Nutrient Cycling, Modelling and Management from Field to Catchment Scale: 3 ECTS course

Brian Kronvang, Daniel Graeber and Guillermo Goyenola

Course Plan

	Monday 14th November	Tuesday 15th November	Wednesday 16th November	Thursday 17th November	Friday 18th November
09.00-11.30	Lecture I	Lecture II + Presentation of research results from two Uruguayan catchments	Lecture III	Lecture IV	Lecture V
11.30-12.00	Introduction to Exercise	Introduction to Exercise	Introduction to Colloquia	Introduction to Exercise	Introduction to Colloquia
12.00-13.00	Lunch	Lunch	Lunch	Lunch	Lunch
13.00-15.00	Group Exercise I	Group Exercise II	Group Colloquia I	Group Exercise III	Group Colloquia II
15.00-16.30	Presentation and discussion of results (Team I: Rivers) (Team III: Agricultural)	Presentation and discussion of outcome (Team II – N scenario)	Presentation and discussion of outcome as PP	Presentation and discussion of results (Team IV – P scenario)	Presentation and discussion of outcome as PP from each group

Lectures

- **Lecture I: Nitrogen cycling in catchments – sources, sinks and transport.**
- **Lecture IIA: Monitoring, Modelling and Management of nitrogen - field to catchment scale.**
- **Lecture IIB: Results from monitoring hydrology and nutrients in two contrasting agricultural catchments in Uruguay**
- **Lecture III: Organic nitrogen – sources, transformation and transport.**
- **Lecture IV : Phosphorus cycling in catchments – sources, sinks and transport.**
- **Lecture V : Monitoring, Modelling and Management of phosphorus - field to catchment scale.**

Final Report as outcome of the course

- **Each team has to produce a joint report with 6 chapters being 40-50 pages long.**
- **The report shall content 6 chapters and each team member will be responsible for one of the 4 result chapters.**
- **The Introductory chapter and the concluding chapter is common chapters for the teams.**
- **The report should be delivered within 3 weeks after finishing the course.**
- **The report is used to grade your performance under the course.**

Content of the report

- **Chapter I: Introduction (jointly).**
- **Chapter II: Nutrient concentrations and trends in world rivers (One team member).**
- **Chapter III: Trends in world agricultural systems (One team member).**
- **Chapter IV: Scenarios for nutrient losses from two different catchment types (One team member).**
- **Chapter V: Mitigation options in catchments – functioning of buffer strips and wetlands (One team member).**
- **Chapter VI: Discussion and conclusions (jointly).**

What do you expect of this course?

- Discuss with your neighbour and write 2-3 keywords

Learning aims – Lecture I

- **Basic understanding of nutrients in ecosystems – inputs, outputs and fluxes.**
- **Basic understanding of nitrogen fluxes in air, soil and water compartments.**
- **How to differentiate between nutrient sources.**
- **The variability of nitrogen concentrations in streams.**
- **How to calculate nutrient transport.**
- **How to perform a source apportionment of nutrients.**
- **Diffuse sources of nitrogen - the importance of agriculture.**

Nutrients in ecosystems: is a basic requirement for life

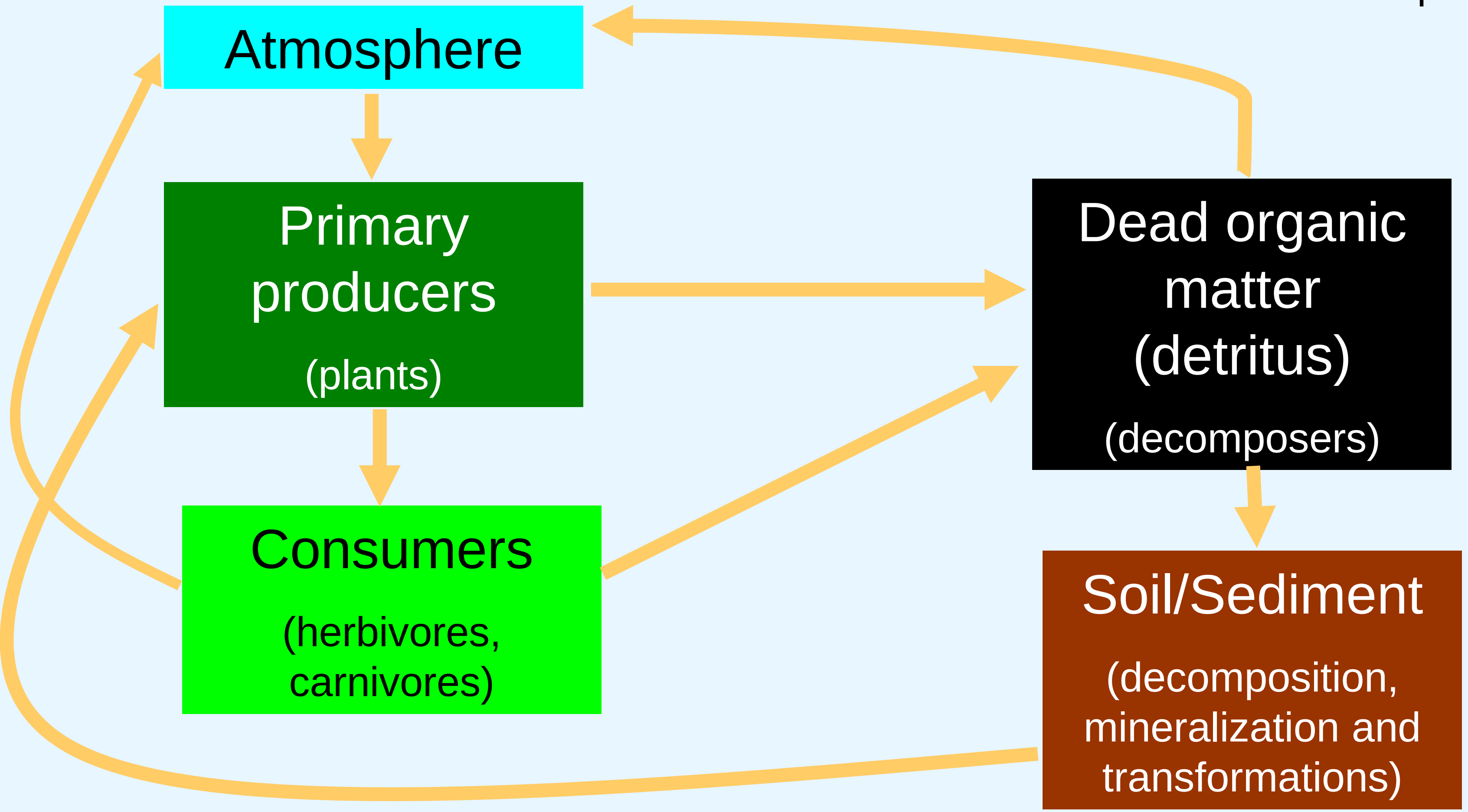
- **We distinguish between macro-nutrients (Carbon (C), oxygen (O), hydrogen (H), nitrogen (N), phosphorus (P), calcium (Ca), potassium (K), etc.)**
- **and micro-nutrients (iron (Fe), copper (Cu), zinc (Zn), boron (B), etc.).**
- **The definition of nutrients refer only to the quantity in which the nutrients are needed not their importance for the organism.**
- **If micro-nutrients are lacking in the habitat, plants and animals fail completely to grow as if they lacked N and P.**

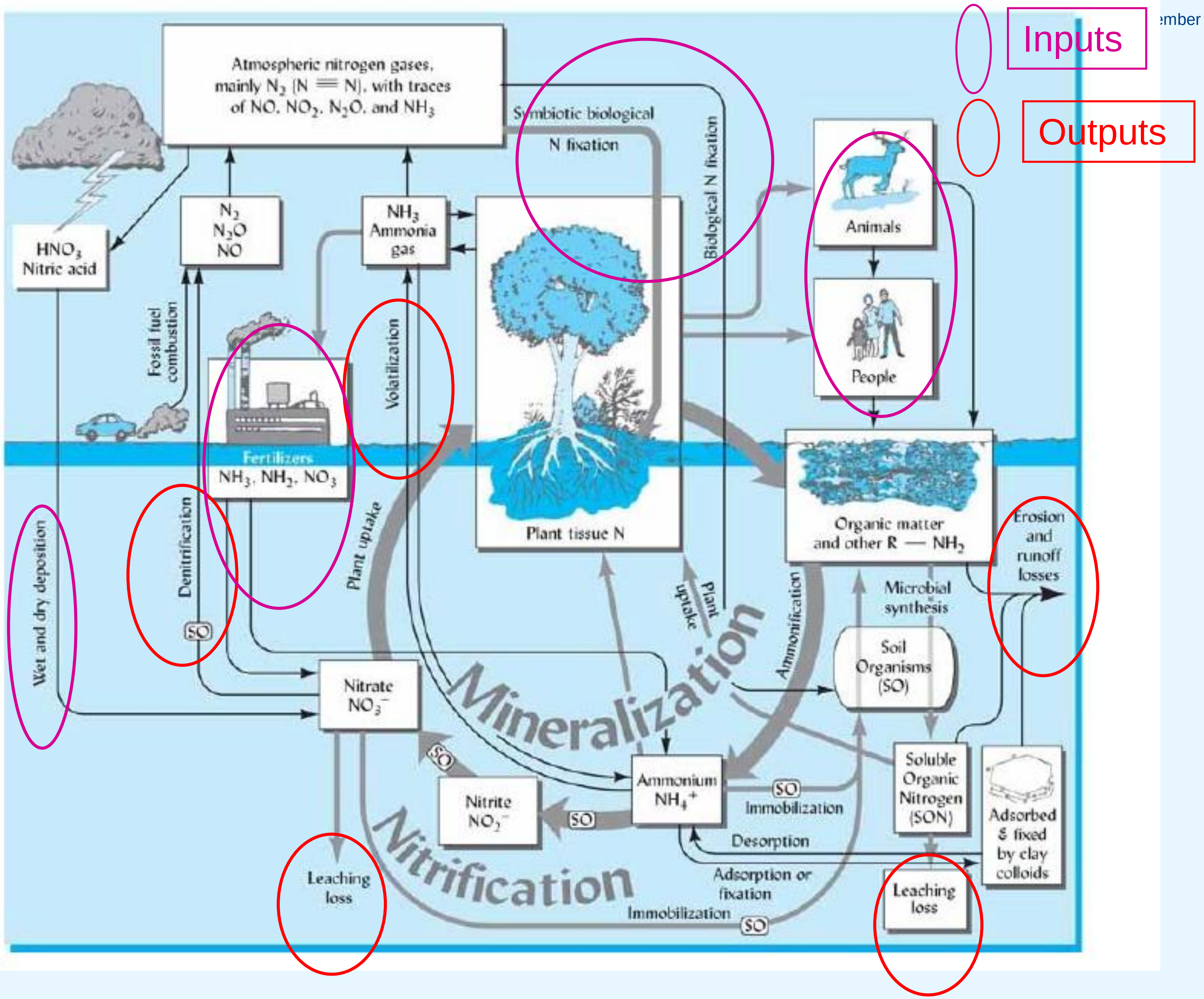
Nutrient Cycling

- **Nutrient are flowing from the nonliving to the living and back to the nonliving components of the ecosystem (Therefore the term Cycling) – known maybe best as the BIOGEOCHEMICAL Cycle.**
- **BIO = Living components (plants, animals)**
- **GEO = Nonliving components (rocks, sediments and soils)**
- **CHEMICAL = the processes involved (e.g. photosynthesis, respiration, denitrification, sorption/desorption, etc.).**

Nutrient fluxes between ecosystem compartments, reservoirs or pools – e.g. C, O, N

Fluxes
Increases with temperature




Inputs
Outputs
Atmospheric nitrogen gases, mainly N_2 (N ≡ N), with traces of NO, NO_2, N_2O, and NH_3
HNO_3 Nitric acid
N_2 N_2O NO
NH_3 Ammonia gas
Symbiotic biological N fixation
Biological N fixation
Fossil fuel combustion
Volatilization
Animals
People
Fertilizers NH_3, NH_2, NO_3
Plant tissue N
Organic matter and other R — NH_2
Wet and dry deposition
Denitrification
SO
Plant uptake
Plant uptake
Ammonification
Microbial synthesis
Soil Organisms (SO)
Erosion and runoff losses
Mineralization
Nitrate NO_3^-
Ammonium NH_4^+
Nitrite NO_2^-
SO
Immobilization
Desorption
Adsorption or fixation
Immobilization
Soluble Organic Nitrogen (SON)
Adsorbed & fixed by clay colloids
Nitrification
Leaching loss
Leaching loss

Processes and flows in ecosystems

- the effectors

- Input: fixation, deposition, fertilisation
- Plant uptake and litter production
- Decomposition and mineralisation:
  - Organic N turnover, ammonification, nitrification, immobilisation
- Output: volatilisation, denitrification, leaching/run off

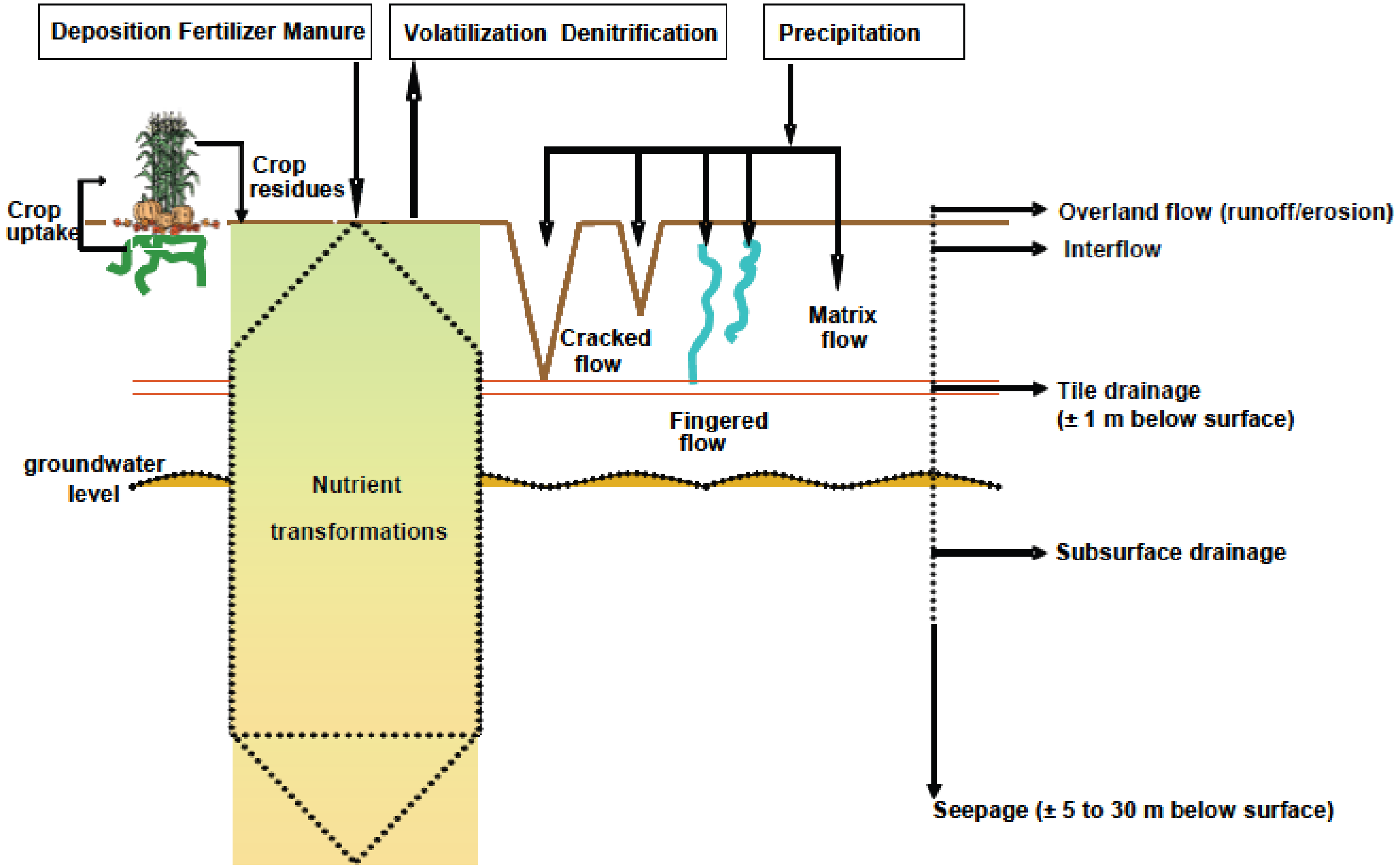


Figure 3.8

Schematic visualization of the nutrient losses at field scale (after Schoumans and Chardon, 2003) (Subsurface drainage may also occur above tile drains at high water table levels during high rainfall events)

Question to discuss during 3 minutes with the person you are sitting beside

- **What hydrological pathways do you believe are most important for delivering nitrate-N to surface waters ?**
- **Make a ranking among the following with the most important as number 1, etc.**

Surface runoff

Deep groundwater seepage.

Upper groundwater seepage.

Interflow.

Tile drainage flow.

