7 2 5
N
Nitrogen
14.007

15 2 8 5
P
Phosphorus
30.974

Nutrients 101

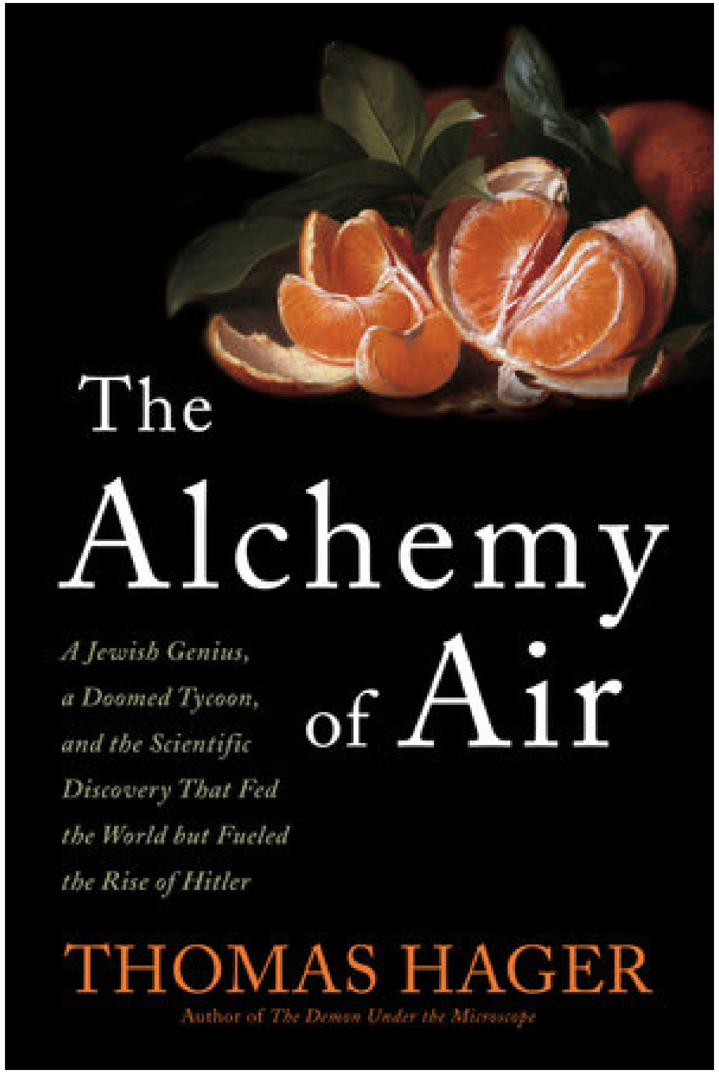
Cycling in Systems
Impacts on Freshwater

