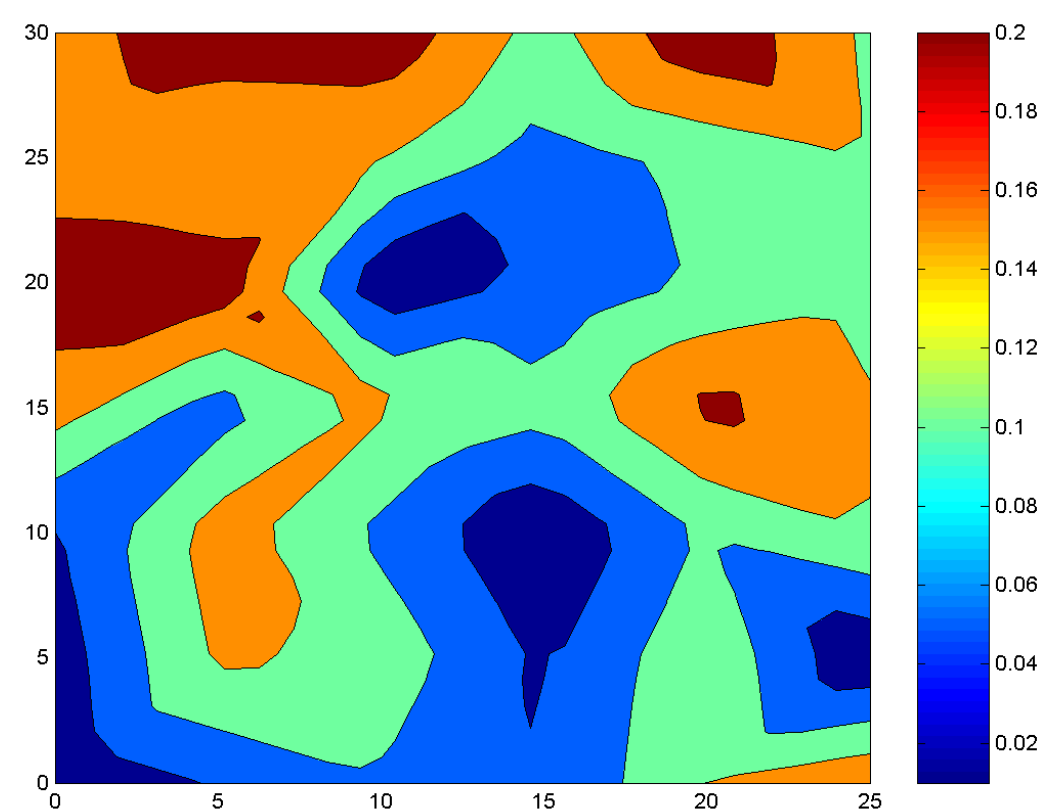
/Kjærgaard/Rubæk et al. unpublished

Spatial variation in P leaching from field

Particulate inorganic P