Human-made interference in the nutrient cycle from land to water

Root zone

Riparian areas

Lakes

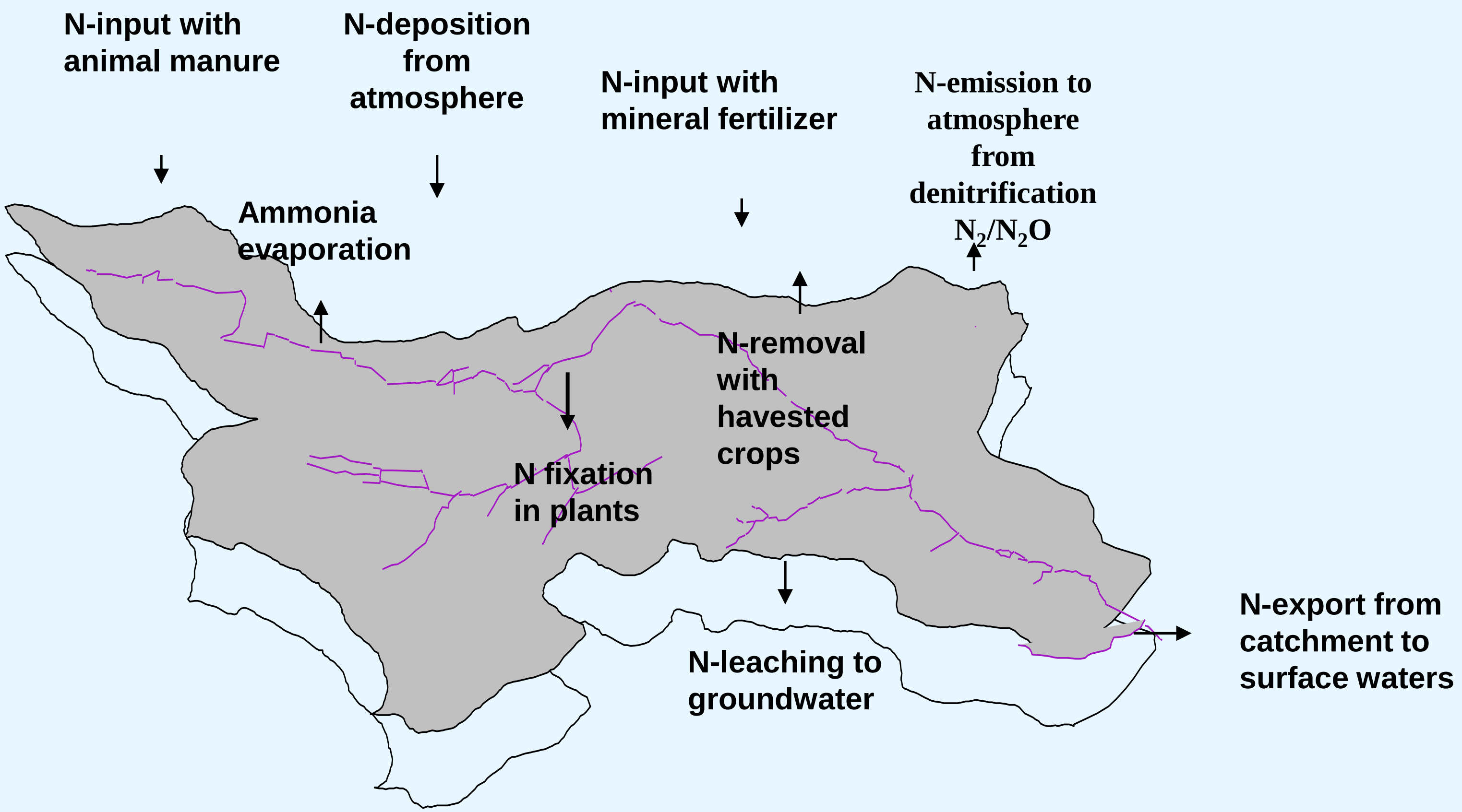
Streams

Forest

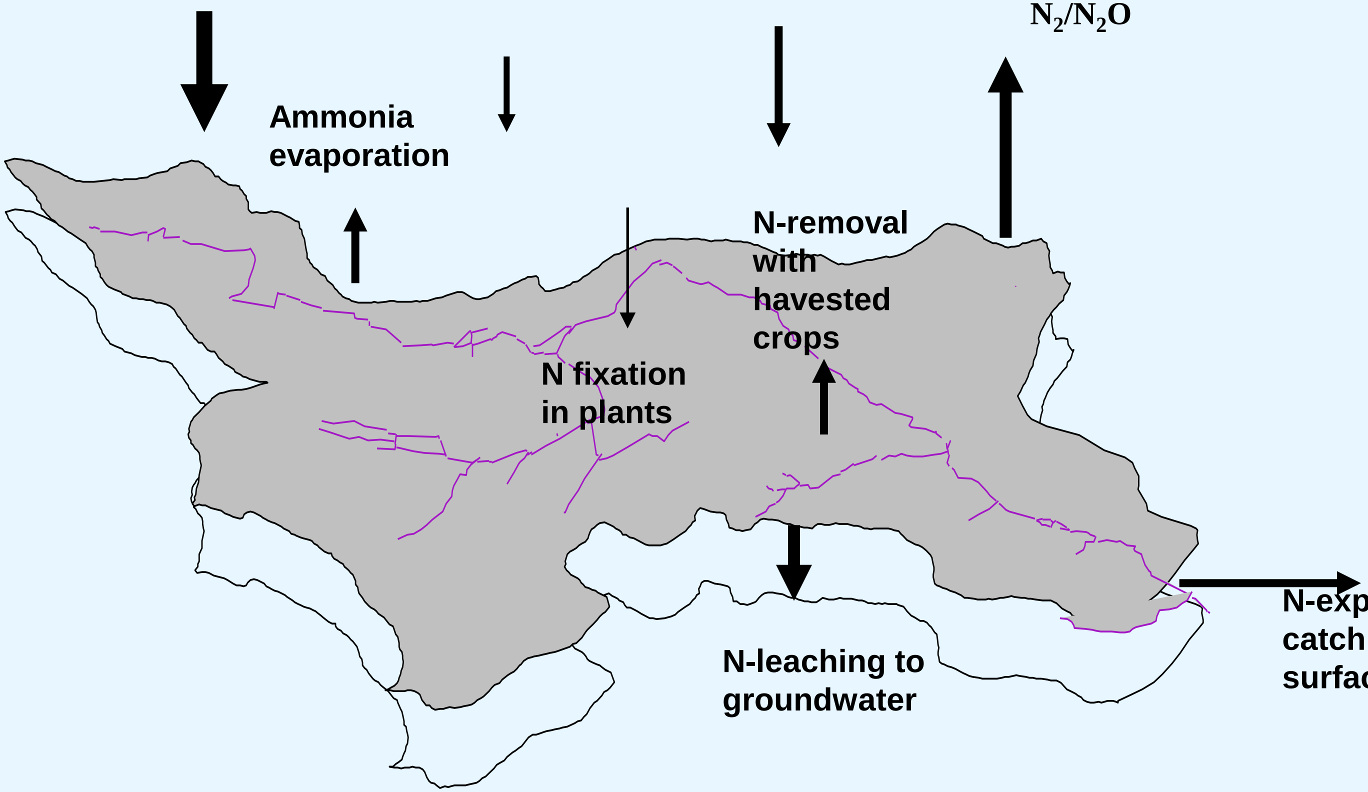
Agriculture

Cities

N-cycling – reference conditions



N-cycling - present situation



N-input with animal manure

N-deposition from atmosphere

N-input with mineral fertilizer

N-emission to atmosphere from denitrification N_2/N_2O

Ammonia evaporation

N-removal with havested crops

N fixation in plants

N-leaching to groundwater

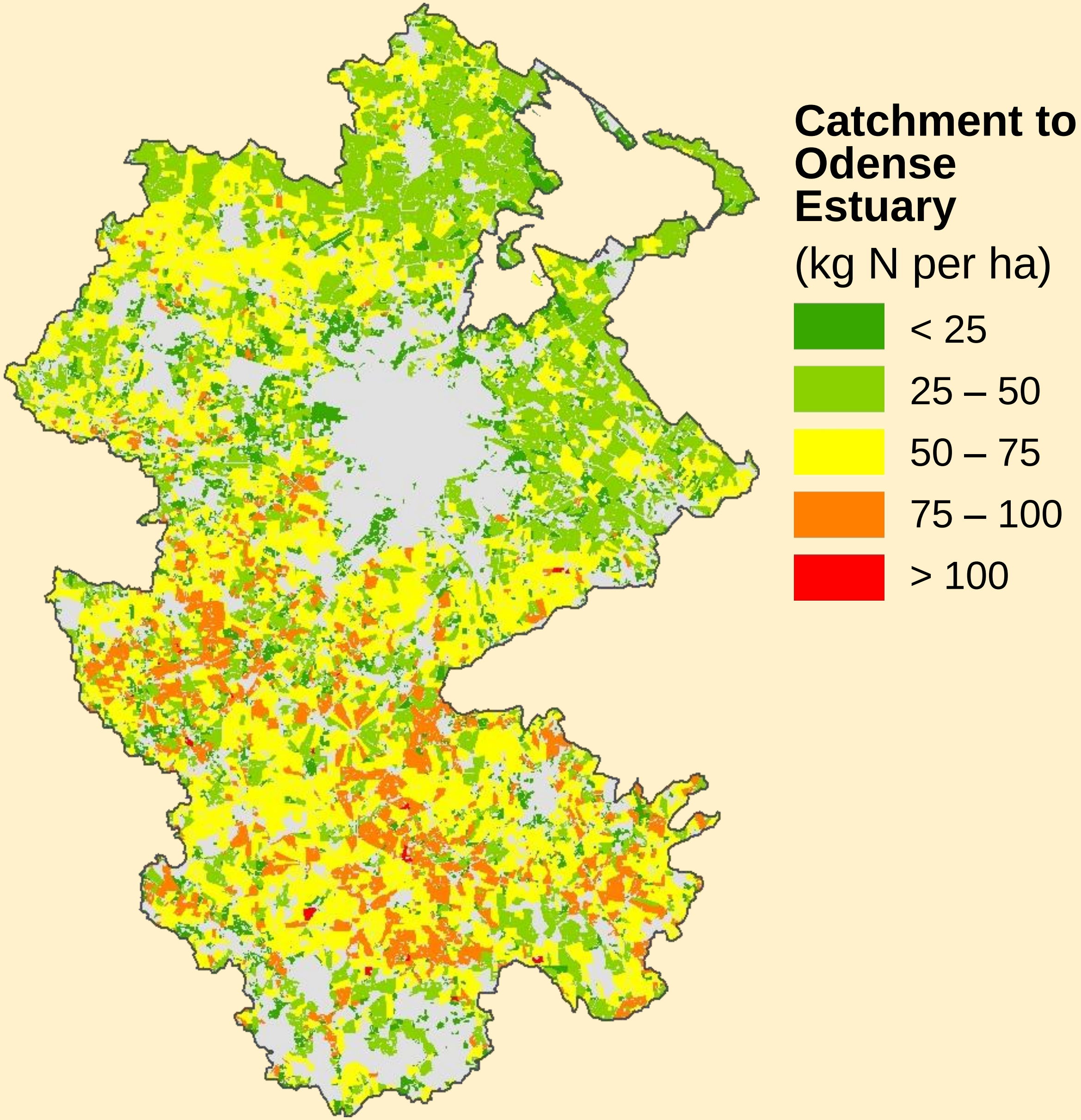
N-export from catchment to surface waters

Eutrophication of the aquatic environment is caused by excess loadings of nitrogen and phosphorus (silicium) to rivers, lakes, estuaries and open marine waters giving rise to algal blooms, oxygen depletion and possible changes in ecosystem structure and function

Foto: Jens M. Andersen

Agriculture with use of nutrients (fertilizer and manure) has increased nutrient inputs to ecosystems (also industry and traffic for air emissions of NO_x = NO, NO_2 and N_2O)

Nitrogen (N) leaching from land (root zone) to water



Facts:

Model: N-LES4

Data for fertilizer and manure from national database.

Data for crop rotation

from national crop database

Nutrients from land to water

Root zone

Riparian areas

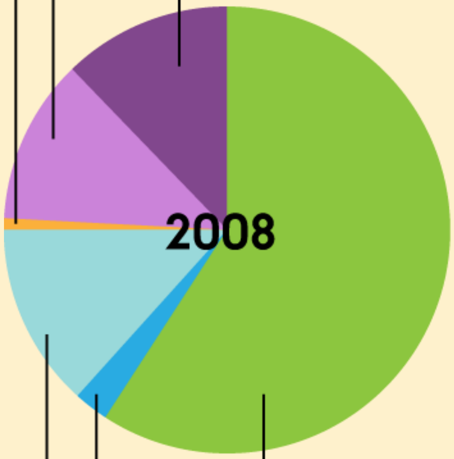
Streams

Forest

Agricu

Cities

Sources of phosphorus (P) loss from land to lakes in Denmark



Fish farms 1%

Rainwater from paved areas 12 %

Waste water treatment plants 12 %

Open land 59 %

Atmospheric deposition 3 %

Scattered Dwellings 13 %

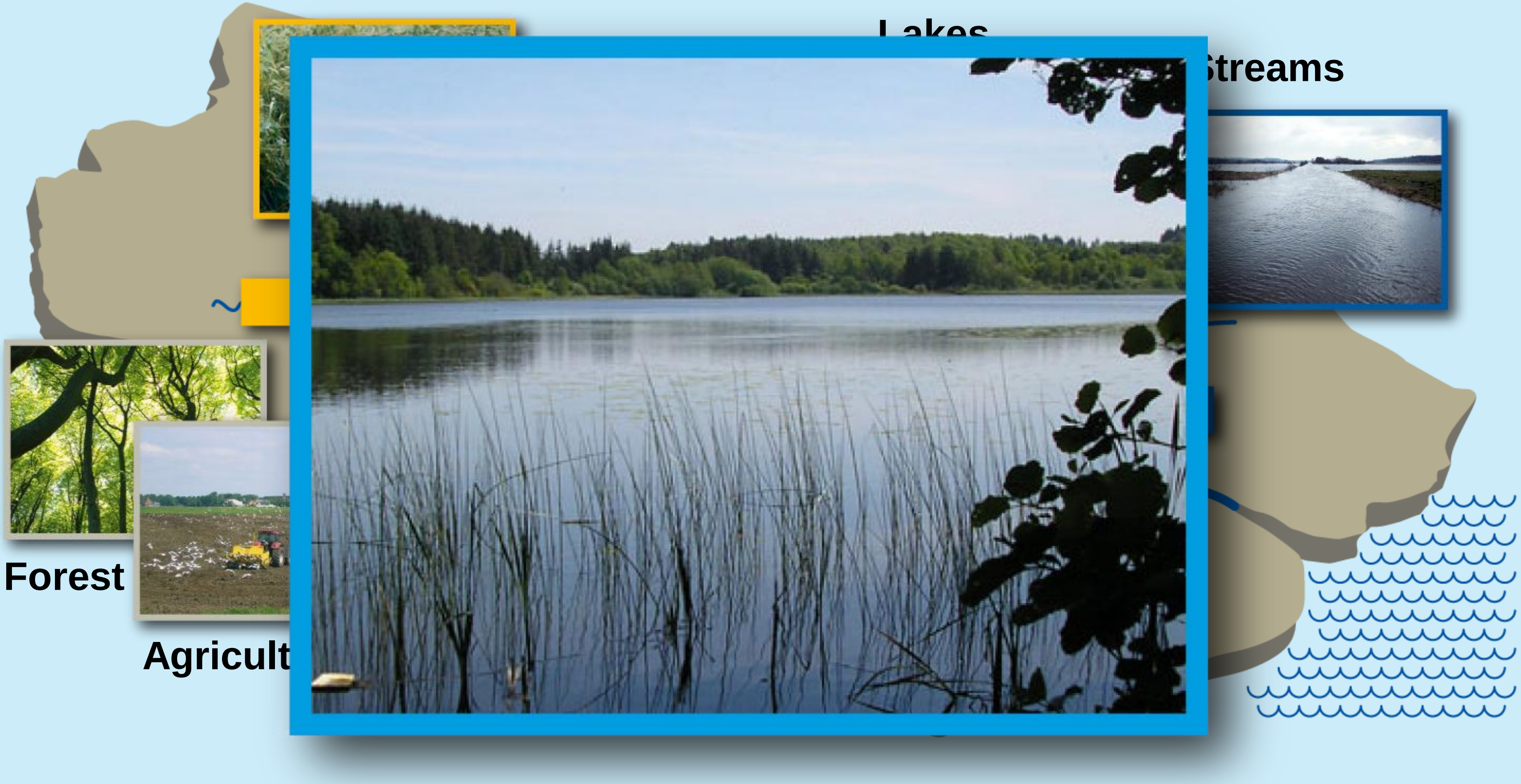
Nutrients from land to water

Riparian areas – how they are managed is important for nutrient losses and in-stream dynamics (uptake, removal and release: nutrient spiralling)