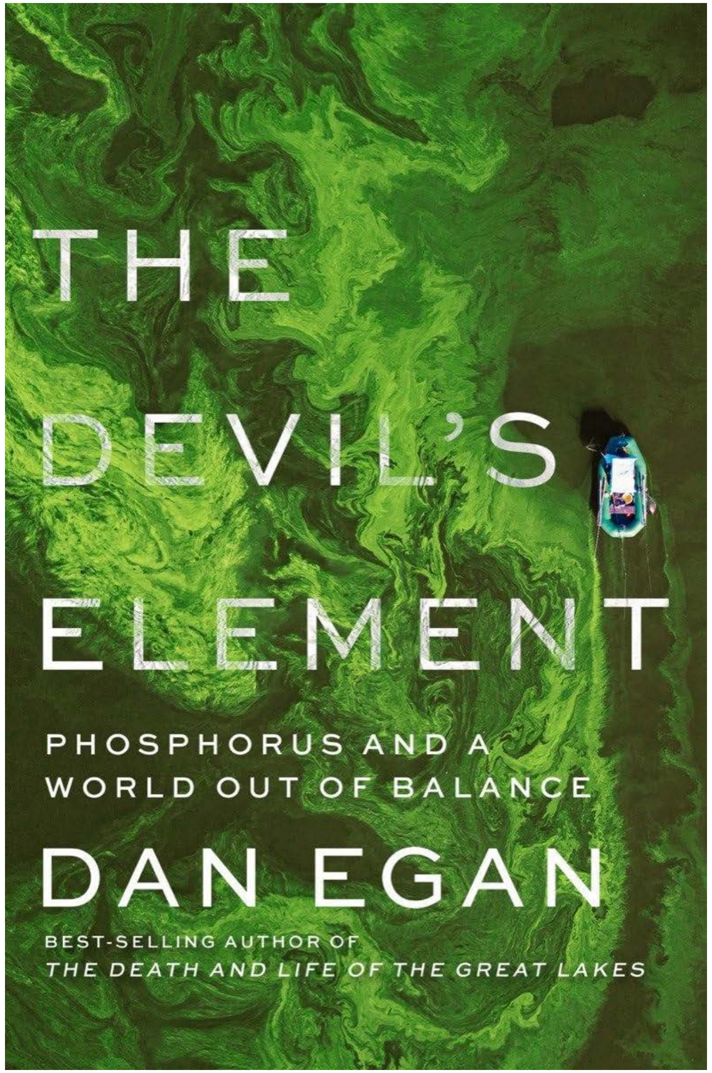
Eric Booth, PhD

Research Scientist - Hydroecology

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

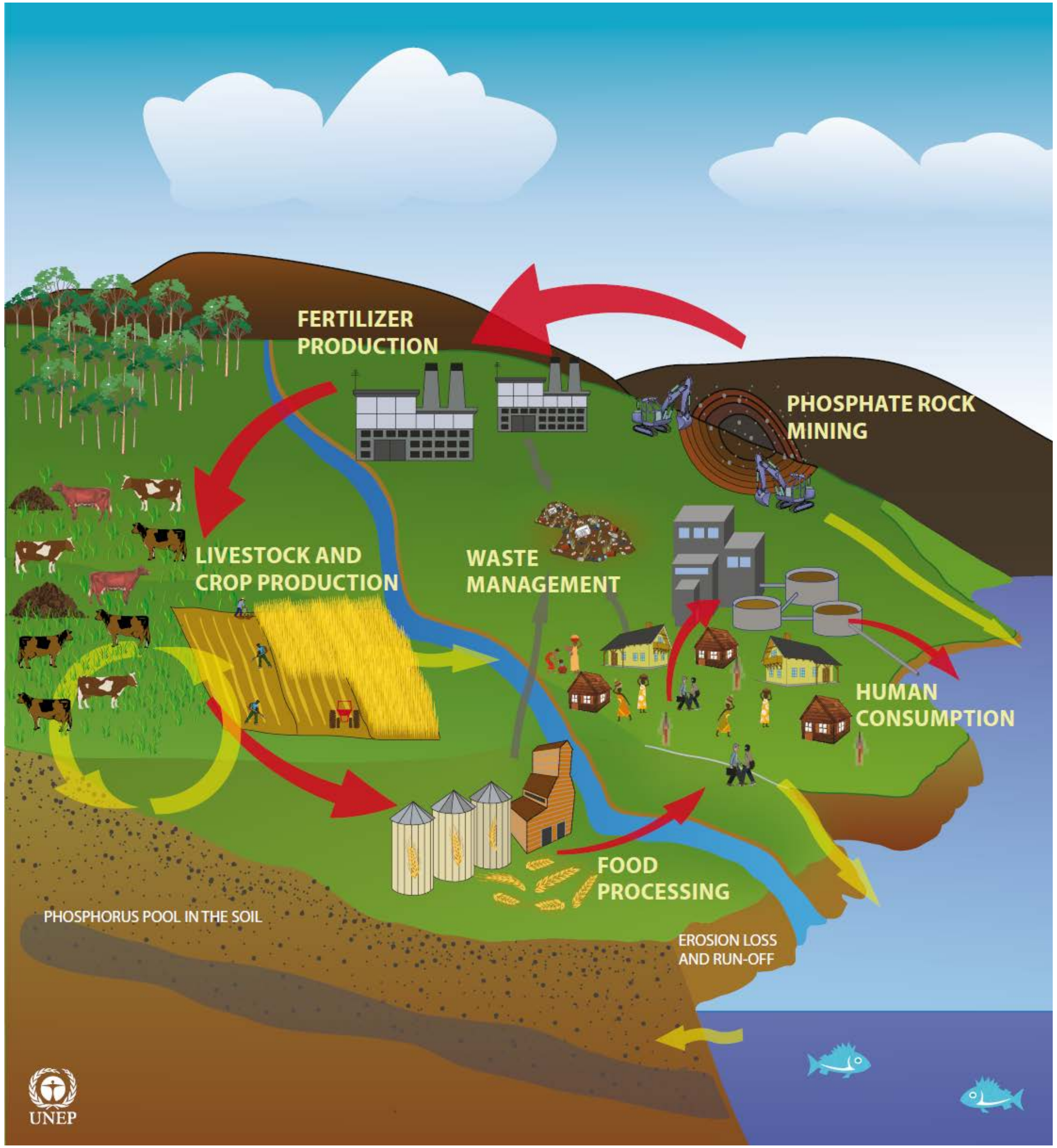
Explore the history





Why are we here?

- Representatives from across this diagram working together to <u>improve water quality</u>
  - Shared responsibility
- While also supporting:
  - Food production
  - Waste management
  - Human health
  - Human livelihoods (urban, rural)
  - Environmental health
  - Climate change mitigation



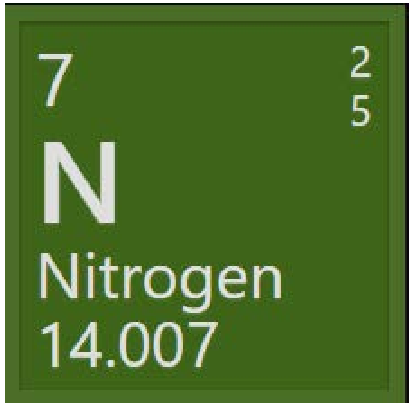
Why are we here?

N & P ENHANCE PHOTOSYNTHESIS

1. Addition of fertilizers containing N and P have long been known to stimulate growth of agricultural plants
   - Manure used for Neolithic agriculture
   - Portion of that additional N and P is now in 8.2 billion people
2. Losses of N and P from agricultural systems to water bodies can stimulate growth of algae and aquatic plants
   - And can be toxic to humans and ecosystems

Answering some basic questions

- What is nitrogen and phosphorus? Why are they important?
- What forms do they take?
- How has their cycling changed through time?
- What impact do they have on water bodies and human water use?
- How do they get into our water bodies?
- How have we tried to keep them out of our waters?