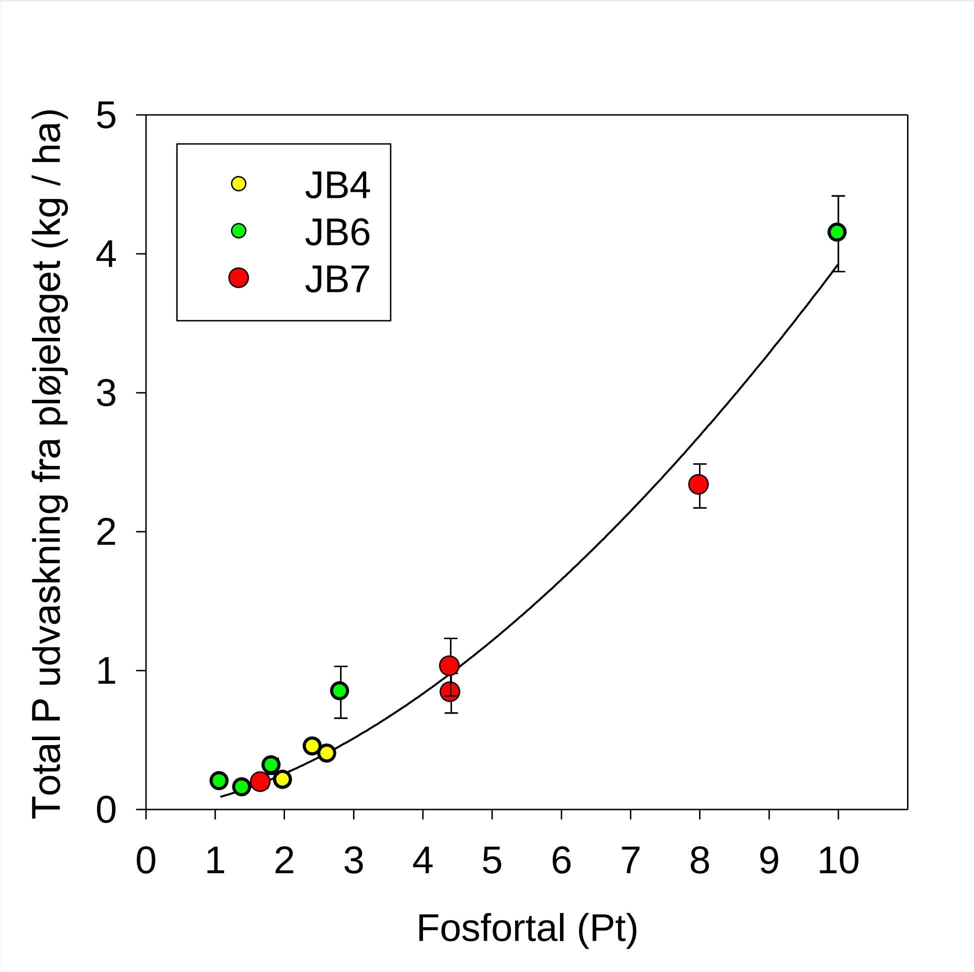


Dissolved inorganic P



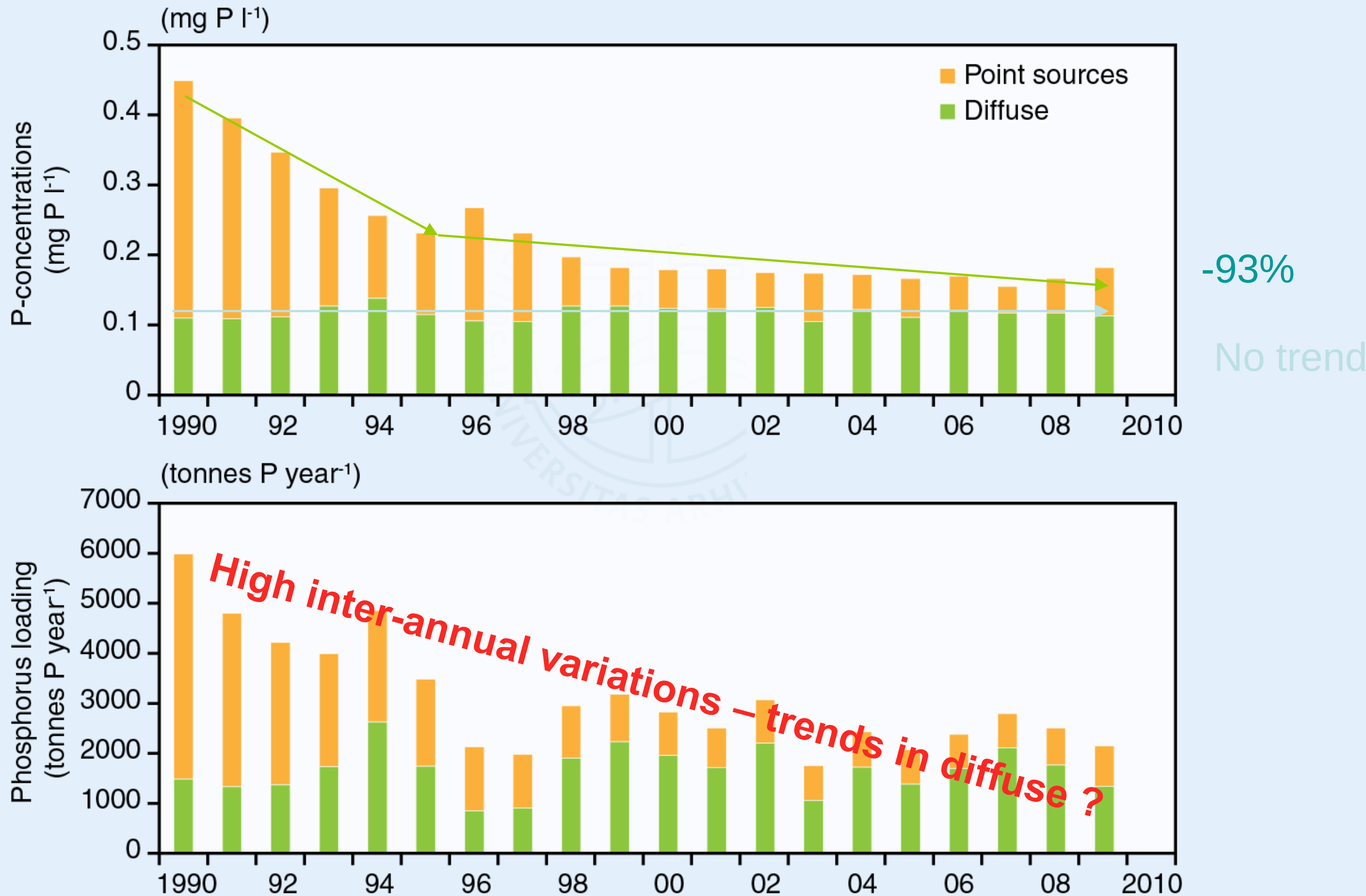
Leached P
(mg/kolonne)

Fosfortal som kildeparameter?