Natural

Farmed

Nutrients from land to water



Root zone

Riparian areas

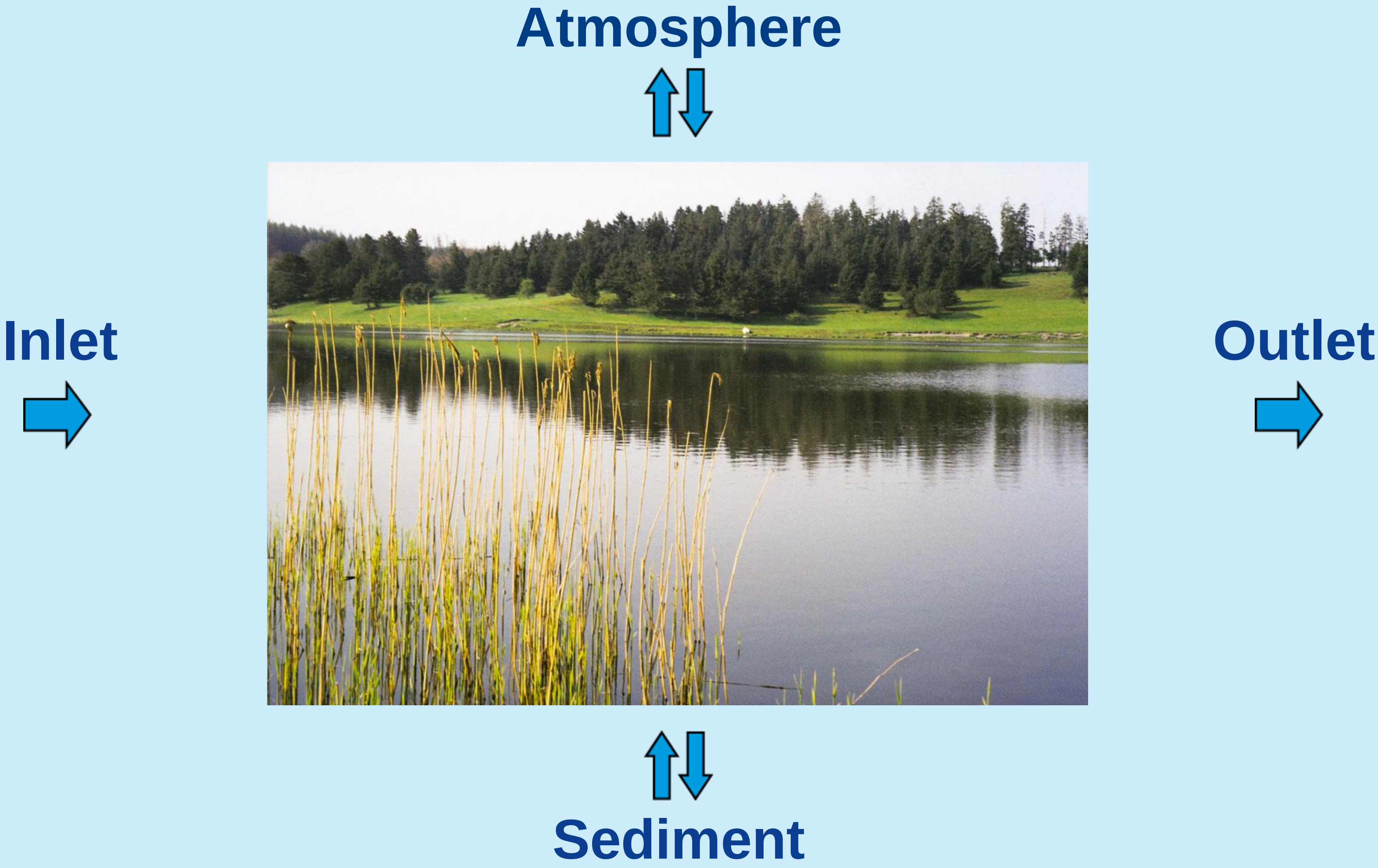
Lakes

Streams

Forest

Agricult

Standing waters – Lakes/reservoirs – nutrient inputs and dynamics



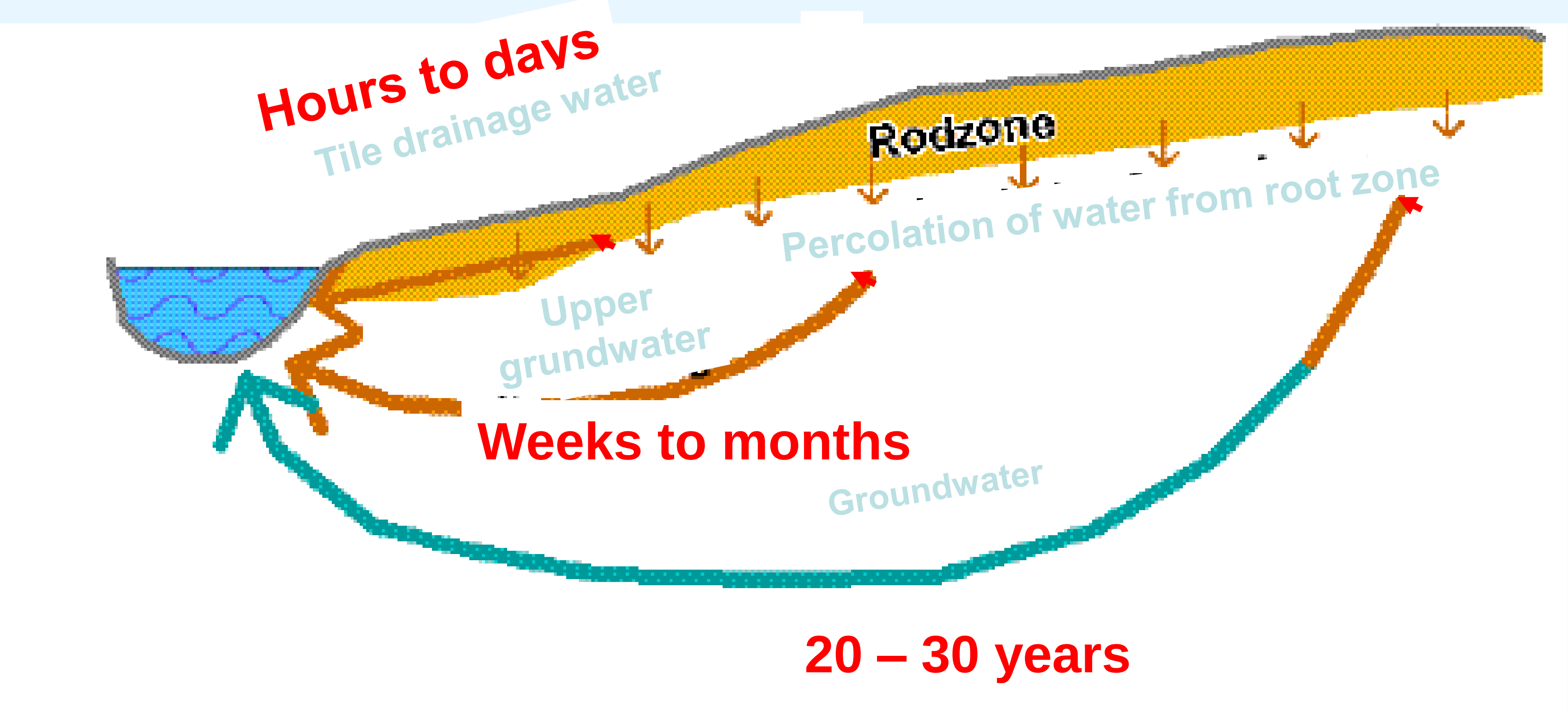
Atmosphere

Inlet

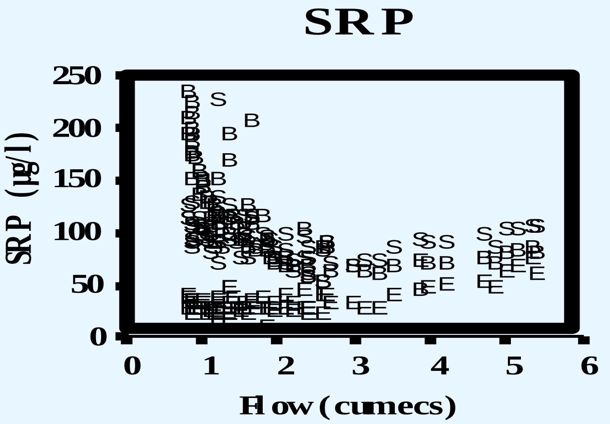
Outlet

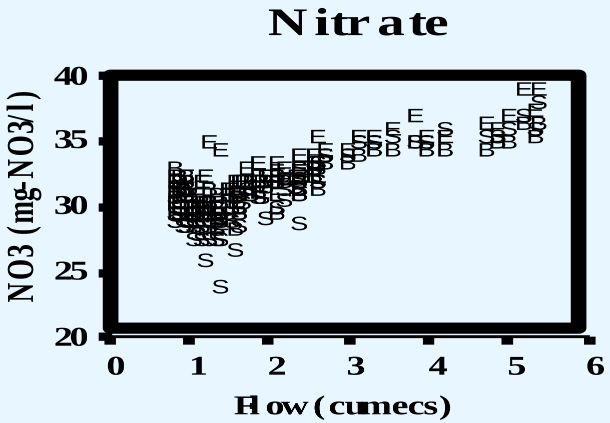
Sediment

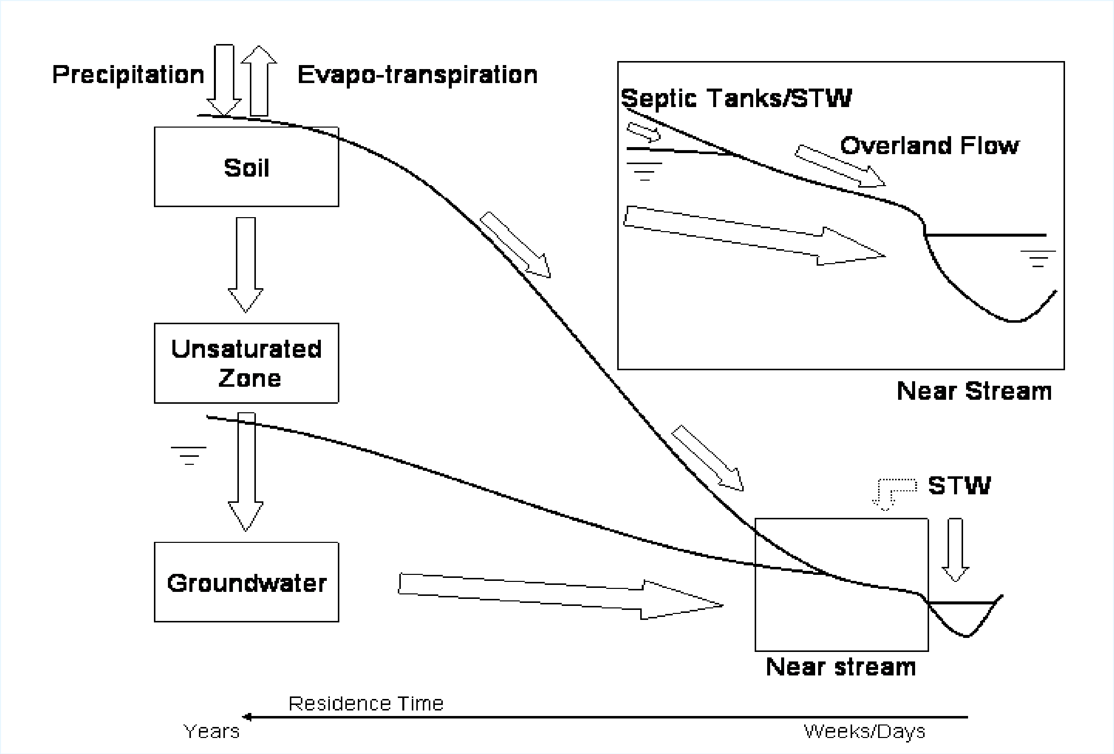
The hydrology of streams is very important for the fluxes and geochemistry of N and P



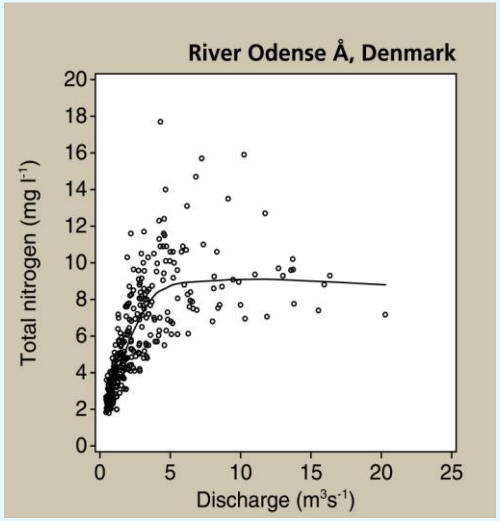
Nutrient response on hydrology for permeable catchments: e.g. sandy catchment

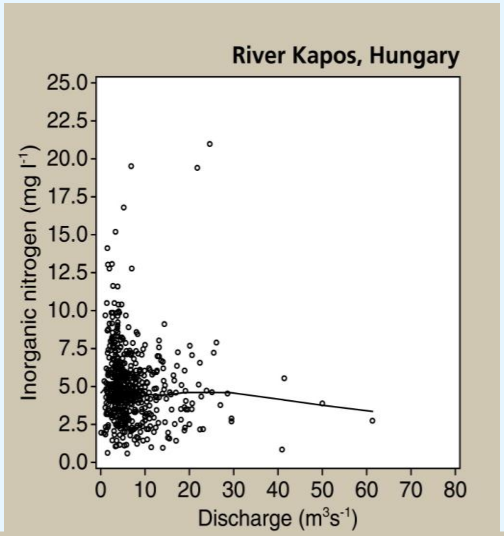

SRP

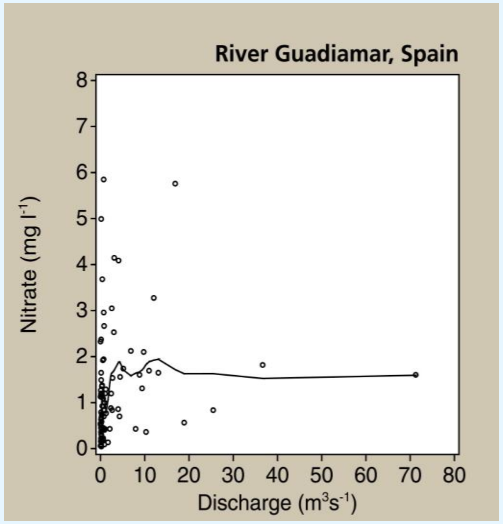

Nitrate

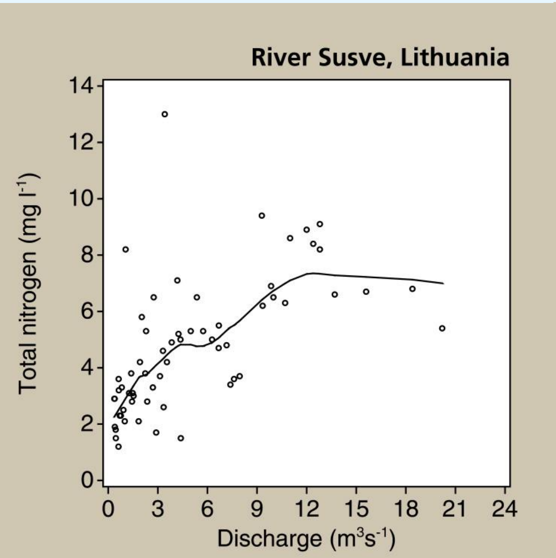


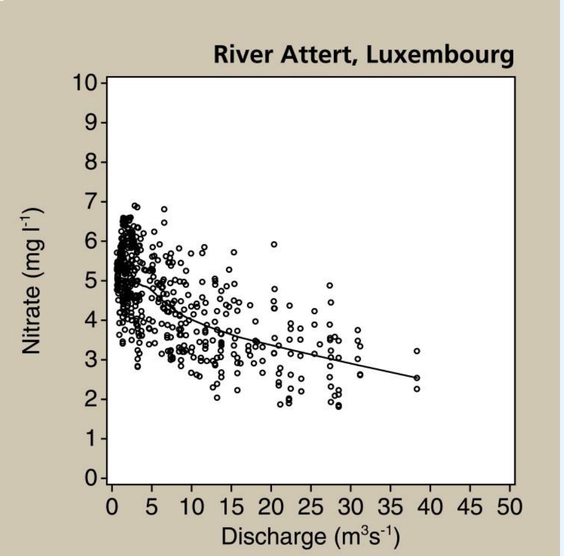
Nitrogen response to changes in discharge in six different European catchments – why do we observe these different responses ?

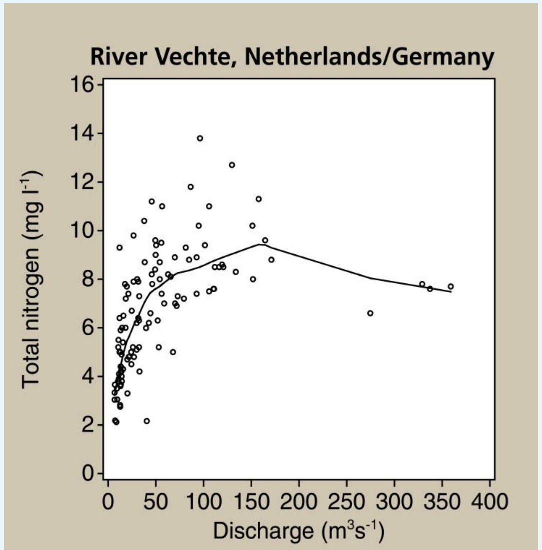












Nutrient load calculation (L)

$$L = \sum_{i=1}^{n} c_i \; q_i$$

Where
C_i is the measured nutrient concentration to time (i)
qi is the measured discharge to time (i)
Nutrient transport is in amounts per time interval:
grammes per time interval e.g. year (g/yr), kilogrammes (kg/yr), tonnes (t/yr)
Often we normalise the transport with the area delivering the nutrient load as e.g. catchment area to a certain monitoring station in a stream (export coefficient, loss coefficient).