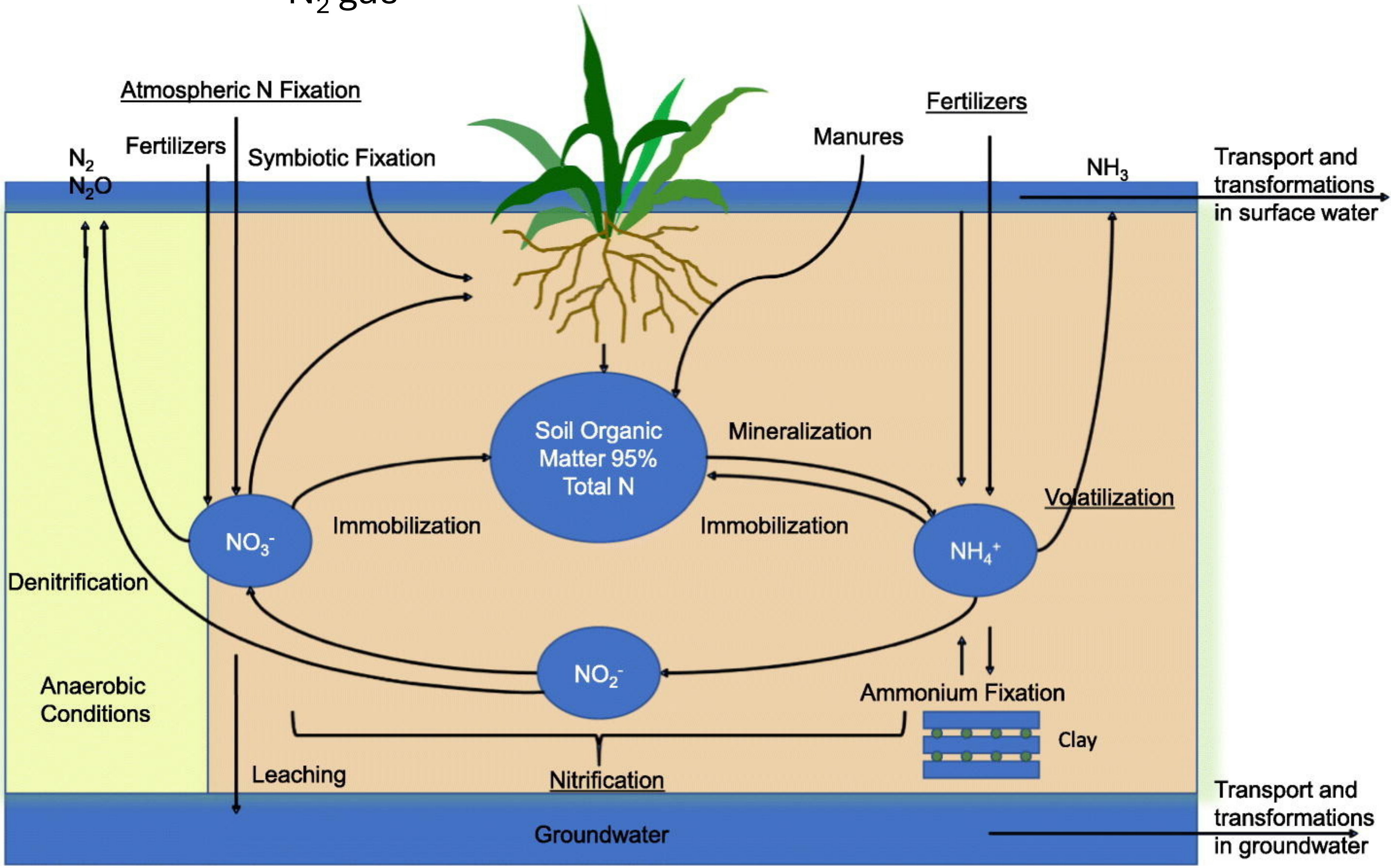
Nitrogen

- Essential building block of life
  - Amino acids (proteins)
  - Nucleic acids (RNA, DNA)
  - Energy transfer molecule (ATP)
- 3% of human body mass
- 78% of Earth's atmosphere is N_2 gas (atmophile)
- Only 0.0019% of Earth's crust

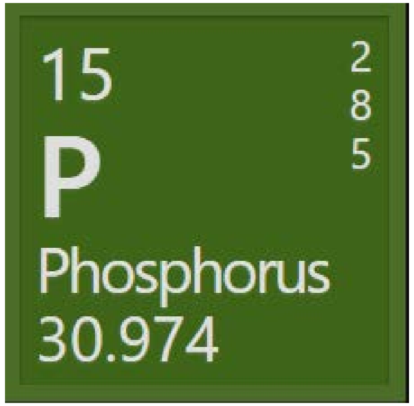
Nitrogen

- N_2 is unusable by vast majority of living organisms
- Mineralization impacted by temperature
- Denitrification requires very low oxygen

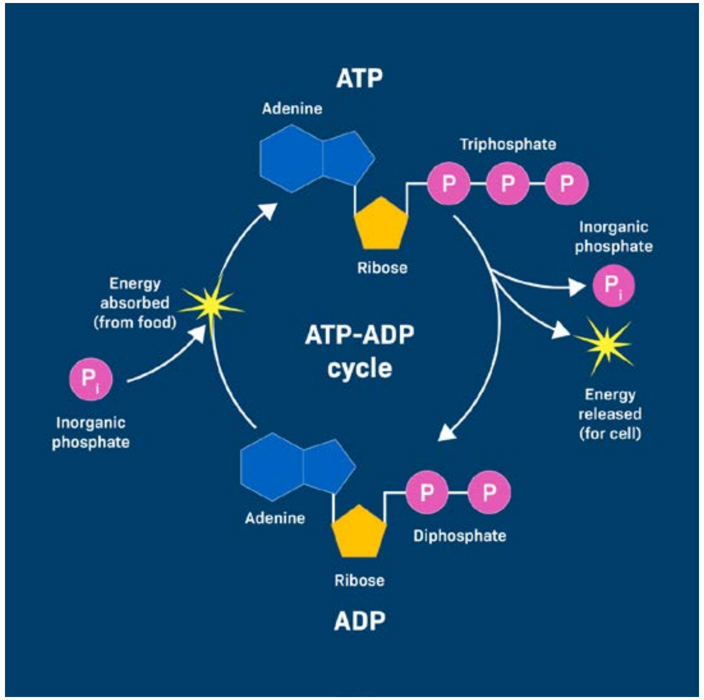
N_2 gas



Qiu et al. 2023



Phosphorus



- Essential building block of life
  - Proteins, carbohydrate polymers, DNA, RNA, cannot be made without P
  - Synthesis of all complex molecules of life is powered by energy released by phosphate bond in ADP→ATP
  - Main component of bone and teeth
- 0.6% of human body mass
- 0.1% of Earth's crust (11th place) – (lithophile)
  - But quite 'scarce' relative to N

Phosphorus

- Majority is unavailable at a given time (fixation)
  - Bound to Fe, Mg, Al, Ca, Mn
- Needs to be dissolved for plant uptake (mineralization)
  - Dependent on temperature, pH, oxygen availability, bacteria / fungi