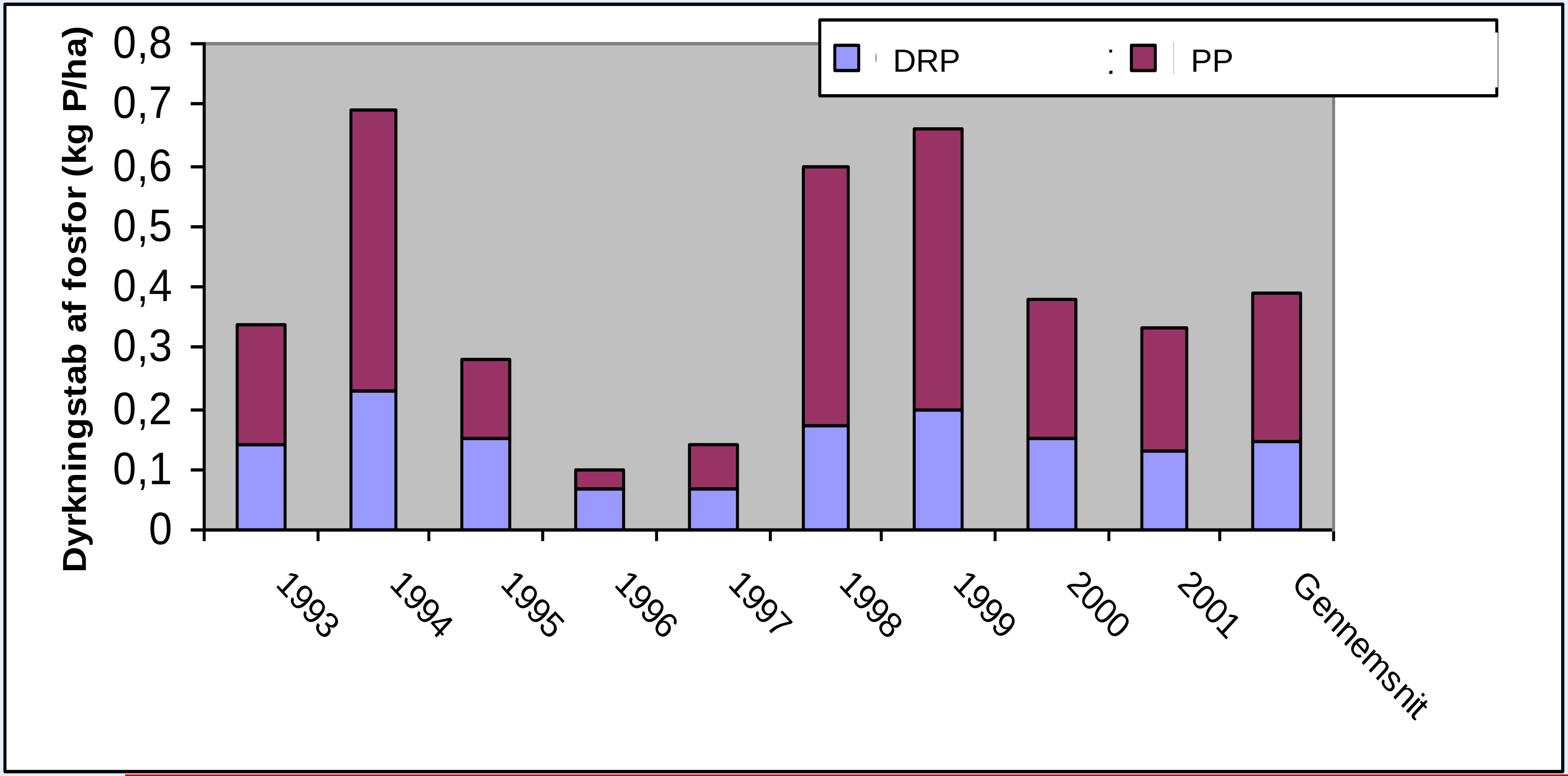


Fosforudvaskning
Kolonneforsøg
12 forskellige jorde
(JB4, JB6, JB7)
Nedbør ~120 mm regn