The unit is given as: x kg NO3-N ha^{-1} yr^{-1}

Linear Interpolation method often used to estimate daily concentrations

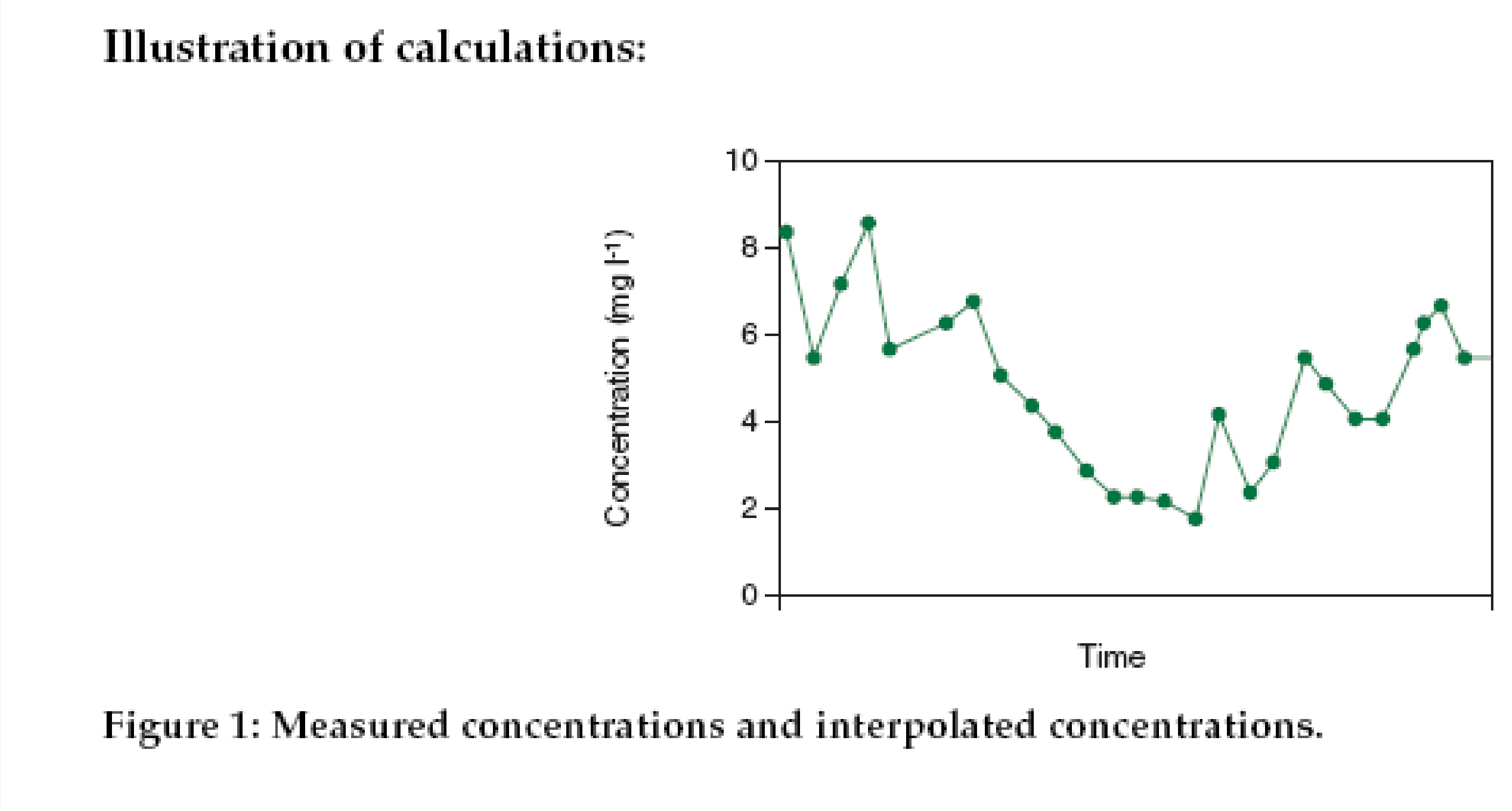
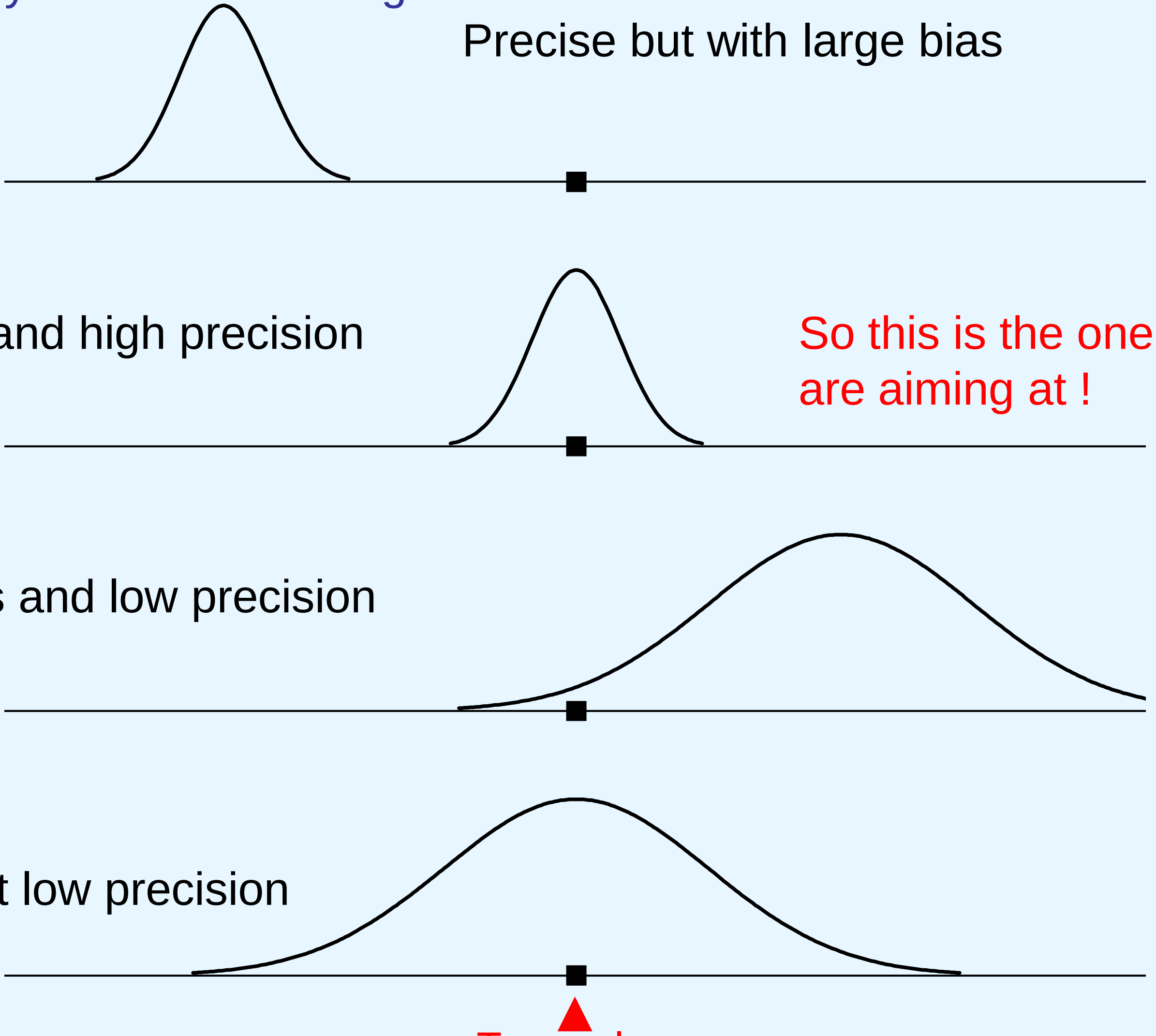


Illustration of calculations:

Figure 1: Measured concentrations and interpolated concentrations.

Statistically speaking – we wan’t to estimate a nutrient transport with a low uncertainty - low Bias and high Precision



Precise but with large bias

No bias and high precision

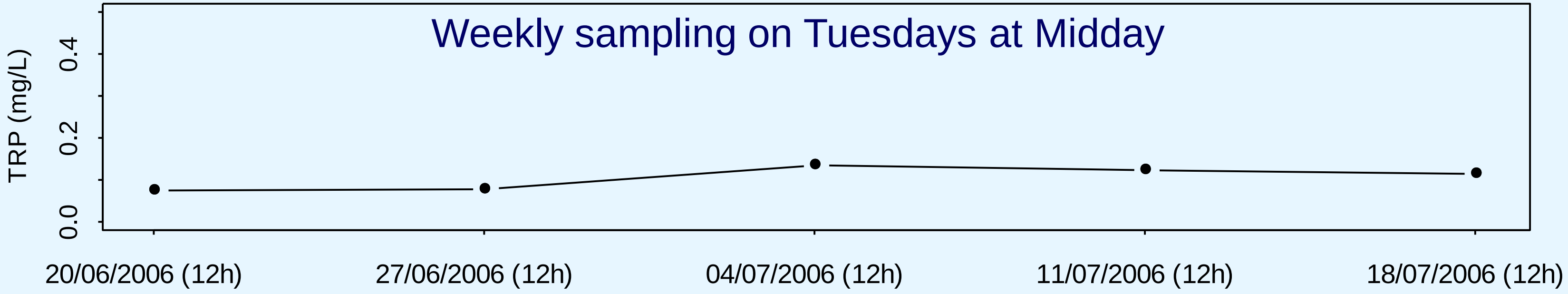
So this is the one we are aiming at !

Large bias and low precision

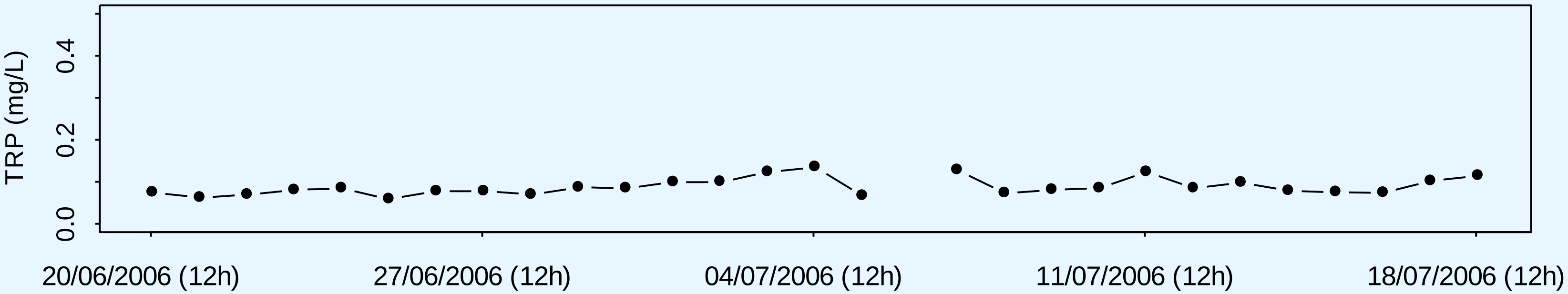
No bias but low precision

True value

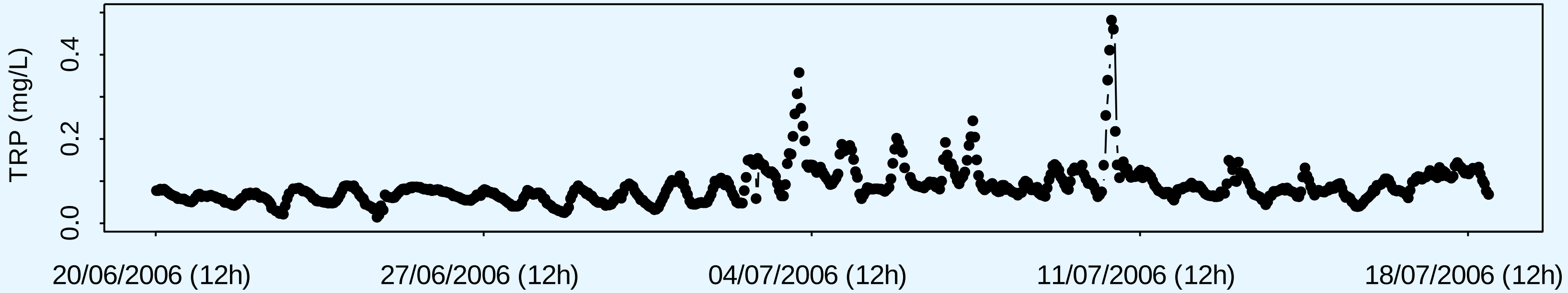
Sampling frequency in streams are vital for depicting the true loads
Total Reactive Phosphorus (mg-P/L) River Kennet at Mildenhall


Weekly sampling on Tuesdays at Midday

Daily sampling at Midday



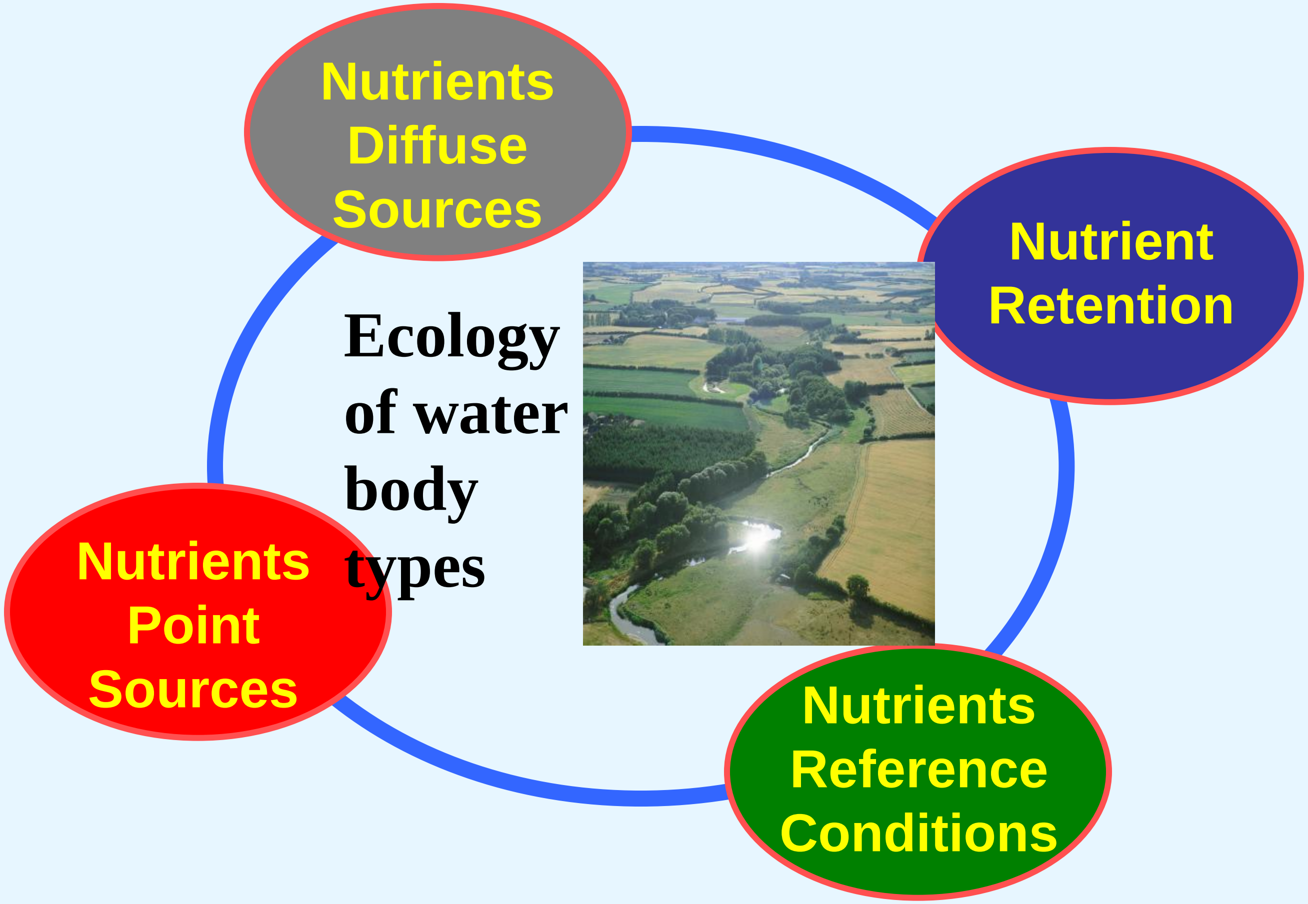
Hourly sampling



Elizabeth Palmer-Felgate et al., J. Hydrol in press

Time for a break ?

Knowledge of nutrient sources, emissions and retention in catchments is needed for improving the ecology of waters