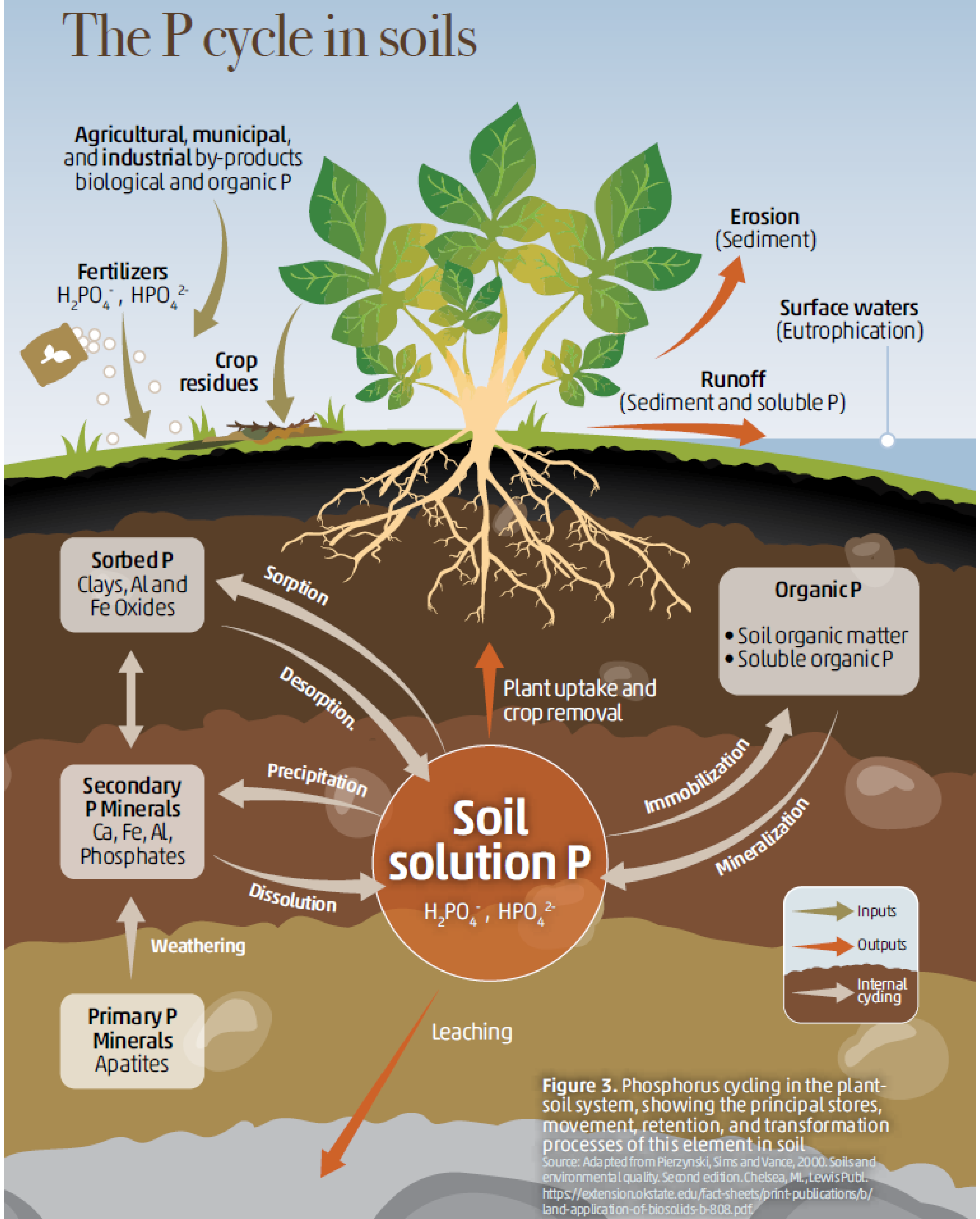


Figure 3. Phosphorus cycling in the plant-soil system, showing the principal stores, movement, retention, and transformation processes of this element in soil
Source: Adapted from Pierzynski, Sims and Vance, 2000. Soils and environmental quality. Second edition. Chelsea, MI., Lewis Publ. https://extension.okstate.edu/fact-sheets/print-publications/b/land-application-of-biosolids-b-808.pdf

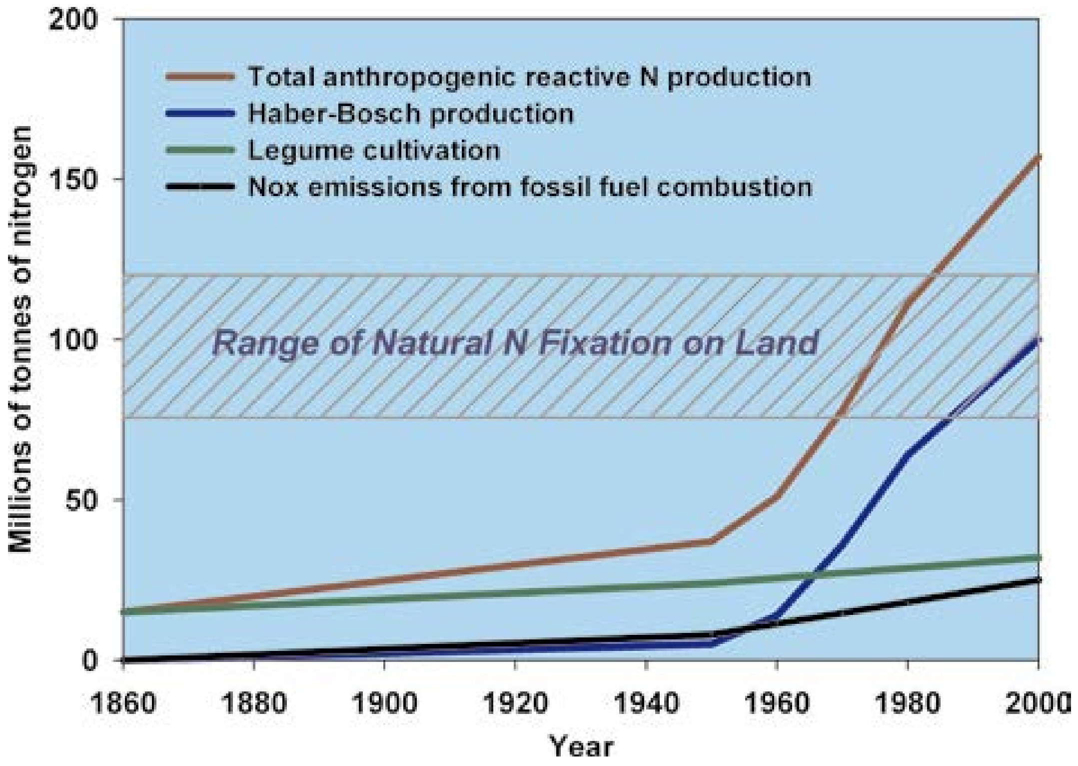
Key differences in N and P cycling

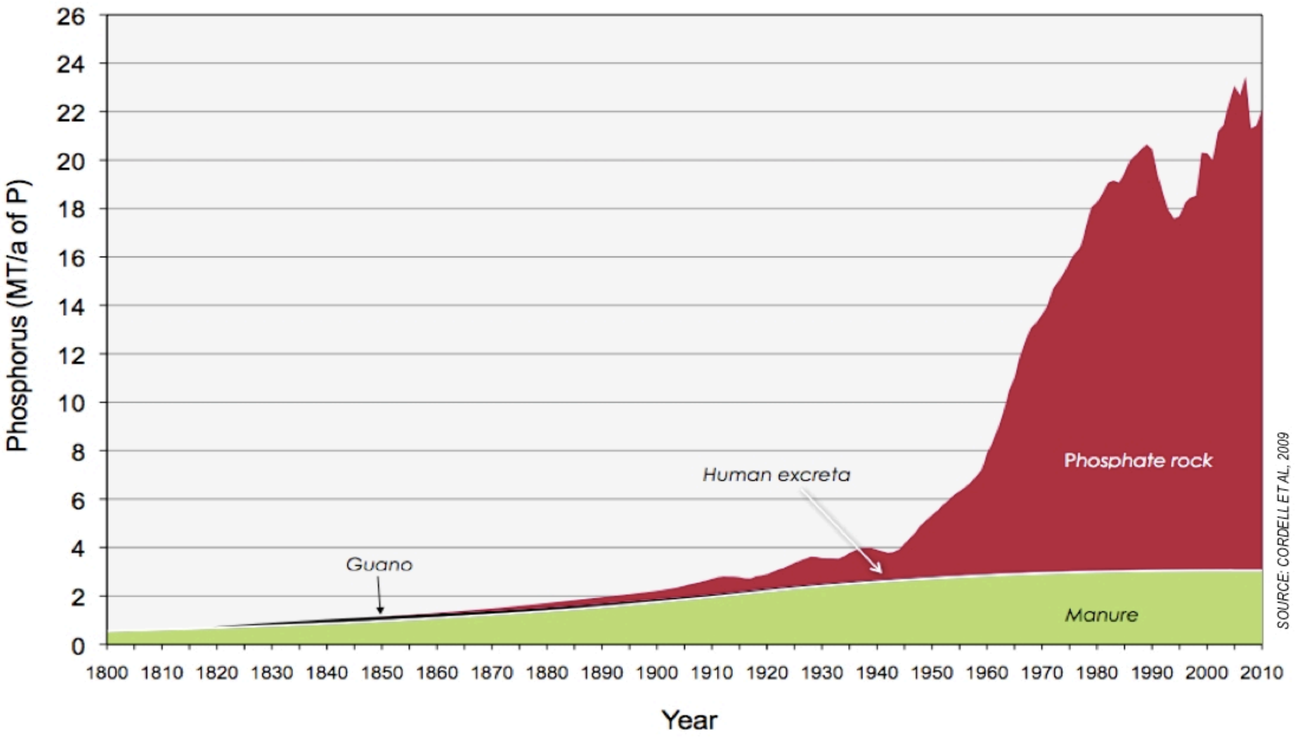
Nitrogen has a gaseous phase & is readily dissolved