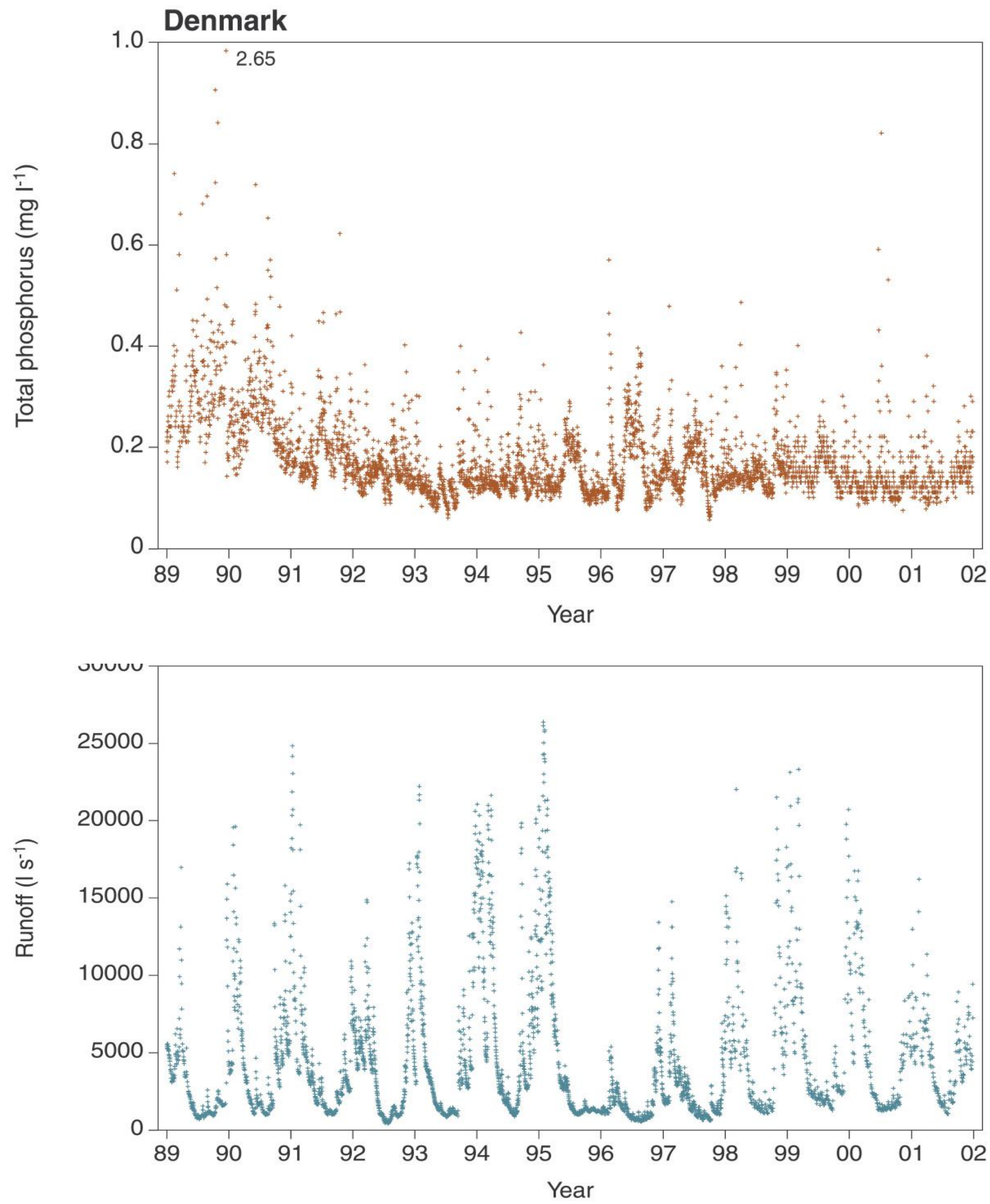
Development in P concentrations in surface waters and P-loadings from Danish land area to coastal waters during 1990-2010



Annual losses of dissolved inorganic P (DRP) and particulate P (PP) from agricultural land in Denmark



Seasonality in total phosphorus concentrations and runoff in a Danish river as represented with daily measurements during 13 years