Nutrients Diffuse Sources

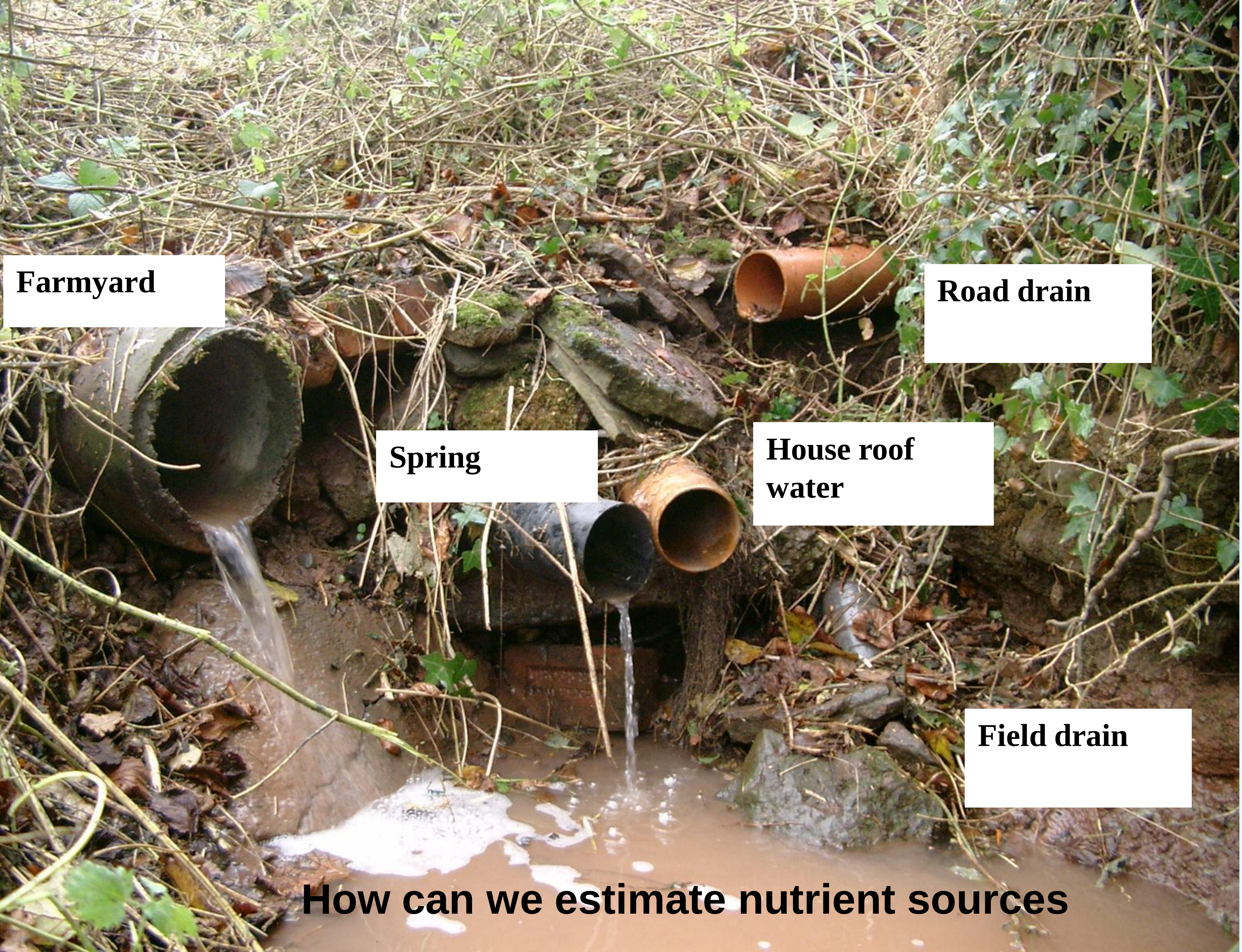
Nutrient Retention

Ecology of water body types

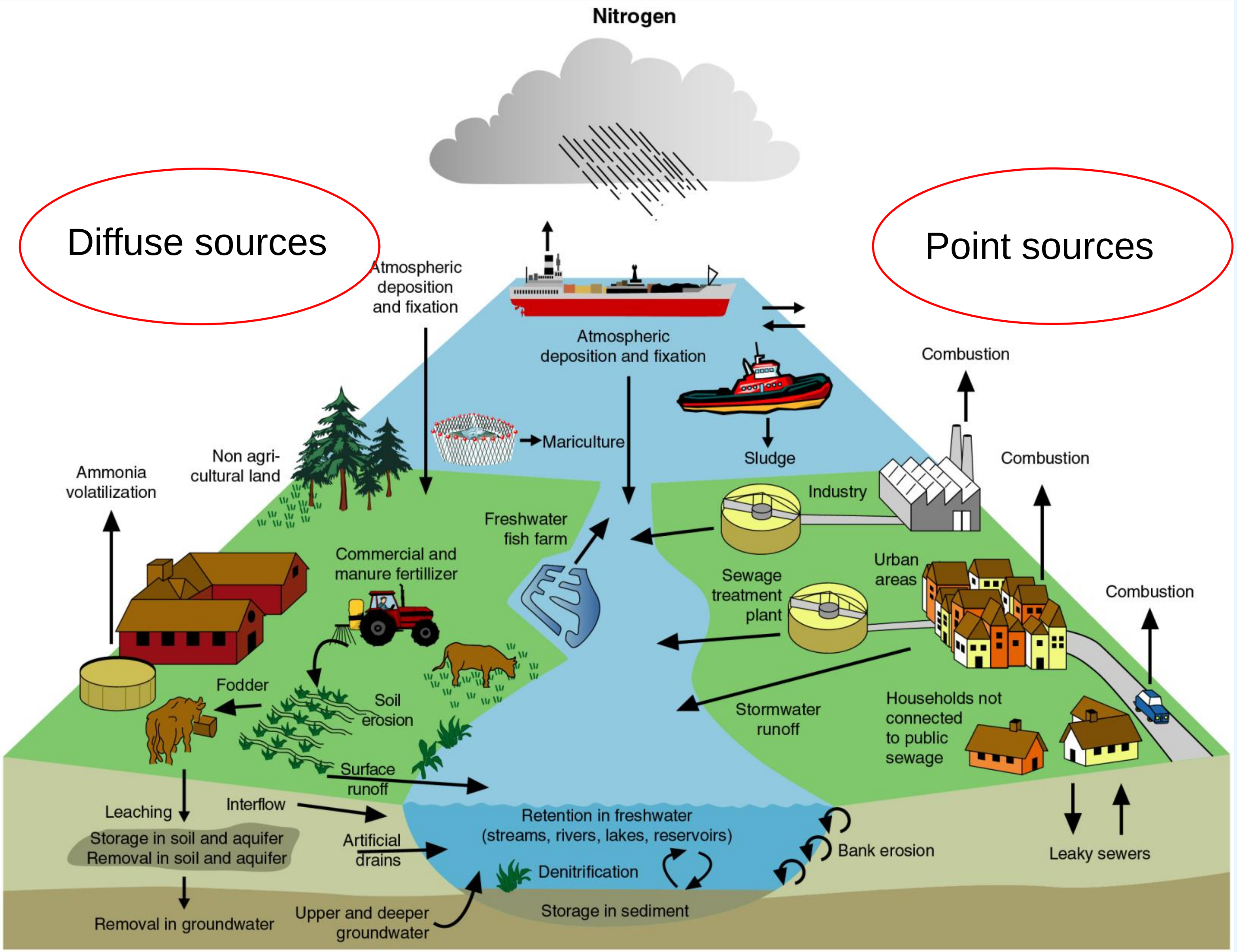
Nutrients Point Sources

Nutrients Reference Conditions

How can we estimate nutrient sources



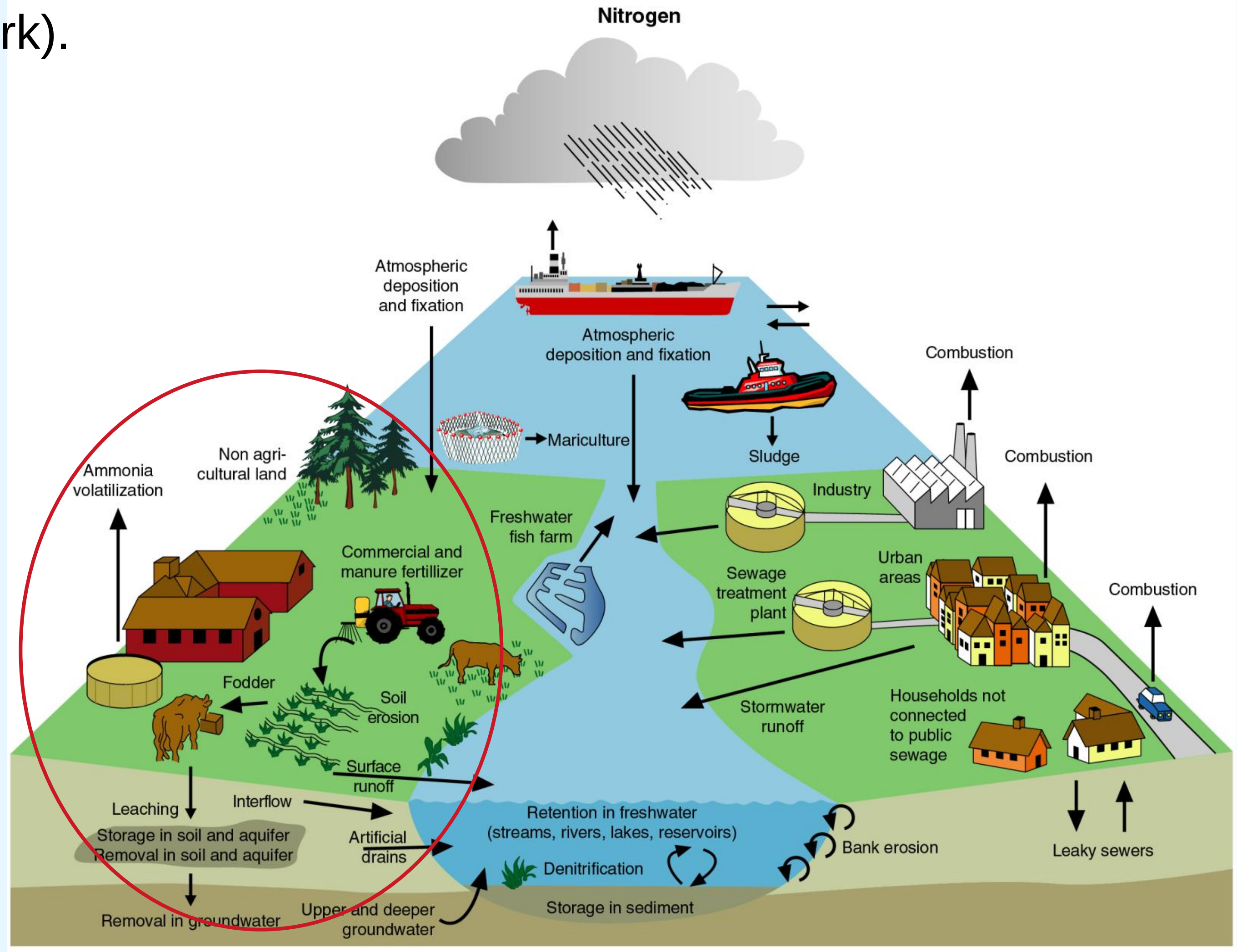
Nutrient Sources



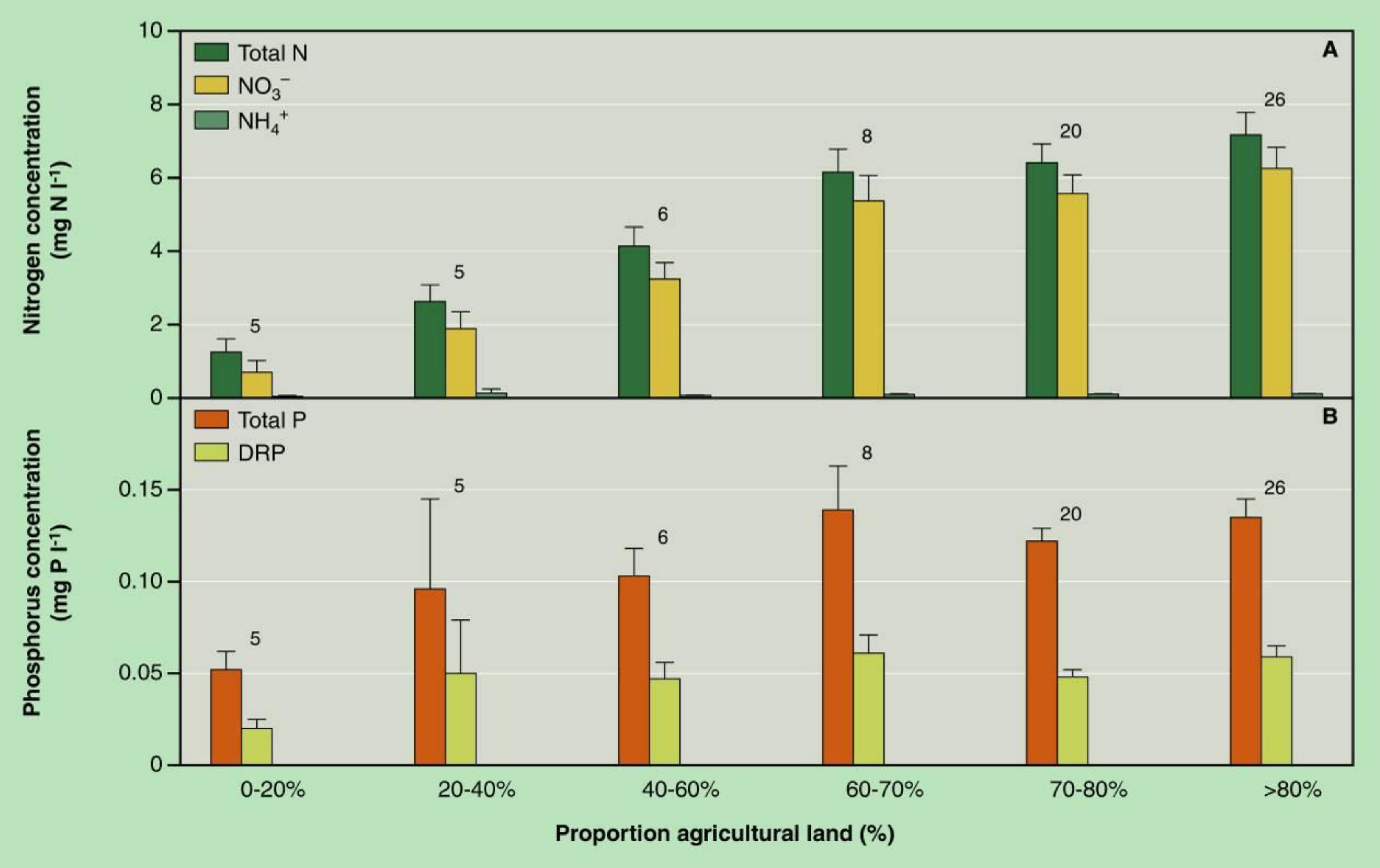
Diffuse sources

Point sources

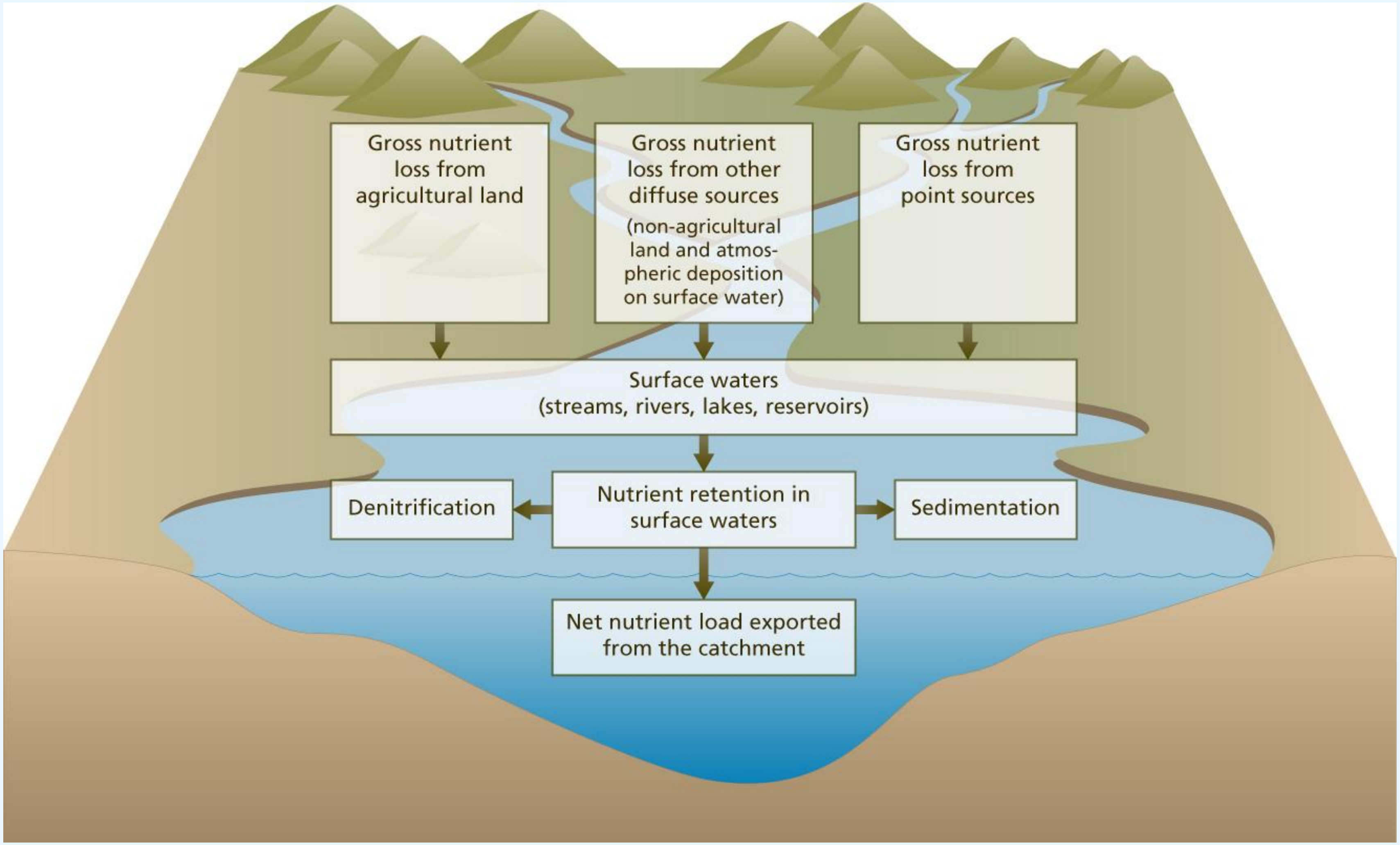
Agriculture represents approximately 62% of nitrogen load to surface waters in Europe, (from a minimum of 18% in Portugal to a maximum of 97% in Denmark).



Nitrogen and phosphorus concentration levels in streams depends on catchment land use



Principles behind source apportionment



Gross nutrient loss from agricultural land

Gross nutrient loss from other diffuse sources (non-agricultural land and atmospheric deposition on surface water)

Gross nutrient loss from point sources

Surface waters (streams, rivers, lakes, reservoirs)

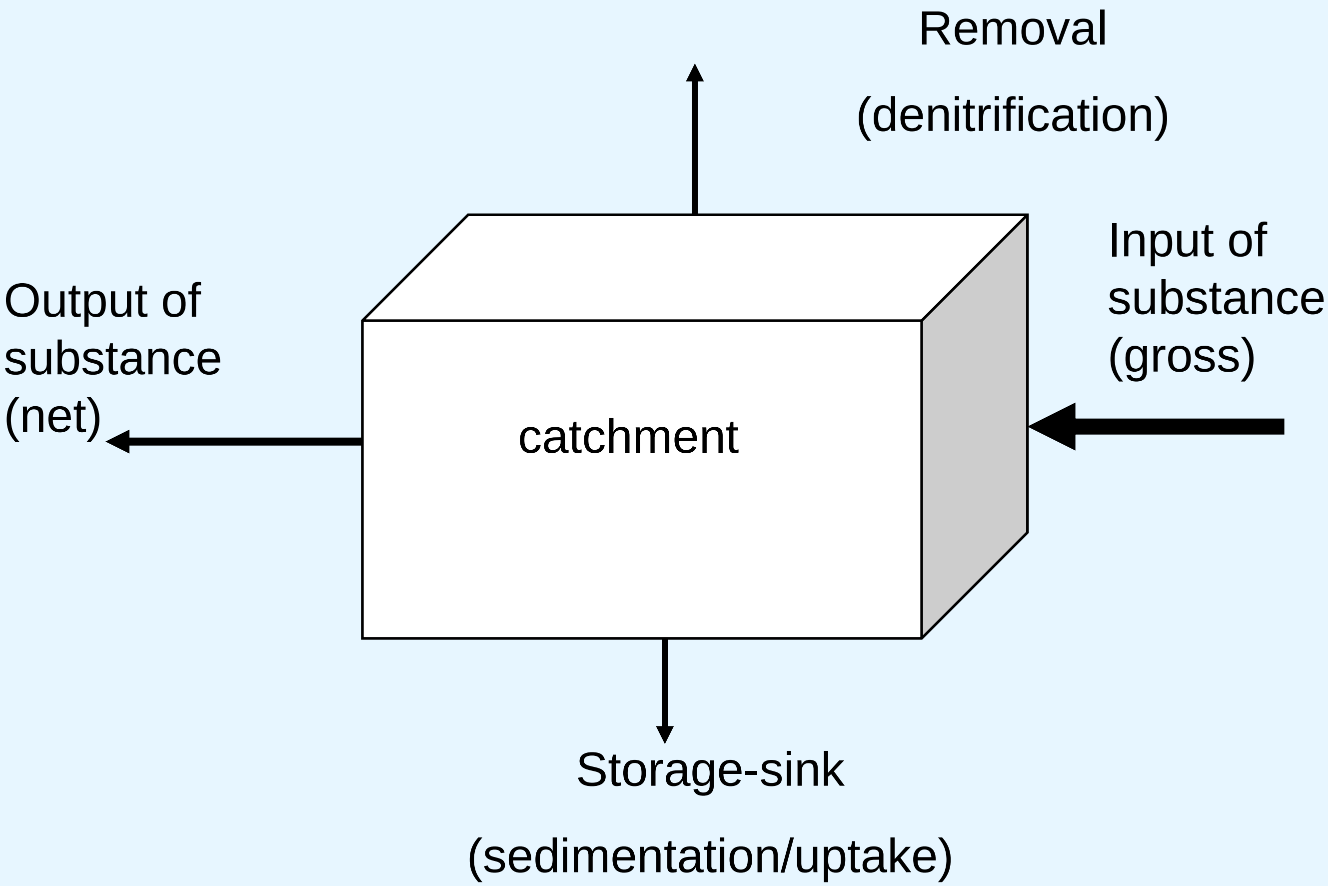
Nutrient retention in surface waters

Denitrification

Sedimentation

Net nutrient load exported from the catchment

Gross input, removal/storage (retention) and net output



Removal

(denitrification)