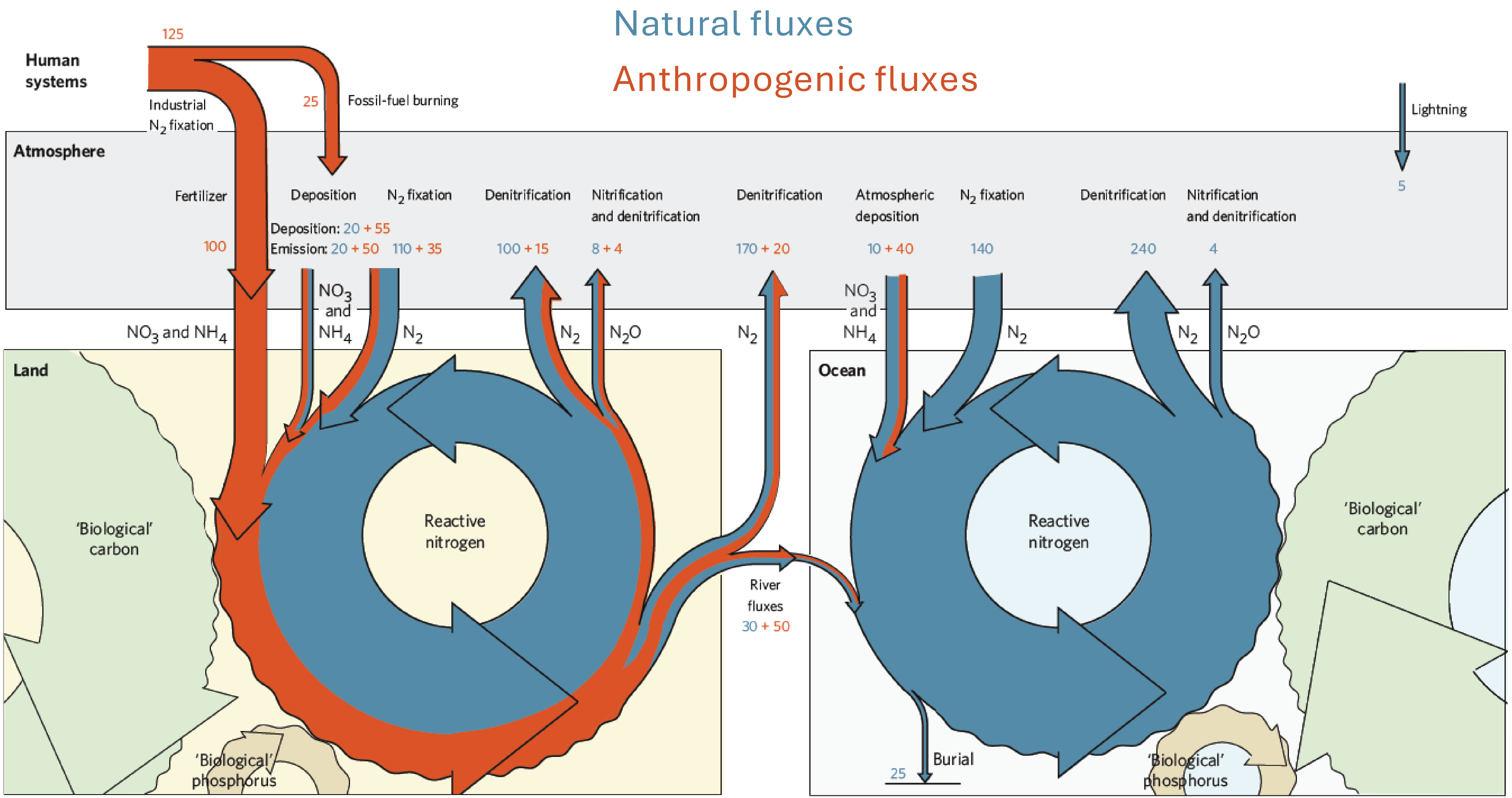
Phosphorus binds to soil particles

Human acceleration of N & P cycles

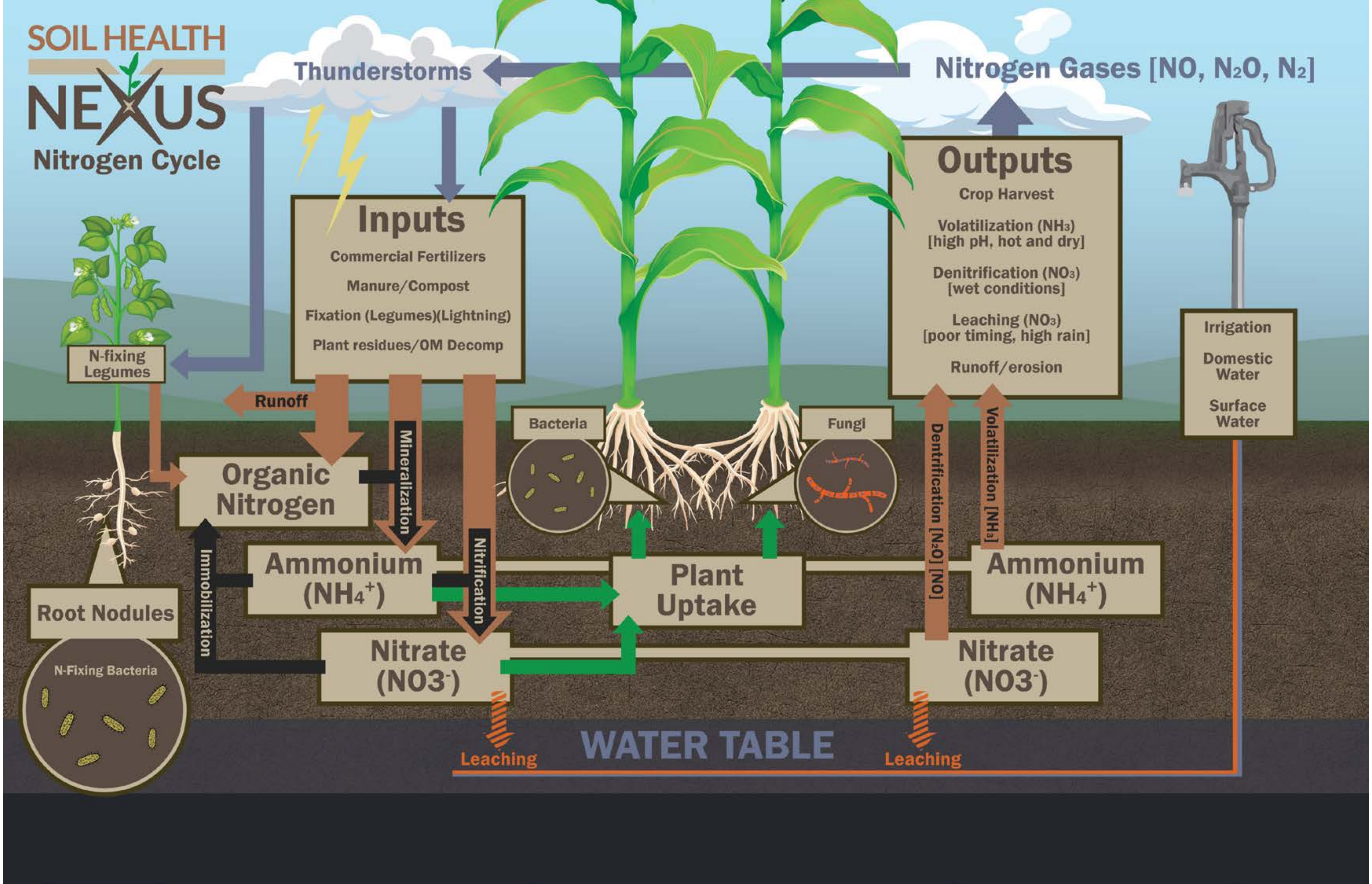
- The invention and discovery of synthetic (N) and mined (P) fertilizer was the start of a massive global biogeochemical experiment that still continues