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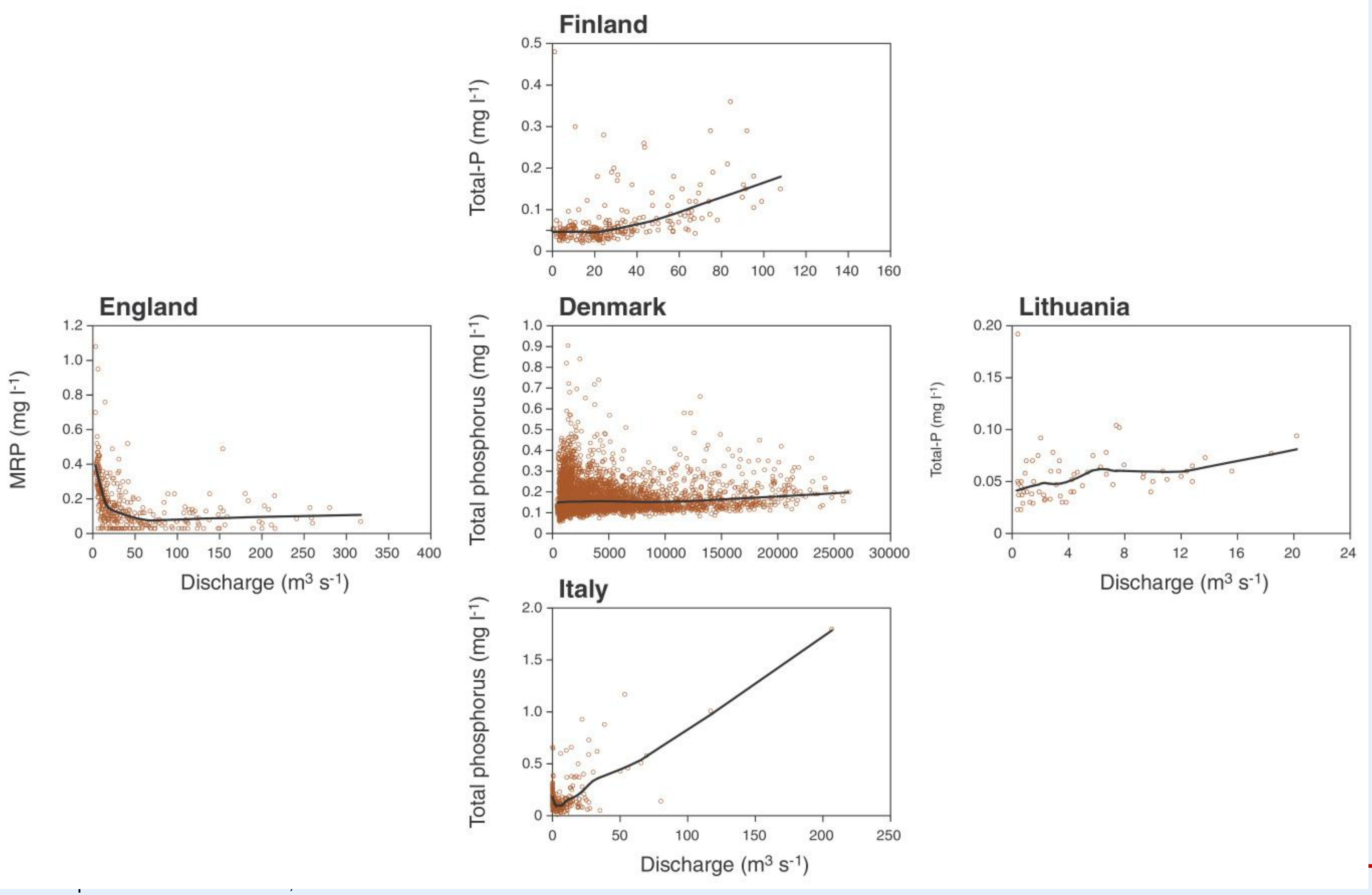
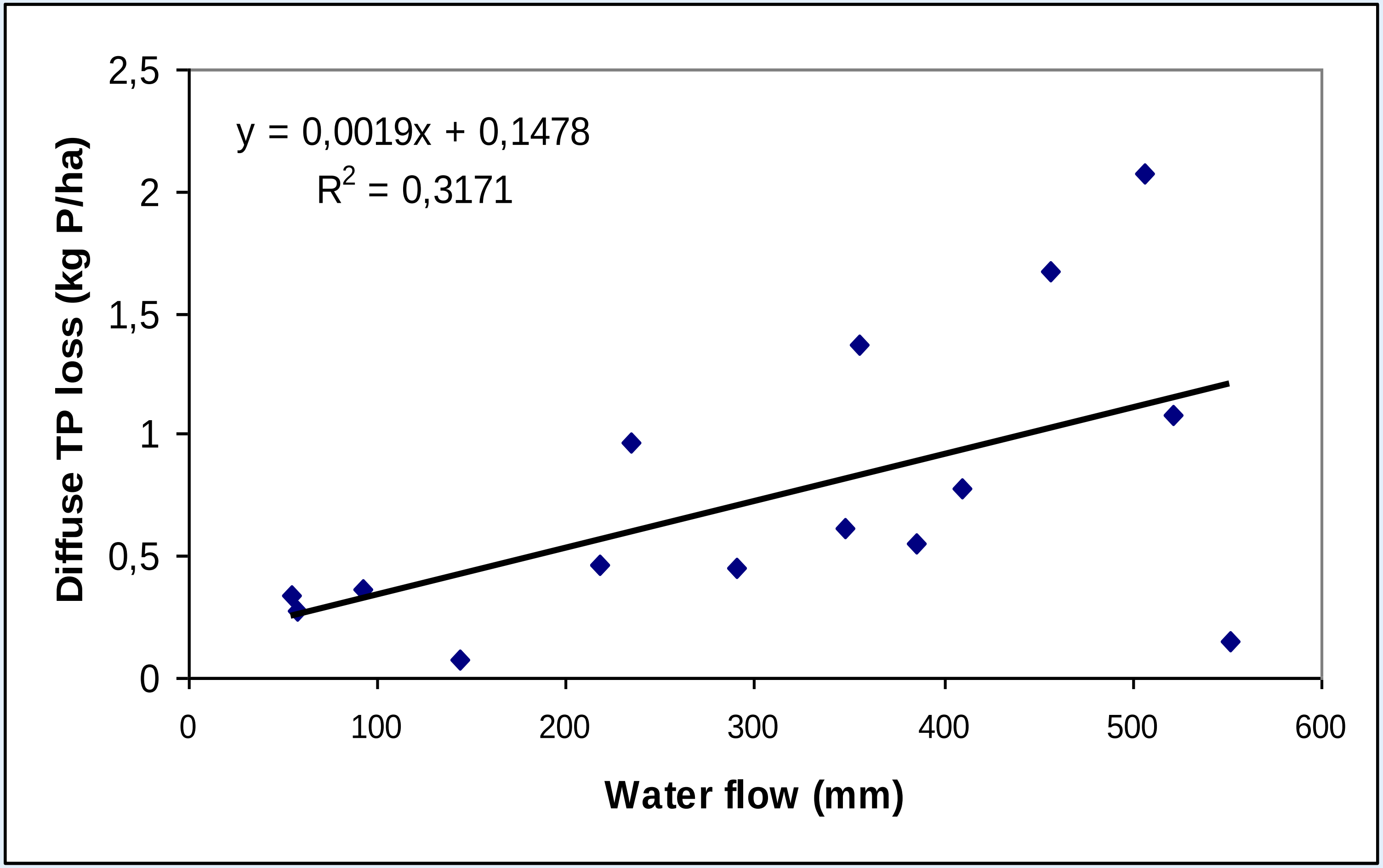
Phosphorus response to changes in discharge in different European river basins