Input of
substance
(gross)

Output of
substance
(net)

catchment

Storage-sink

(sedimentation/uptake)

Source apportionment methods

Immission method: Load oriented approach

- **Monitoring of all point sources and river N loads**
- **Diffuse load = river load – point source load + retention**

- **Problems**
  - **Very intensive water quality monitoring**
  - **Expensive**

Source apportionment

Transport measured in a stream (T_V) = Emission from point sources (E_P)+ emission from agricultural areas (E_L) + background emissions from all areas except water areas (E_B) + atmospheric deposition on surface water (A_O) – retention in surface waters (R)

With known T_V & E_P & E_B & A_O & R we can estimate the unknown variable E_L from:

$$E_L = T_V - E_P - E_B - A_O + R$$

Retention of nutrients in waters

Different mechanisms

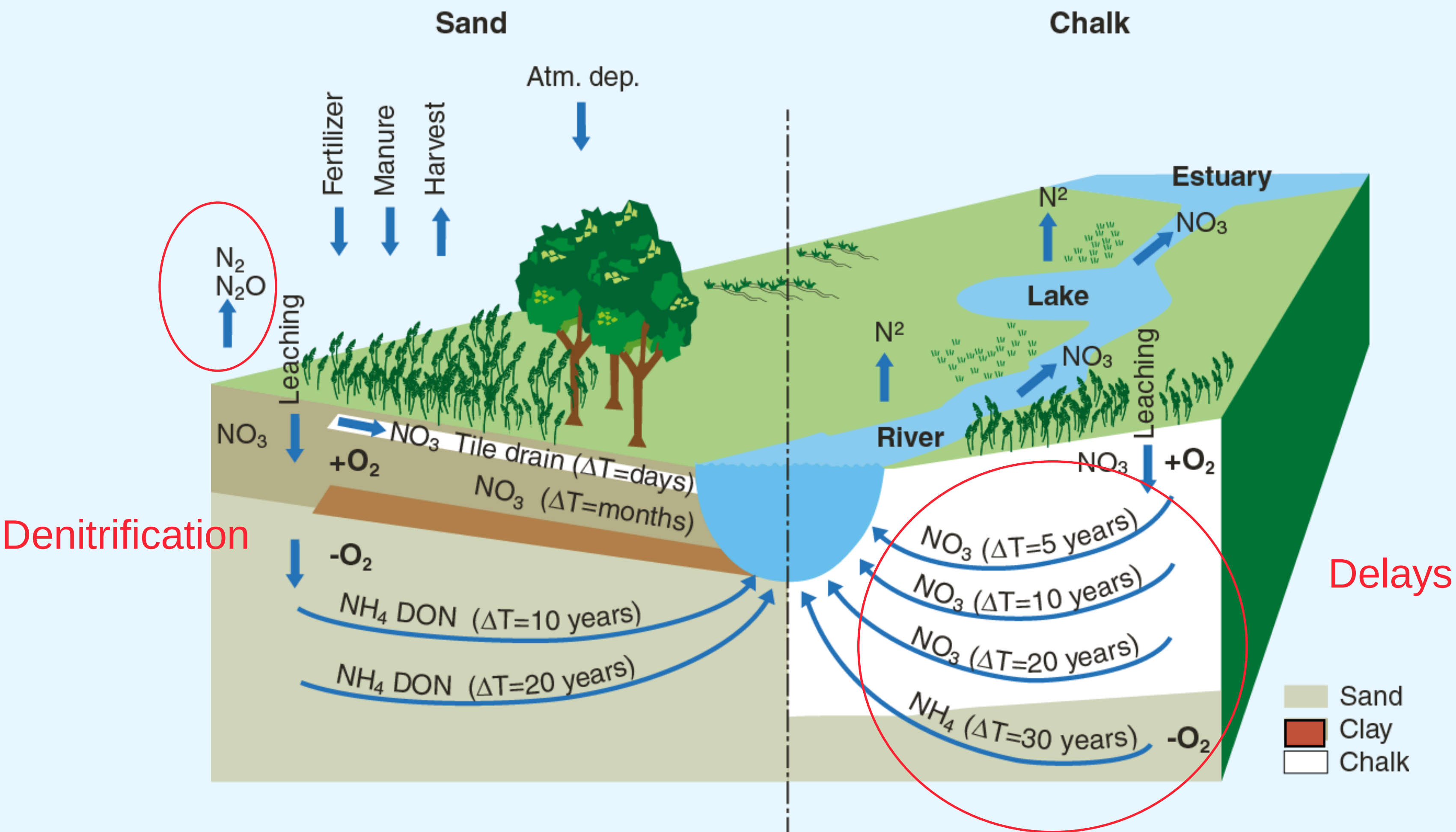
Physical processes

- **Sedimentation of particles in streams lakes and wetlands (organic and inorganic) with nutrients sorbed or included in the minerals and organic material.**

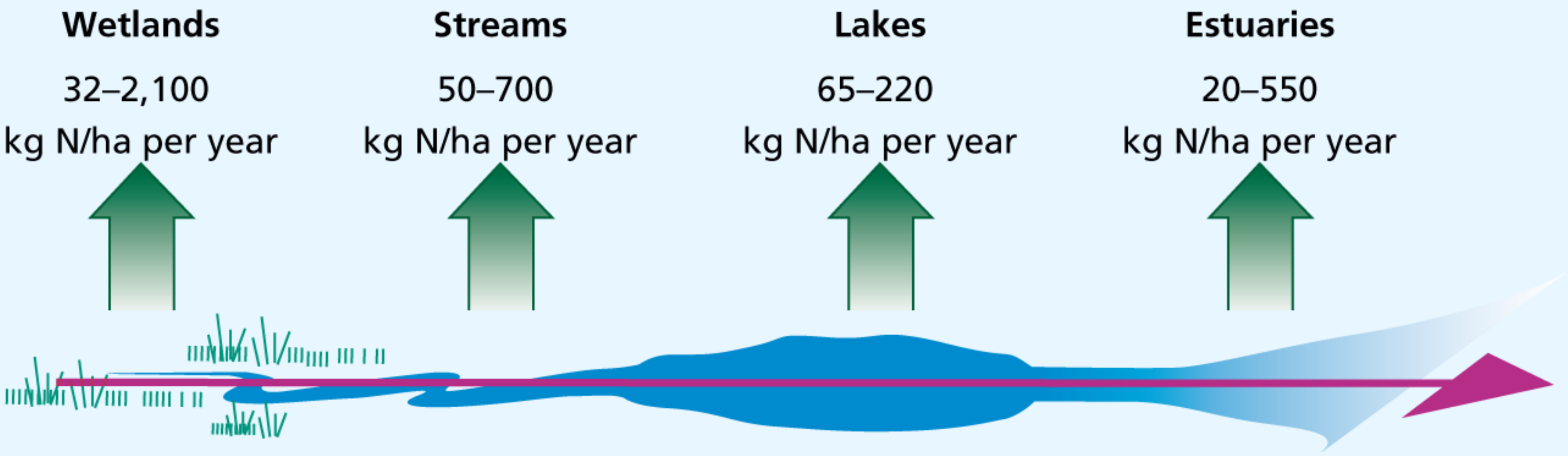
Biogeochemical processes

- **Denitrification of nitrate-nitrogen to N_2 & N_2O under anaerobic conditions.**
- **Sorption or precipitation processes for PO_4-P – SRP or DRP (Fe,Al,Ca)**

Hydrological and biogeochemical processes in catchments influences nitrogen cycling (removal and inertia)



Denitrification takes place in all compartments



Wetlands

32–2,100
kg N/ha per year

Streams

50–700
kg N/ha per year

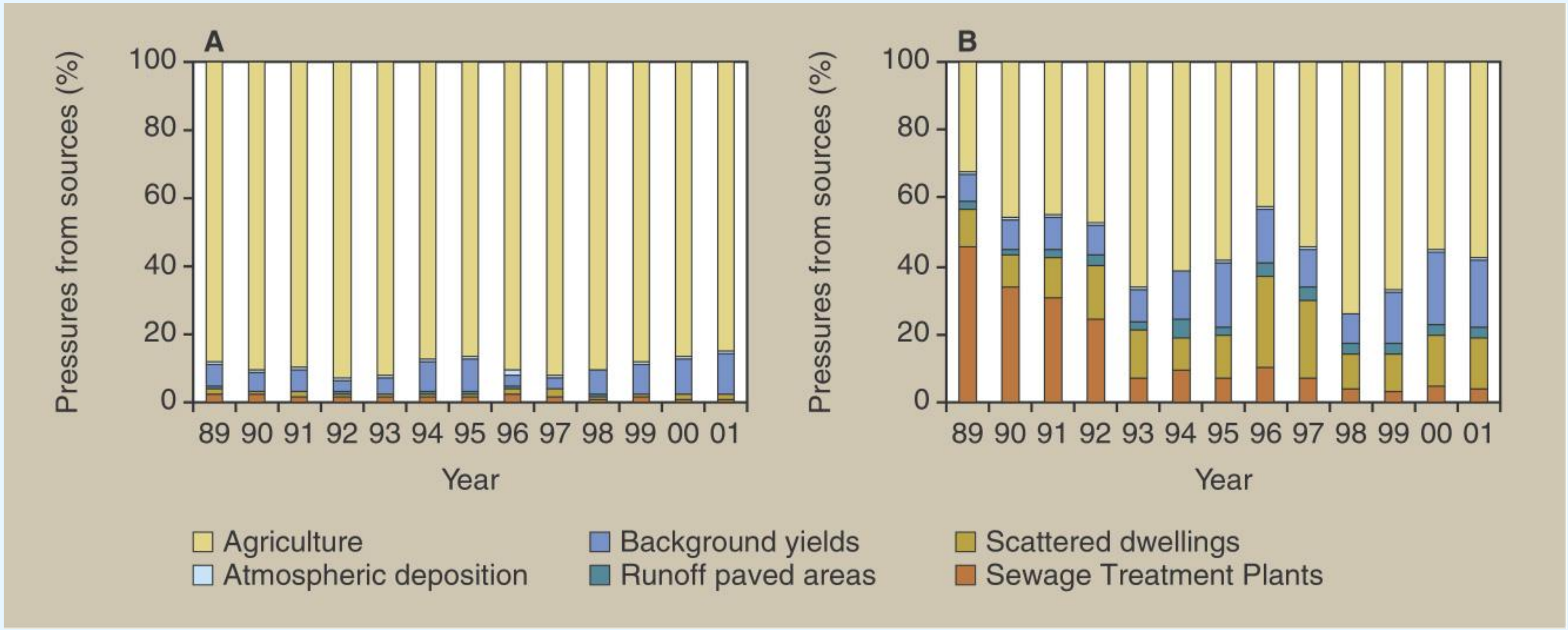
Lakes

65–220
kg N/ha per year

Estuaries

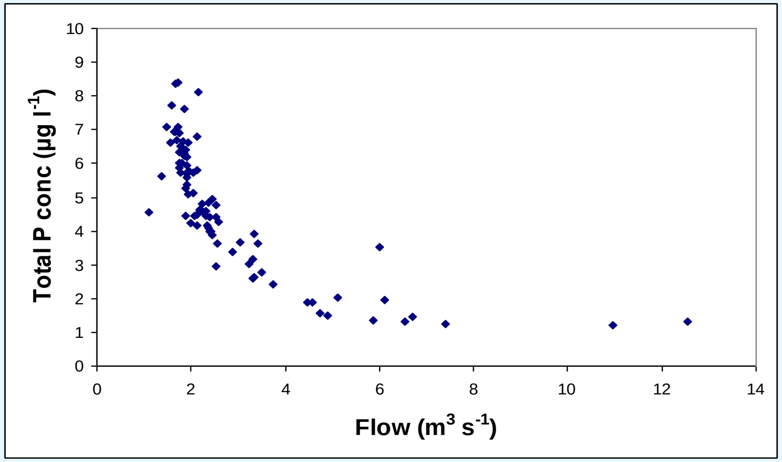
20–550
kg N/ha per year

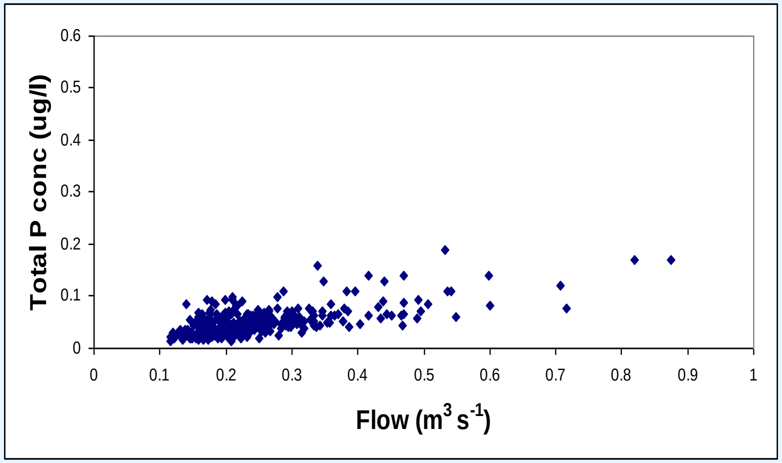
Source apportionment Odense River



Load apportionment modelling

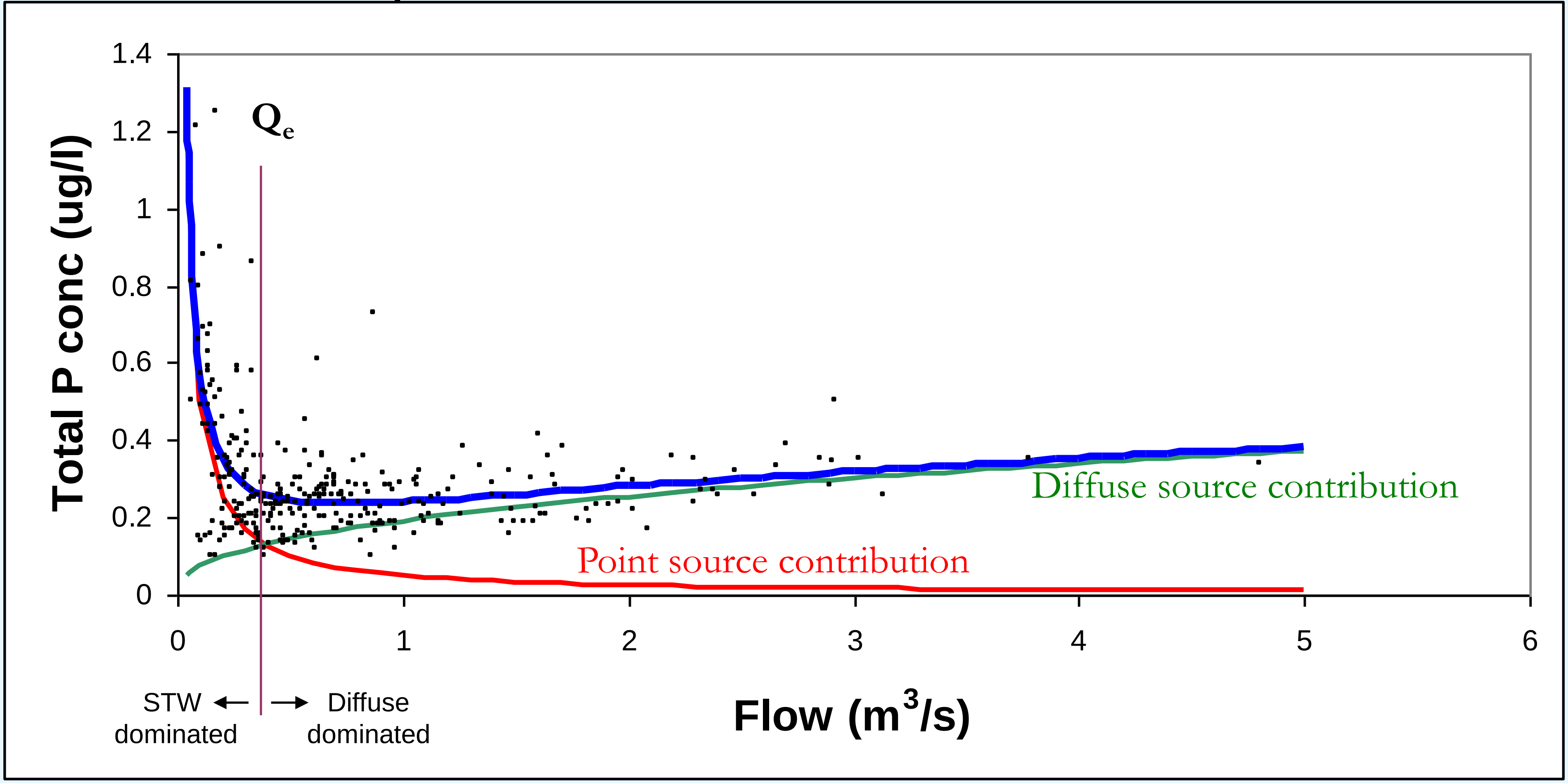
- **Point source P input is relatively constant, and independent of flow.**
- **Diffuse P inputs are usually flow-dependent.**





Difference in P concentration/ flow relationship used to estimate point and diffuse inputs.

Model example



Agriculture – a dominant pressure for water quality of surface waters

Principles for calculations of N surplus

Farm scale :

- N input (N fertilization, N fixation, N deposition, imported N with cereals, N in green fodder and other types of fodder, imported animals)
- -N removed from farm with cash crops, meat products, dairy products, exported manure/slurry, sold animals)
- = N surplus_farm.