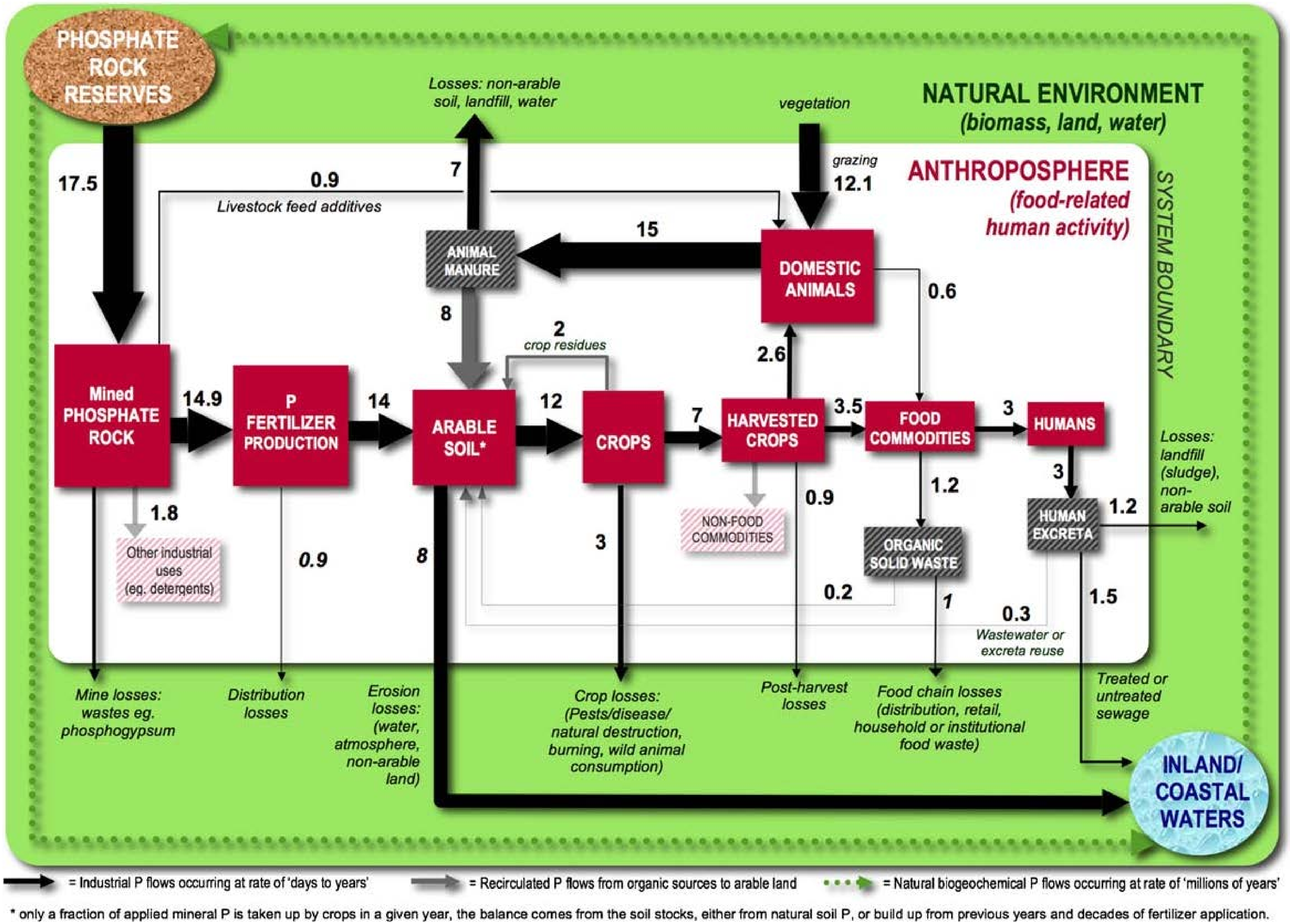






Gruber and Galloway 2008


SOIL HEALTH
NEXUS
Nitrogen Cycle
Thunderstorms
Nitrogen Gases [NO, N_2O, N_2]
Inputs
Commercial Fertilizers
Manure/Compost
Fixation (Legumes)(Lightning)
Plant residues/OM Decomp
Outputs
Crop Harvest
Volatilization (NH_3)
[high pH, hot and dry]
Denitrification (NO_3)
[wet conditions]
Leaching (NO_3)
[poor timing, high rain]
Runoff/erosion
N-fixing Legumes
Runoff
Bacteria
Fungi
Irrigation
Domestic Water
Surface Water
Organic Nitrogen
Mineralization
Nitrification
Immobilization
Dentrification [N_2O] [NO]
Volatilization [NH_3]
Ammonium (NH_4^+)
Plant Uptake
Ammonium (NH_4^+)
Root Nodules
N-Fixing Bacteria
Nitrate ($NO3^-$)
Nitrate ($NO3^-$)
Leaching
WATER TABLE
Leaching