Relationship between water flow and diffuse P-loss in 15 European river basins



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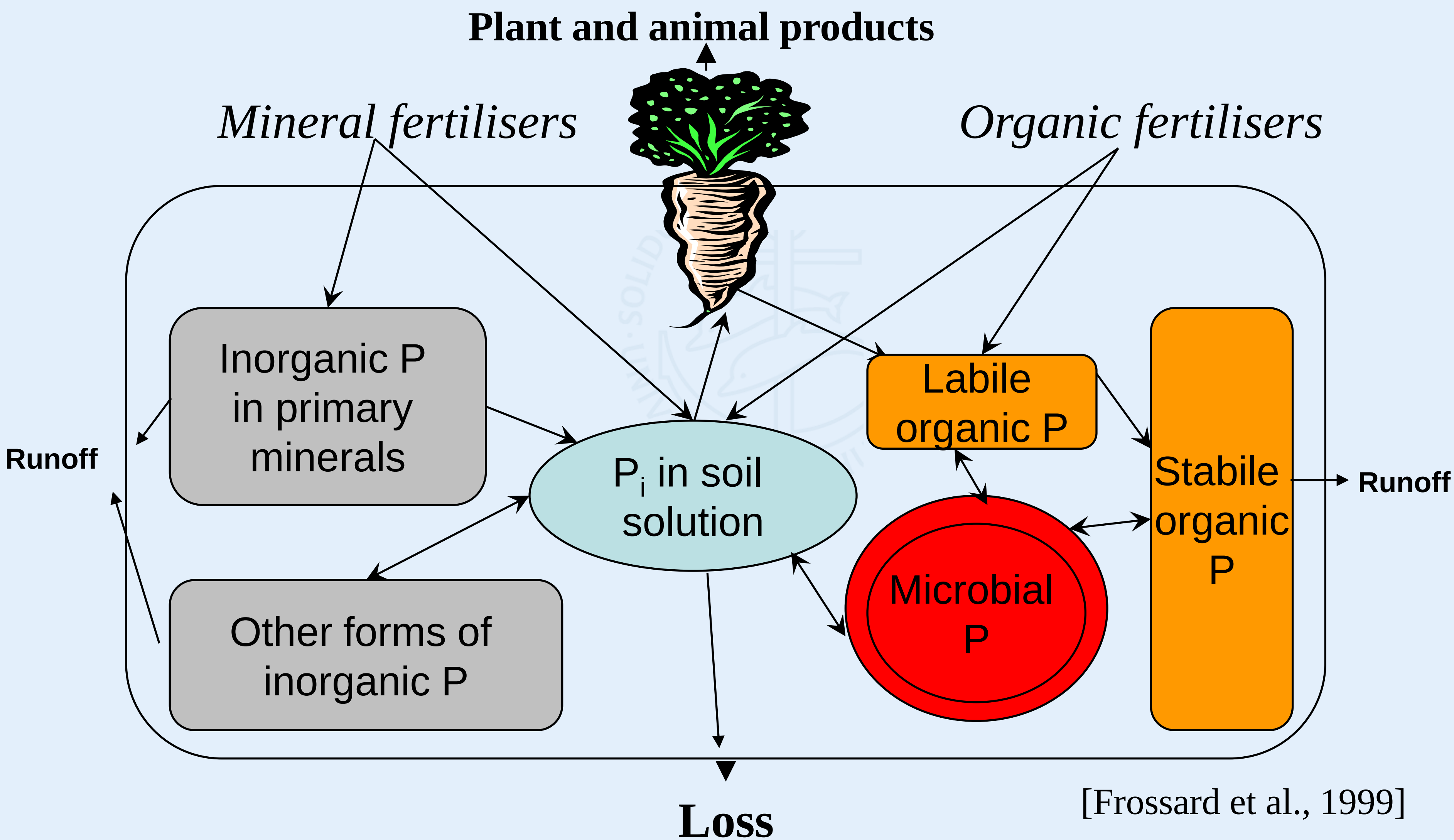
Time for an exercise?