N surplus_farm_scale = N losses by:

- field N leaching,
- NH4-volatilization (from stables,manure storage facilities and losses from the field)
- denitrification (field , stable, storage).
- Change in number of animals, change in feed and cereals stored on the farm and the change in soil N pools

Principles for calculations on field scale

Field scale method:

- N input (manure, chemical fertilizer, N fixation, N deposition)
- minus N harvested from the field with crops

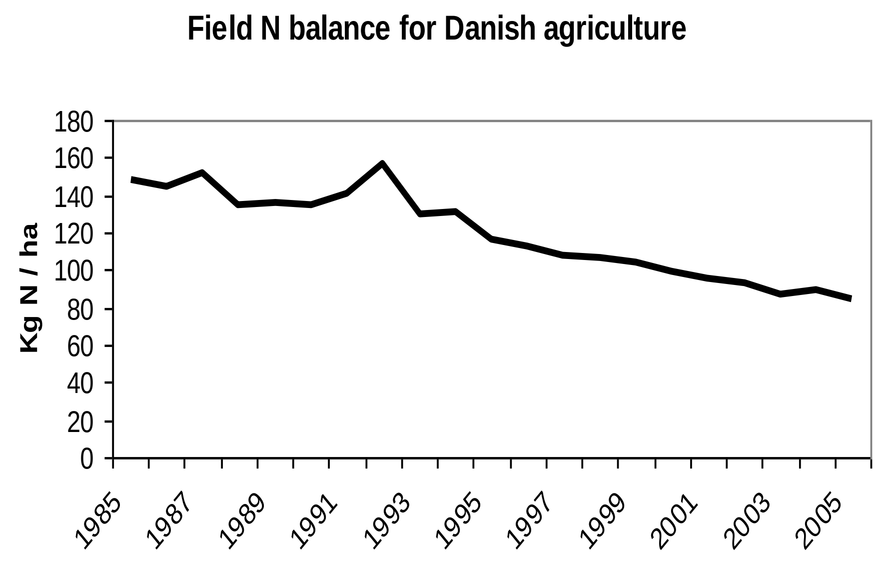
- = N surplus_field.

- N surplus_field= N losses by: leaching+ NH4-volatilization+ denitrification+soil N storage.

Source of N in soils

Data for 2005. Numbers in kg N/ha

Inorganic fertilizer	77.8
Organic fertilizer	88.8
Sludge	4.2
N fixation	15.2
Atmospheric N deposition	15.4
Total input	201.2
Harvest	116.3
Balance	84.9

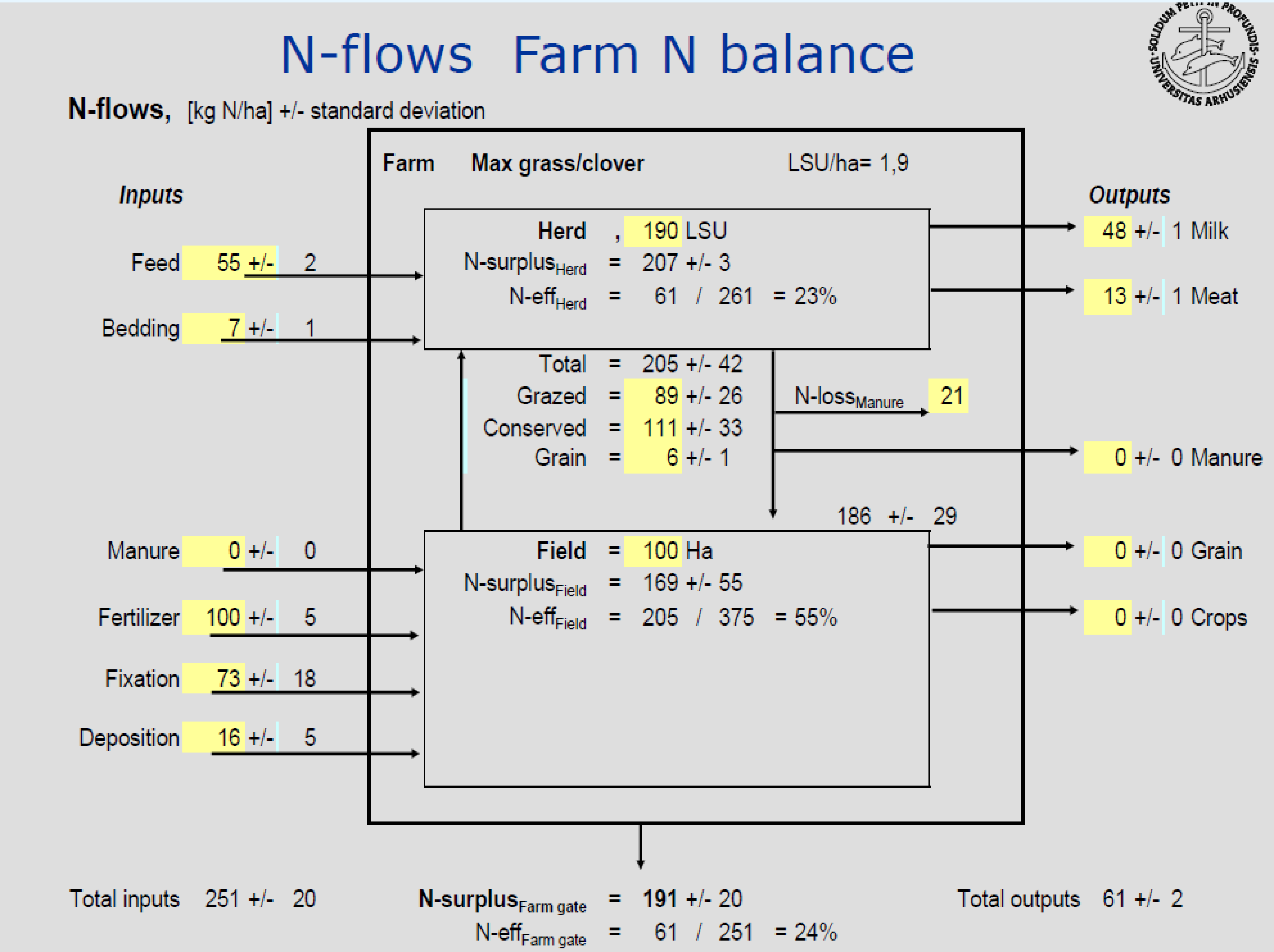


$N_{soil} + NH_3 + N_2 = 25$

Leaching $NO_3^- = 60$

Time for an exercise ?

Dairy farm with 1.9 Livestock units (LSU) per ha



N-flows Farm N balance

N-flows, [kg N/ha] +/- standard deviation

Farm **Max grass/clover** LSU/ha= 1,9

Inputs

Feed 55 +/- 2

Bedding 7 +/- 1

Manure 0 +/- 0

Fertilizer 100 +/- 5

Fixation 73 +/- 18

Deposition 16 +/- 5

Herd , 190 LSU

$\text{N-surplus}_{\text{Herd}}$ = 207 +/- 3

$\text{N-eff}_{\text{Herd}}$ = 61 / 261 = 23%

Total = 205 +/- 42

Grazed = 89 +/- 26

Conserved = 111 +/- 33

Grain = 6 +/- 1

$\text{N-loss}_{\text{Manure}}$ 21

186 +/- 29

Field = 100 Ha

$\text{N-surplus}_{\text{Field}}$ = 169 +/- 55

$\text{N-eff}_{\text{Field}}$ = 205 / 375 = 55%

Outputs

48 +/- 1 Milk

13 +/- 1 Meat

0 +/- 0 Manure

0 +/- 0 Grain

0 +/- 0 Crops

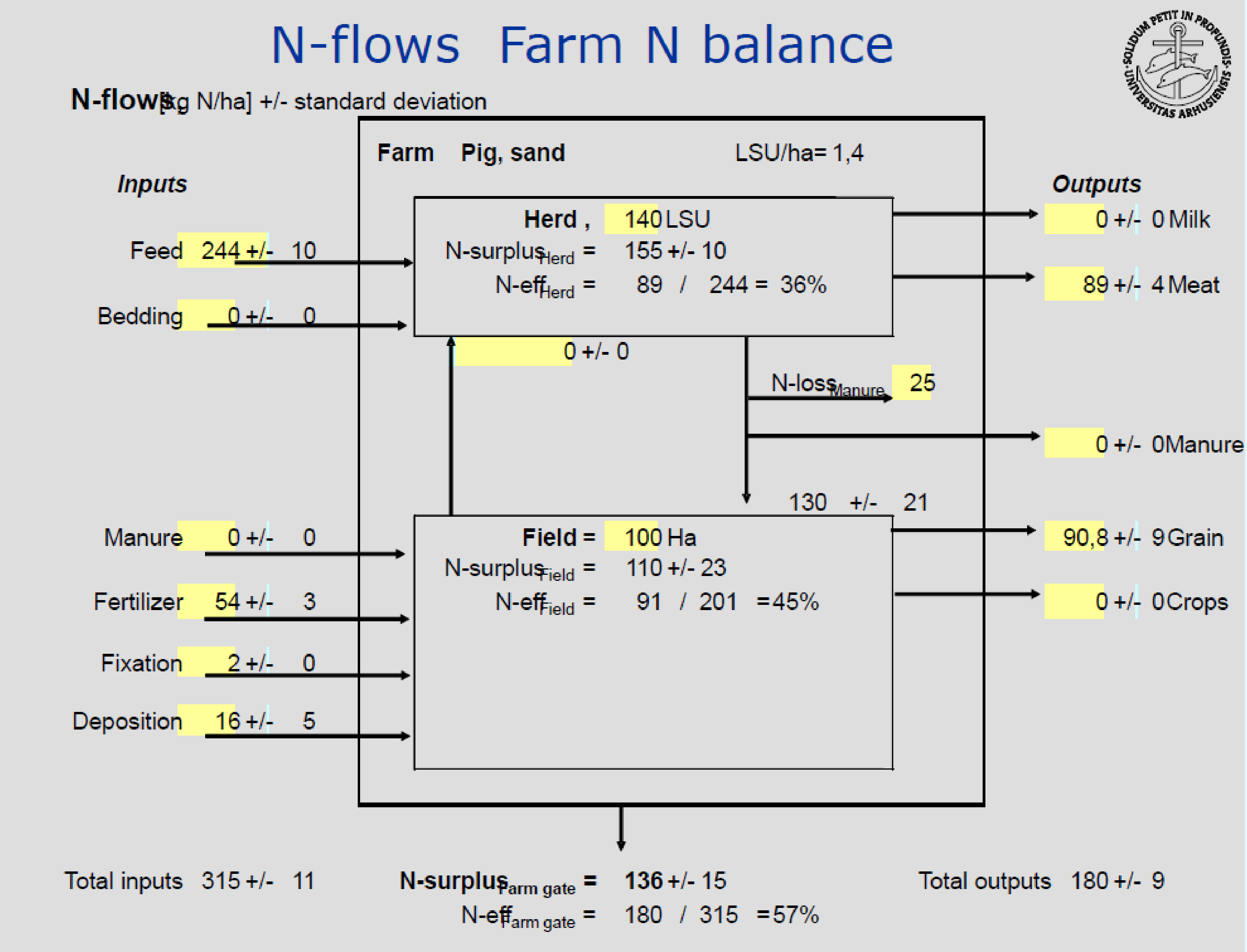
Total inputs 251 +/- 20

$\text{N-surplus}_{\text{Farm gate}}$ = 191 +/- 20

$\text{N-eff}_{\text{Farm gate}}$ = 61 / 251 = 24%

Total outputs 61 +/- 2

Arable farm with 1.4 livestock units per ha (pigs)



N-flows Farm N balance

N-flows [kg N/ha] +/- standard deviation

Farm **Pig, sand** LSU/ha= 1,4

Inputs

Feed 244 +/- 10

Bedding 0 +/- 0

Herd , 140 LSU
$\text{N-surplus}_{\text{Herd}}$ = 155 +/- 10
$\text{N-eff}_{\text{Herd}}$ = 89 / 244 = 36%

0 +/- 0

$\text{N-loss}_{\text{Manure}}$ 25

130 +/- 21

Manure 0 +/- 0

Fertilizer 54 +/- 3

Fixation 2 +/- 0

Deposition 16 +/- 5

Field = 100 Ha
$\text{N-surplus}_{\text{Field}}$ = 110 +/- 23
$\text{N-eff}_{\text{Field}}$ = 91 / 201 =45%

Outputs

0 +/- 0 Milk

89 +/- 4 Meat

0 +/- 0 Manure

90,8 +/- 9 Grain

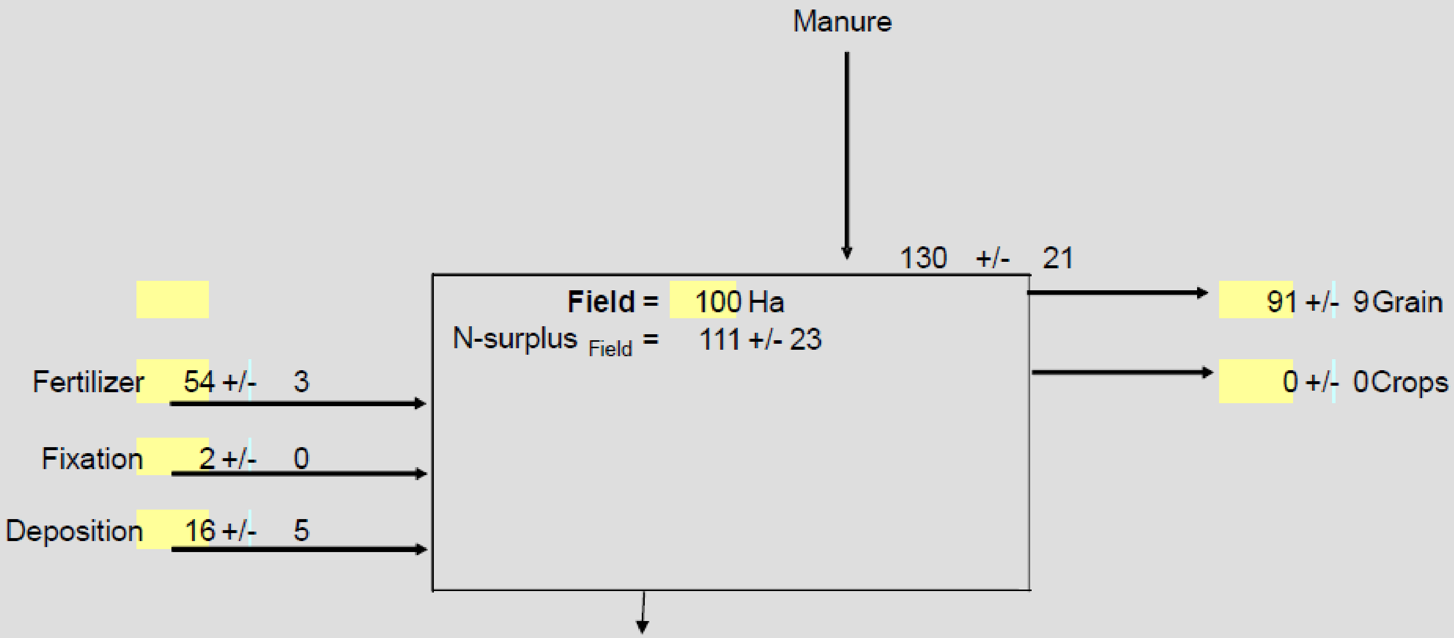
0 +/- 0 Crops

Total inputs 315 +/- 11

$\text{N-surplus}_{\text{Farm gate}}$ = **136** +/- 15
$\text{N-eff}_{\text{Farm gate}}$ = 180 / 315 =57%