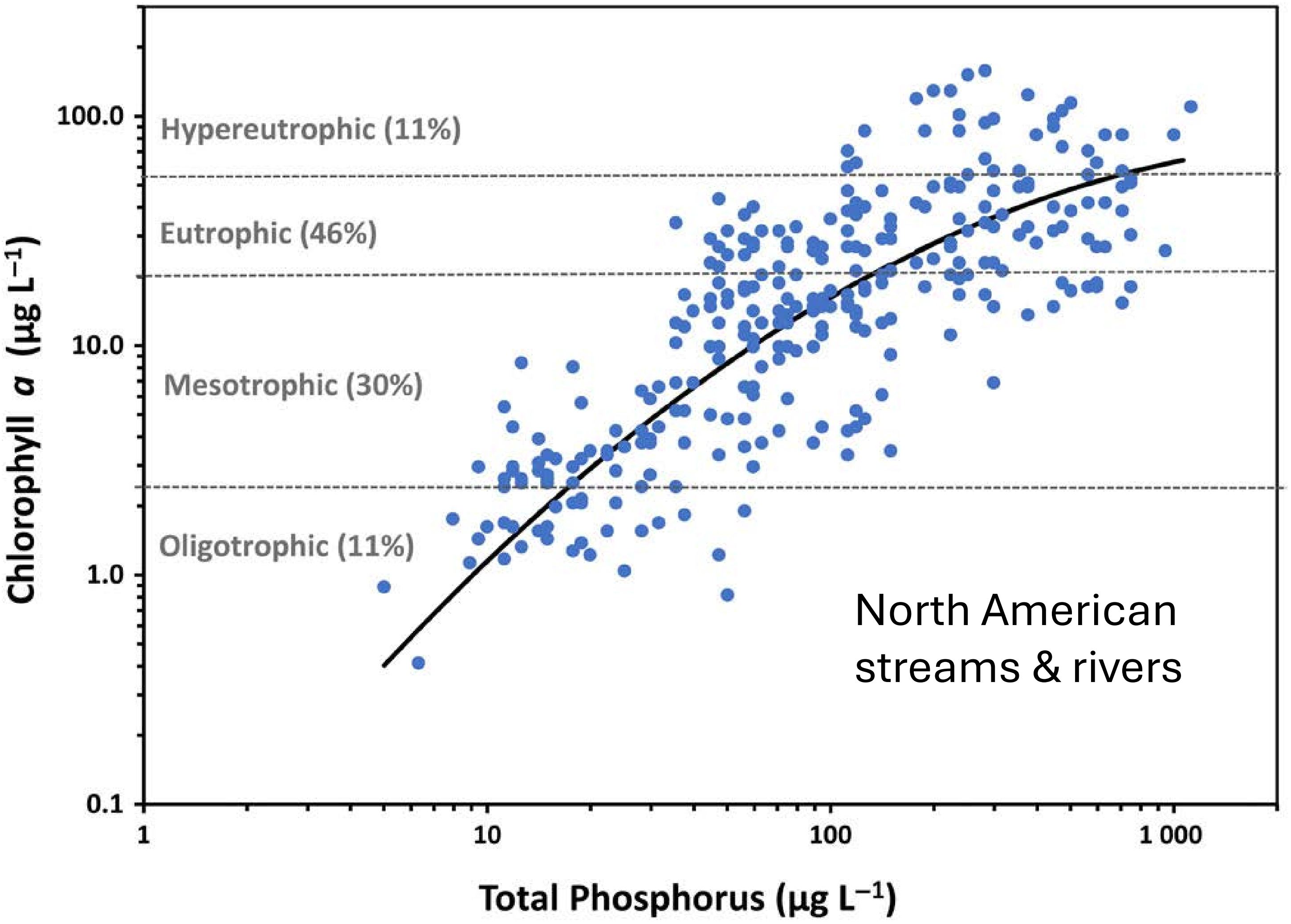
PHOSPHATE ROCK RESERVES
NATURAL ENVIRONMENT (biomass, land, water)
ANTHROPOSPHERE (food-related human activity)
SYSTEM BOUNDARY
Losses: non-arable soil, landfill, water
vegetation
grazing
12.1
17.5
0.9
Livestock feed additives
7
15
ANIMAL MANURE
DOMESTIC ANIMALS
0.6
8
2
crop residues
2.6
Mined PHOSPHATE ROCK
14.9
P FERTILIZER PRODUCTION
14
ARABLE SOIL*
12
CROPS
7
HARVESTED CROPS
3.5
FOOD COMMODITIES
3
HUMANS
Losses: landfill (sludge), non-arable soil
1.8
Other industrial uses (eg. detergents)
0.9
8
3
NON-FOOD COMMODITIES
0.9
1.2
ORGANIC SOLID WASTE
3
HUMAN EXCRETA
1.2
0.2
1
0.3
Wastewater or excreta reuse
1.5
Mine losses: wastes eg. phosphogypsum
Distribution losses
Erosion losses: (water, atmosphere, non-arable land)
Crop losses: (Pests/disease/ natural destruction, burning, wild animal consumption)
Post-harvest losses
Food chain losses (distribution, retail, household or institutional food waste)
Treated or untreated sewage
INLAND/ COASTAL WATERS
= Industrial P flows occurring at rate of 'days to years'
= Recirculated P flows from organic sources to arable land
= Natural biogeochemical P flows occurring at rate of 'millions of years'
* only a fraction of applied mineral P is taken up by crops in a given year, the balance comes from the soil stocks, either from natural soil P, or build up from previous years and decades of fertilizer application.

What impacts do excess N & P have on water bodies and human water use?

- Water quality depends on use
  - Drinking, recreation, ecosystem, aesthetics
- Nitrogen & phosphorus can be limiting nutrients for aquatic plant and algal growth
  - In most freshwater systems, P is limiting but depends on N:P ratio
  - In most estuary and coastal, N is limiting
- Eutrophication
  - Harmful algal blooms, hypoxia
- Nitrate in drinking water
  - Blue baby syndrome
  - Increased risk of certain types of cancer