Exercise 2:

- This figure shows the important P pools in managed agricultural systems, but all the arrows linking the pools are missing.
- Link with arrows the different pools based on your best judgement.
- Discuss the linkages.

Fosforomsætning i jord

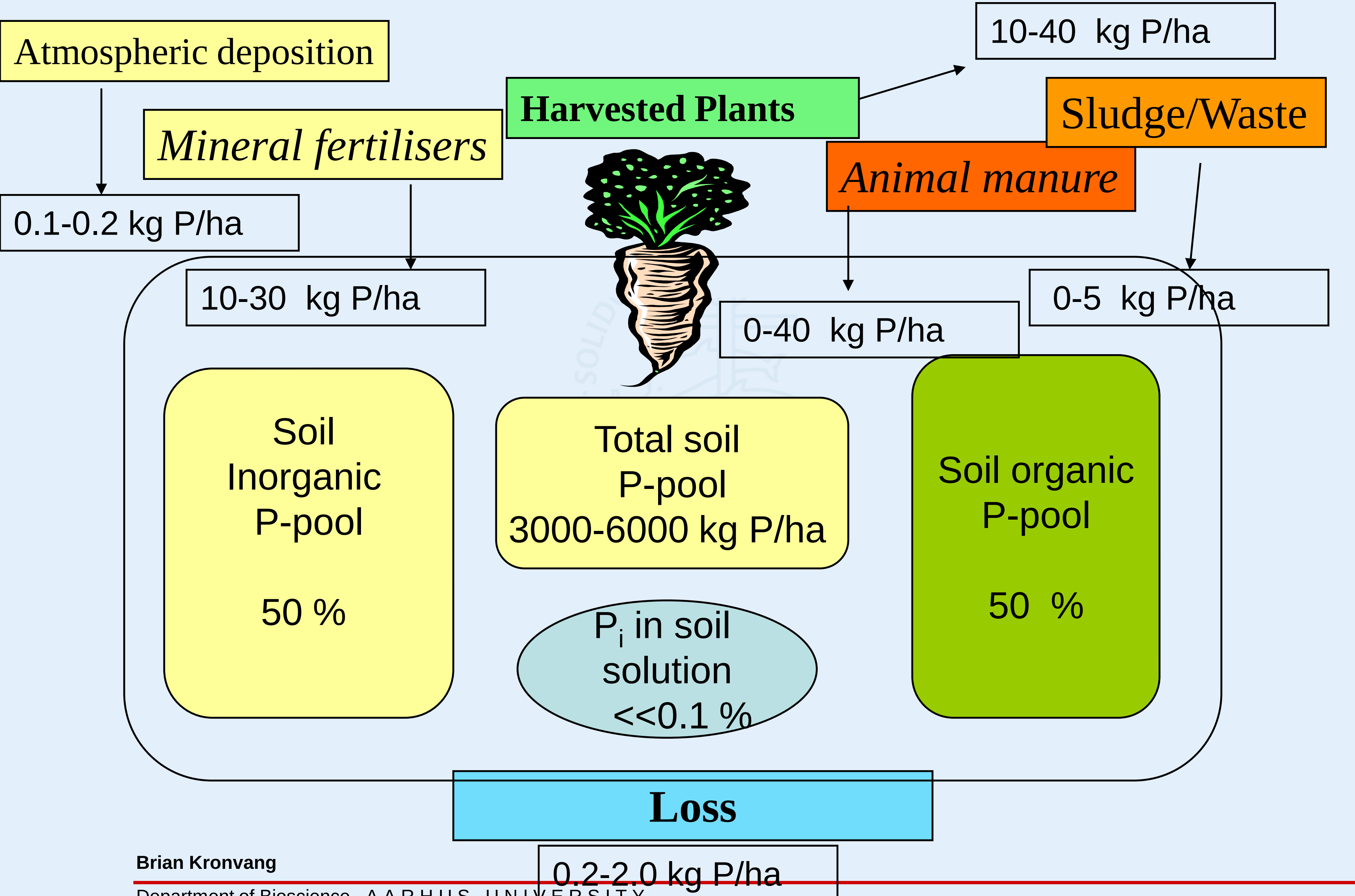


[Frossard et al., 1999]