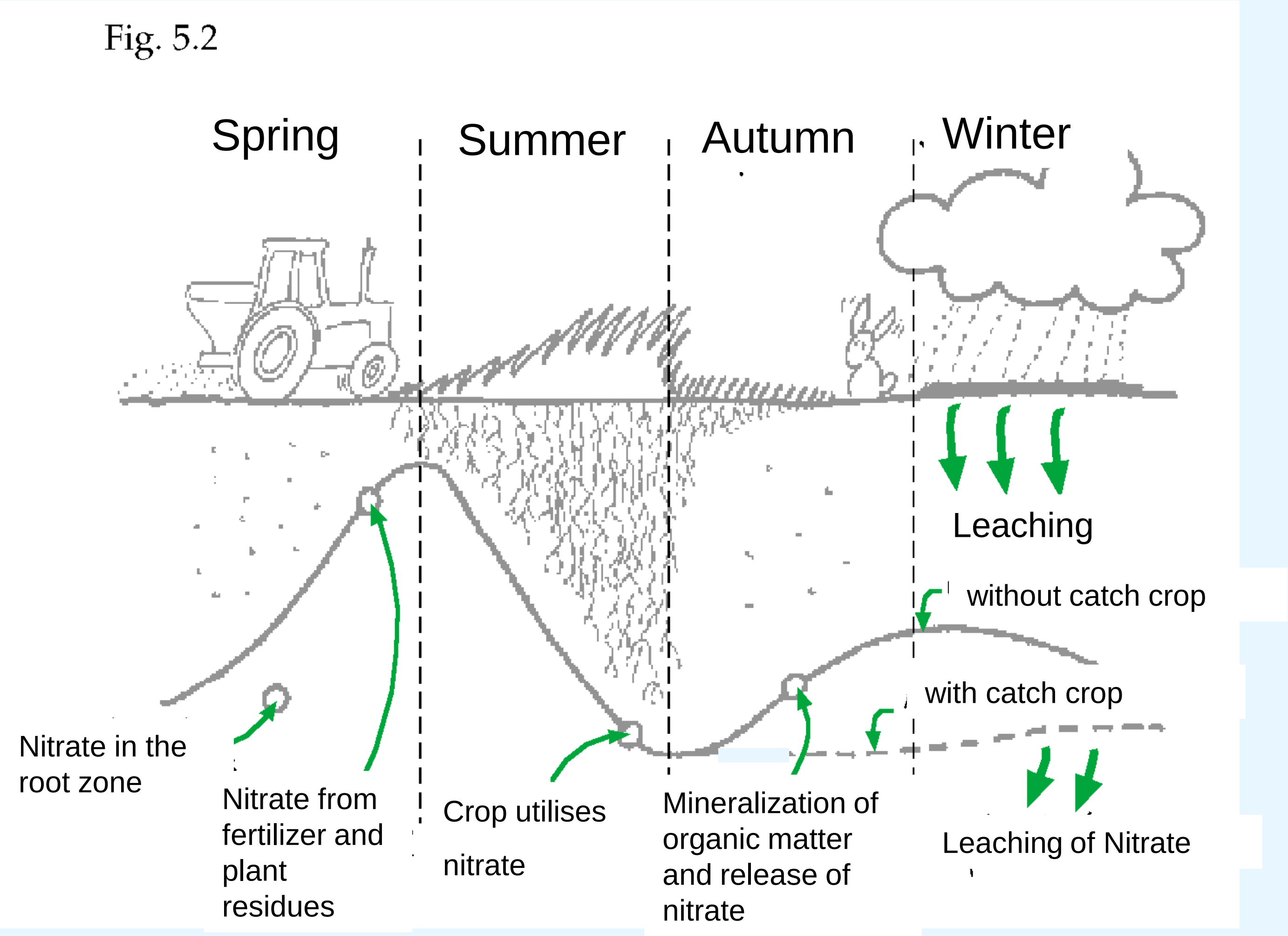
Total outputs 180 +/- 9

N surplus_field Example

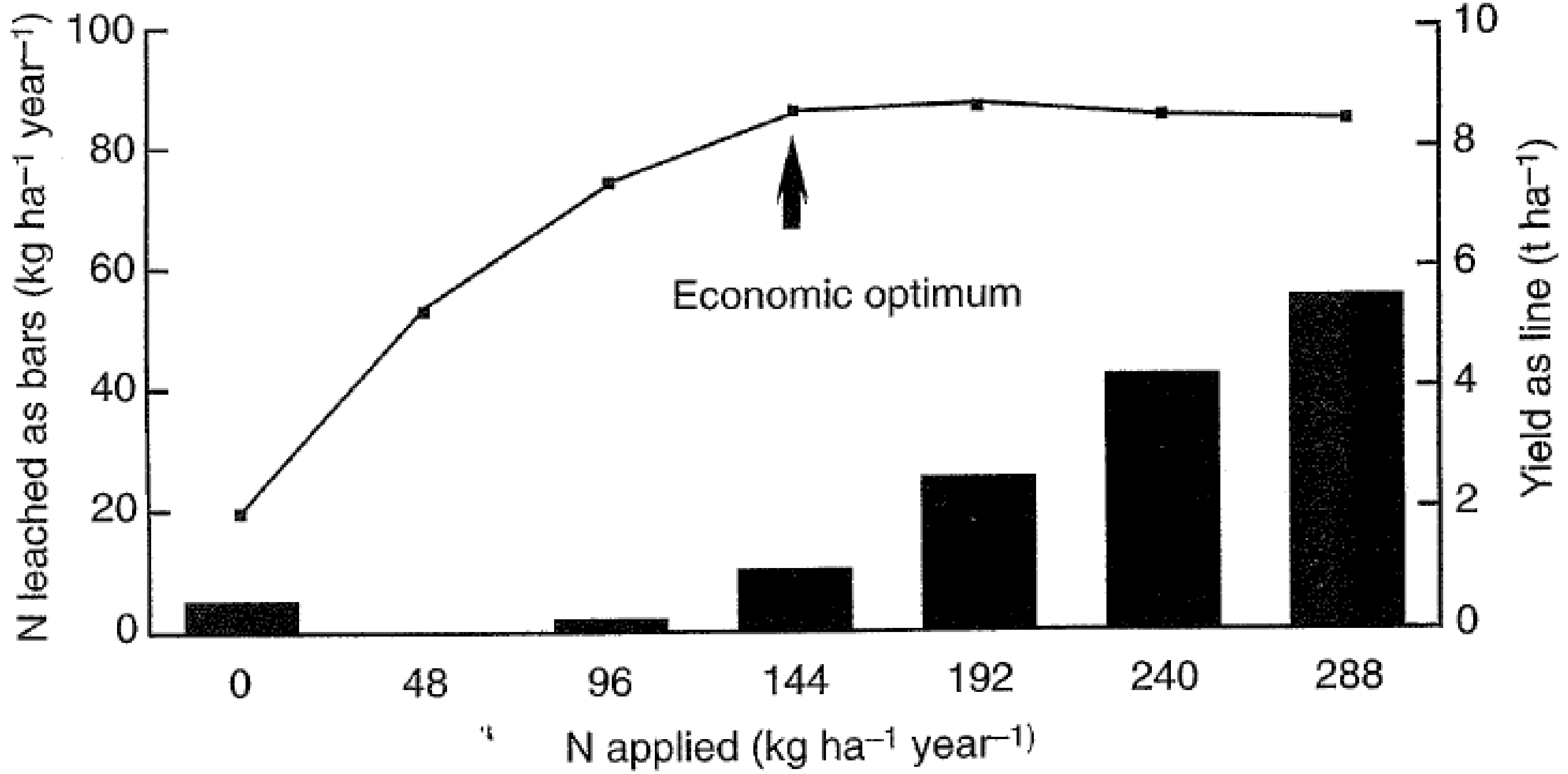


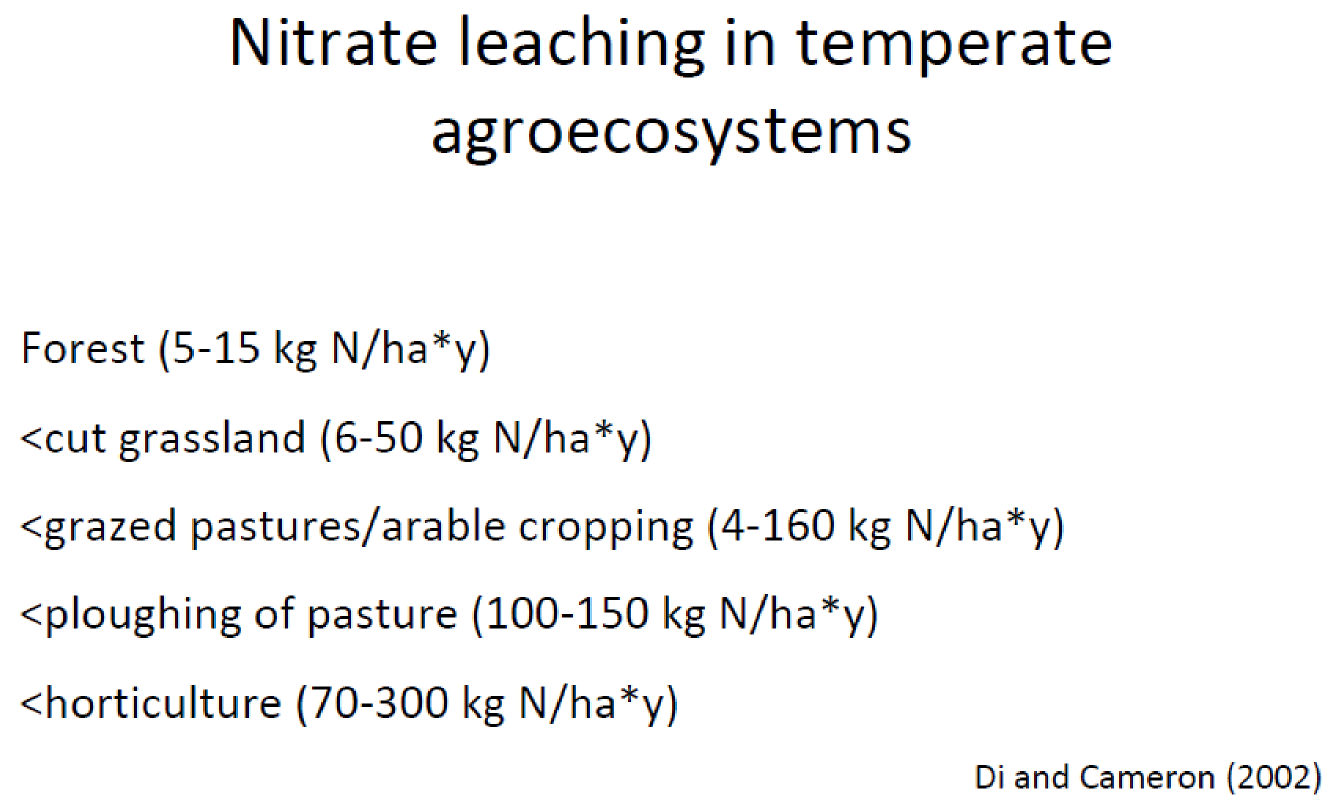
N surplus field=Manure N+ Fertilizer N+ N Fixation+N deposition
-N Grain- N crops
N surplus=130+54+2+16-91=111kg N/ha

Variation in root zone nitrate concentration during a year



Yield and N leaching as reponse to N applied





Nitrate leaching in temperate agroecosystems

Forest (5-15 kg N/ha*y)

<cut grassland (6-50 kg N/ha*y)

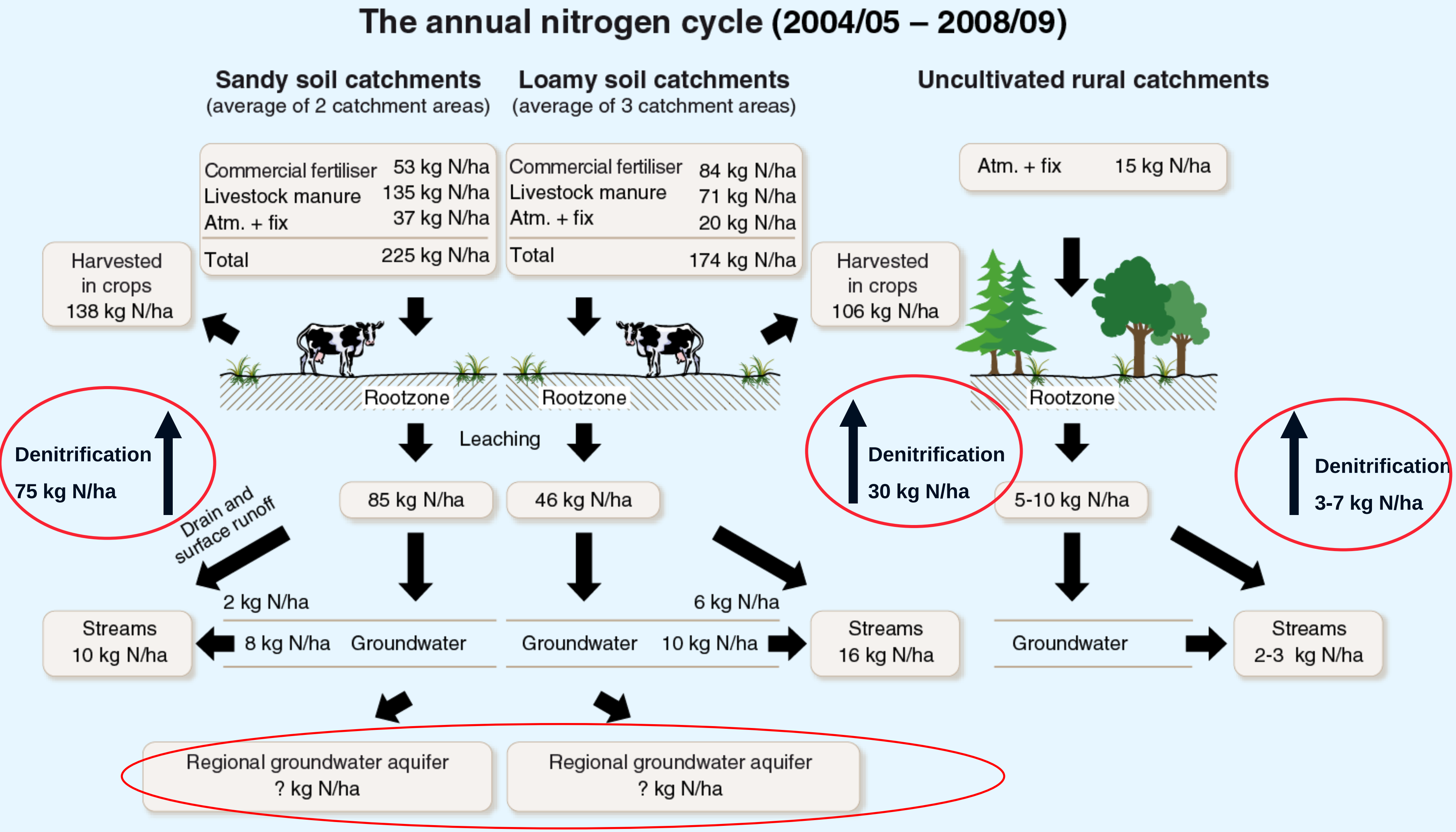
<grazed pastures/arable cropping (4-160 kg N/ha*y)

<ploughing of pasture (100-150 kg N/ha*y)

<horticulture (70-300 kg N/ha*y)

Di and Cameron (2002)

Field balance for Danish agricultural and non-agricultural systems



The annual nitrogen cycle (2004/05 – 2008/09)

Sandy soil catchments
(average of 2 catchment areas)

Commercial fertiliser	53 kg N/ha
Livestock manure	135 kg N/ha
Atm. + fix	37 kg N/ha
Total	225 kg N/ha

Harvested in crops 138 kg N/ha

Rootzone

Denitrification 75 kg N/ha

Leaching

85 kg N/ha

Drain and surface runoff

2 kg N/ha

Streams 10 kg N/ha

8 kg N/ha Groundwater

Regional groundwater aquifer ? kg N/ha

Loamy soil catchments
(average of 3 catchment areas)

Commercial fertiliser	84 kg N/ha
Livestock manure	71 kg N/ha
Atm. + fix	20 kg N/ha
Total	174 kg N/ha

Harvested in crops 106 kg N/ha

Rootzone

Denitrification 30 kg N/ha

46 kg N/ha

6 kg N/ha

Groundwater 10 kg N/ha

Streams 16 kg N/ha

Regional groundwater aquifer ? kg N/ha

Uncultivated rural catchments

Atm. + fix	15 kg N/ha

Rootzone

5-10 kg N/ha

Denitrification 3-7 kg N/ha

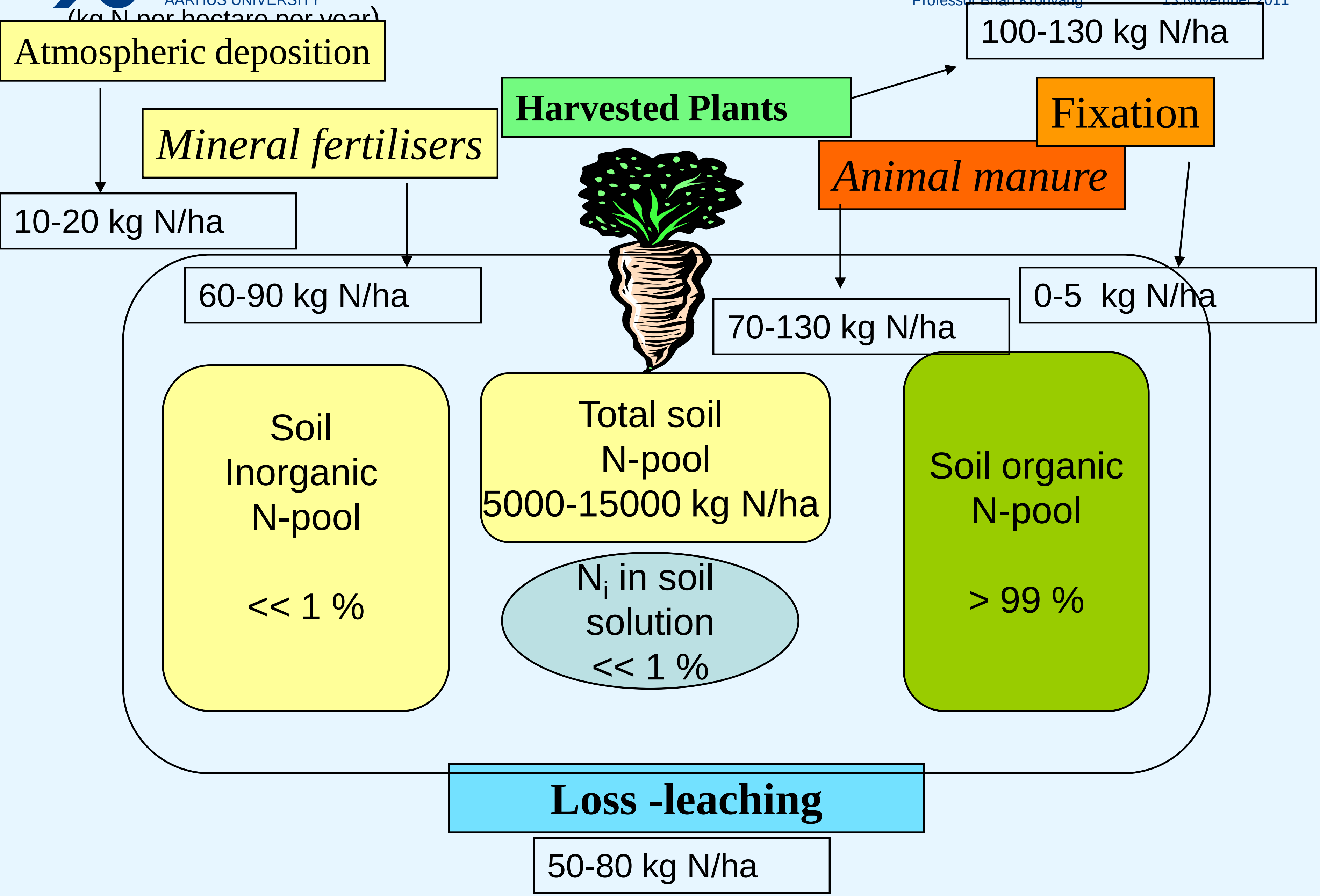
Groundwater

Streams 2-3 kg N/ha

Time for an exercise ?

N inputs, pools and outputs in agricultural systems

(kg N per hectare per year)



Atmospheric deposition

10-20 kg N/ha

Mineral fertilisers

60-90 kg N/ha

Harvested Plants

100-130 kg N/ha

Fixation

0-5 kg N/ha

Animal manure

70-130 kg N/ha

Soil Inorganic N-pool

<< 1 %

Total soil N-pool 5000-15000 kg N/ha

N_i in soil solution << 1 %

Soil organic N-pool

> 99 %

Loss -leaching

50-80 kg N/ha