Summing up todays lecture

- Phosphorus cycling quick overview of the global transfers and cycles, little on the aquatic, more the terrestrial (agricultural)
- P an essential nutrient –and ”eutrofier”
- Pools and processes of P in soil.
- Agricultural phosphorus surplusses, where, why and distribution
- P mobility
- P loss pathways
- P forms lost from agriculture

P inputs, pools and outputs in agricultural systems (kg P per hectare per year)



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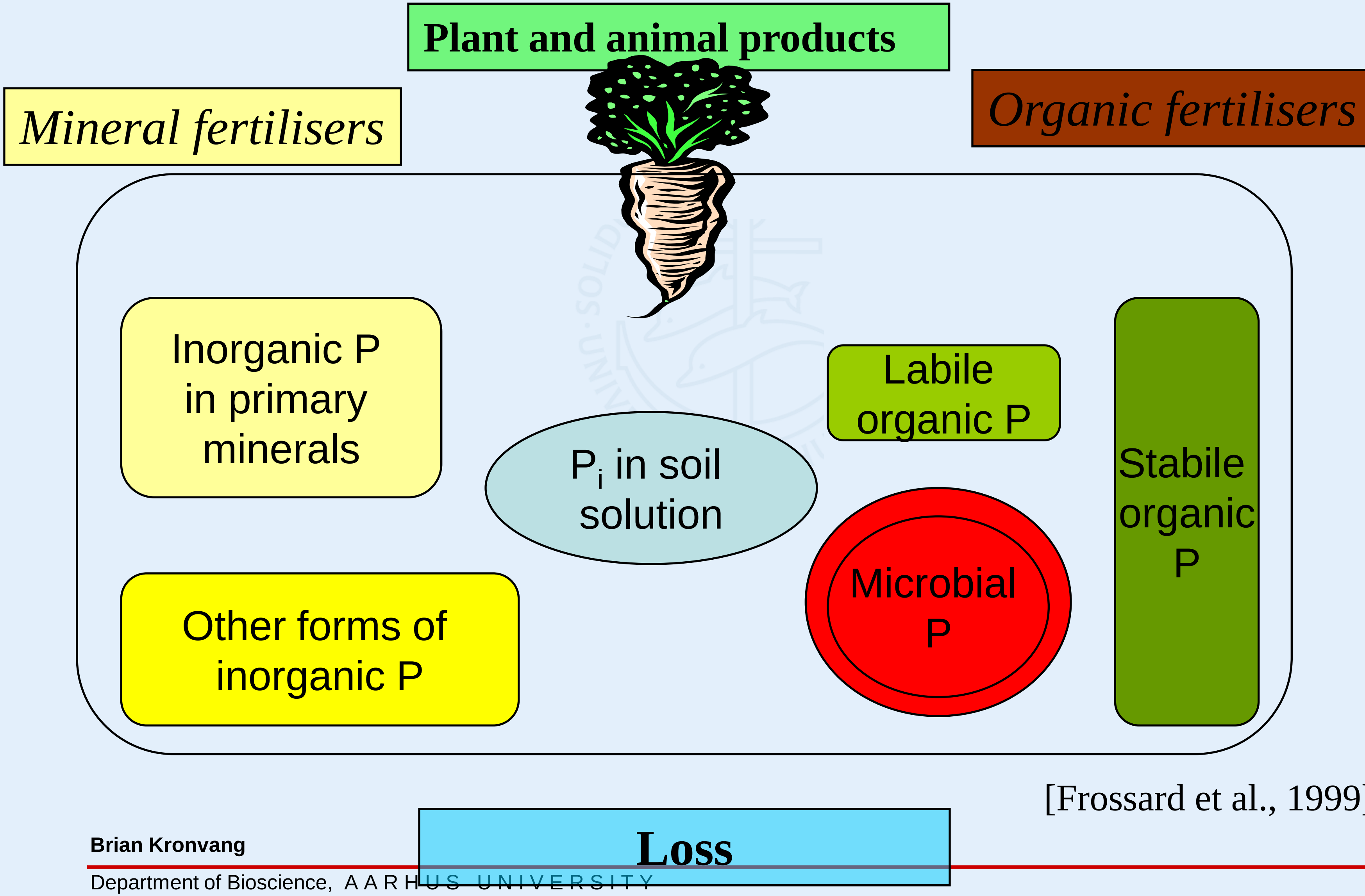
P turn-over in terrestrial systems



[Frossard et al., 1999]