Nutrients & Water Quality

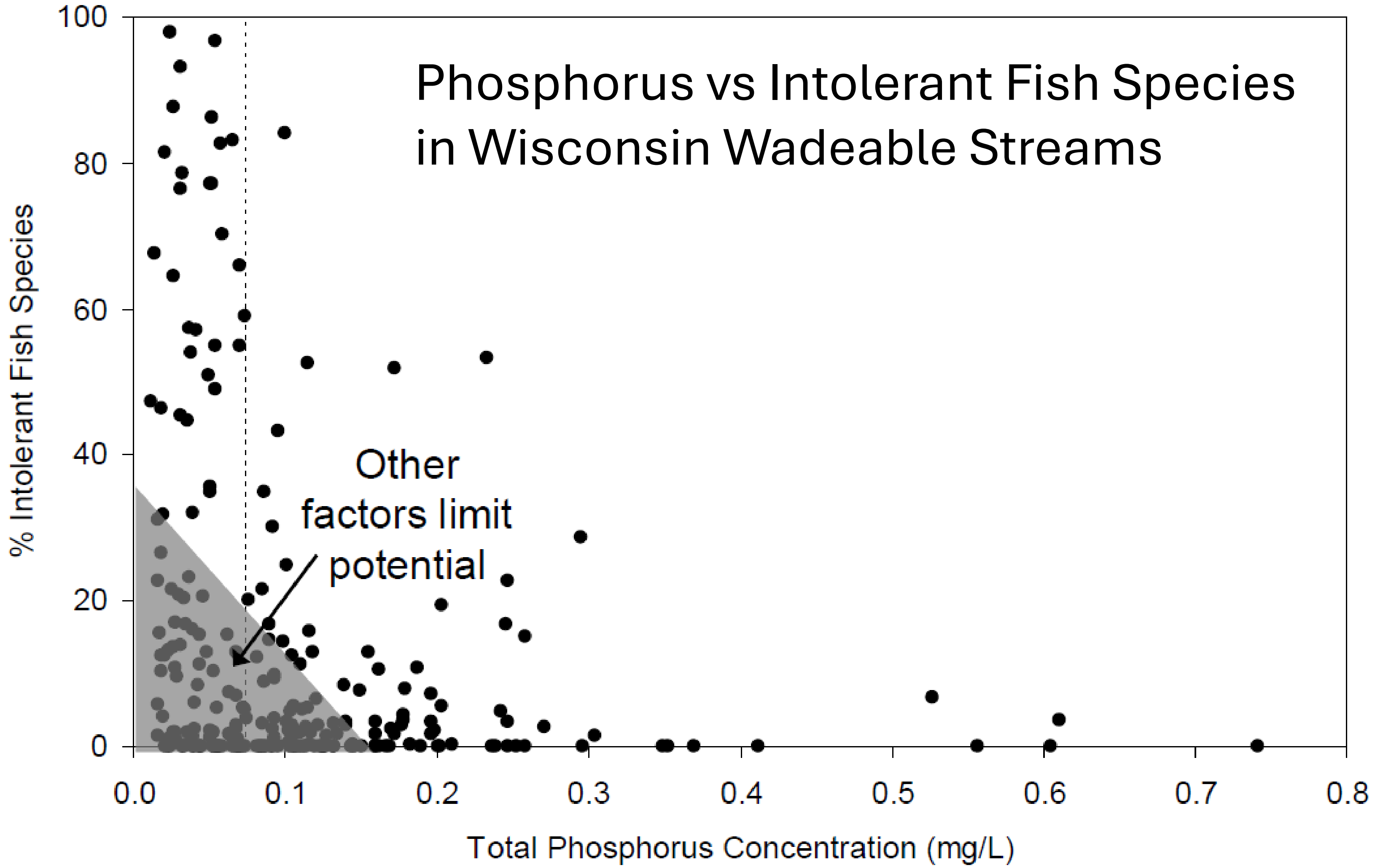
- Connection between nutrients and water quality indicators can be quite complex
- Algal concentration depends on weather and food web (grazing)
- Physical habitat can be altered without nutrients



Dodds et al. 1998

Nutrients & Water Quality

- Connection between nutrients and water quality indicators can be quite complex
- Algal concentration depends on weather and food web (grazing)
- Physical habitat can be altered without nutrients

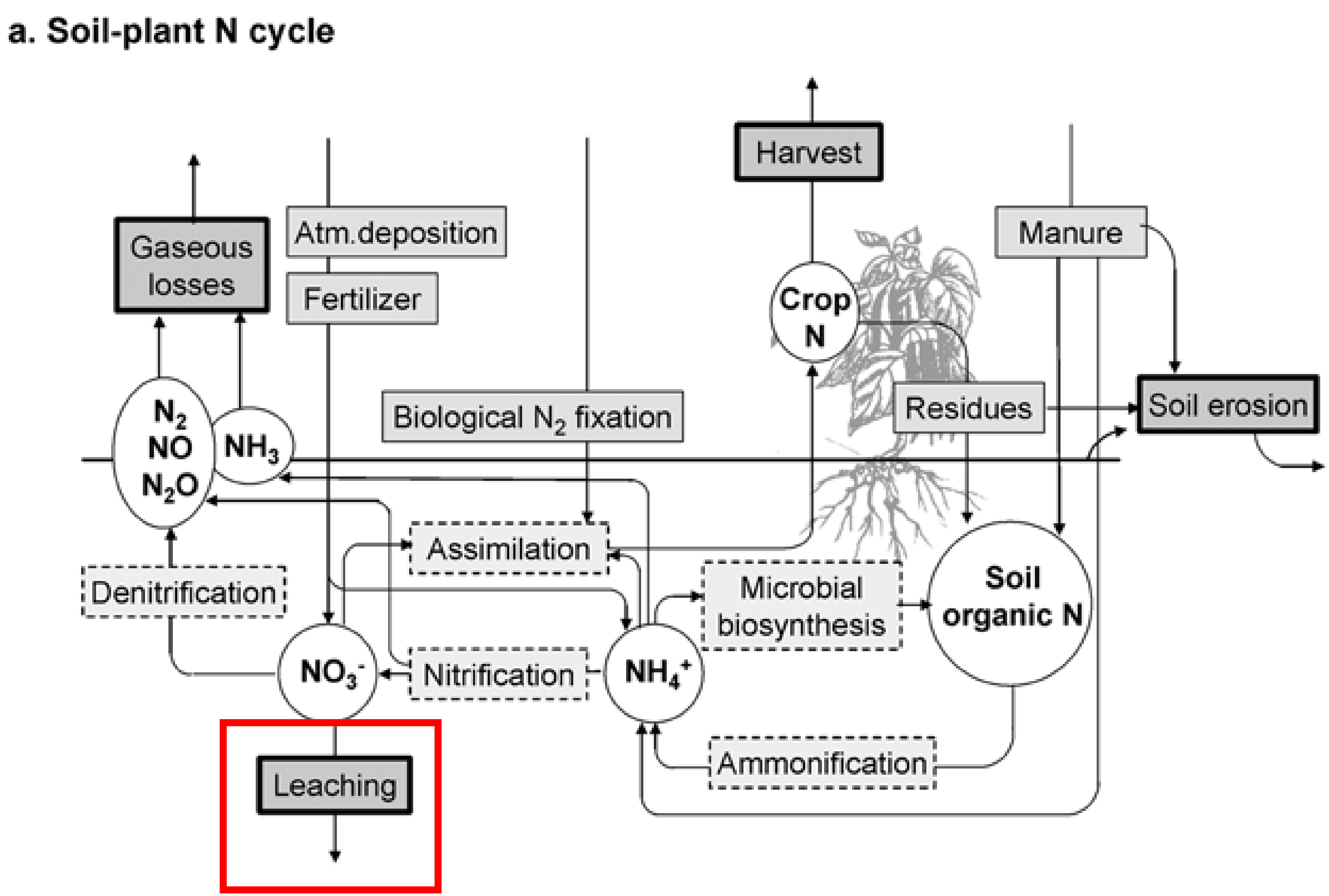


Wang et al. 2007

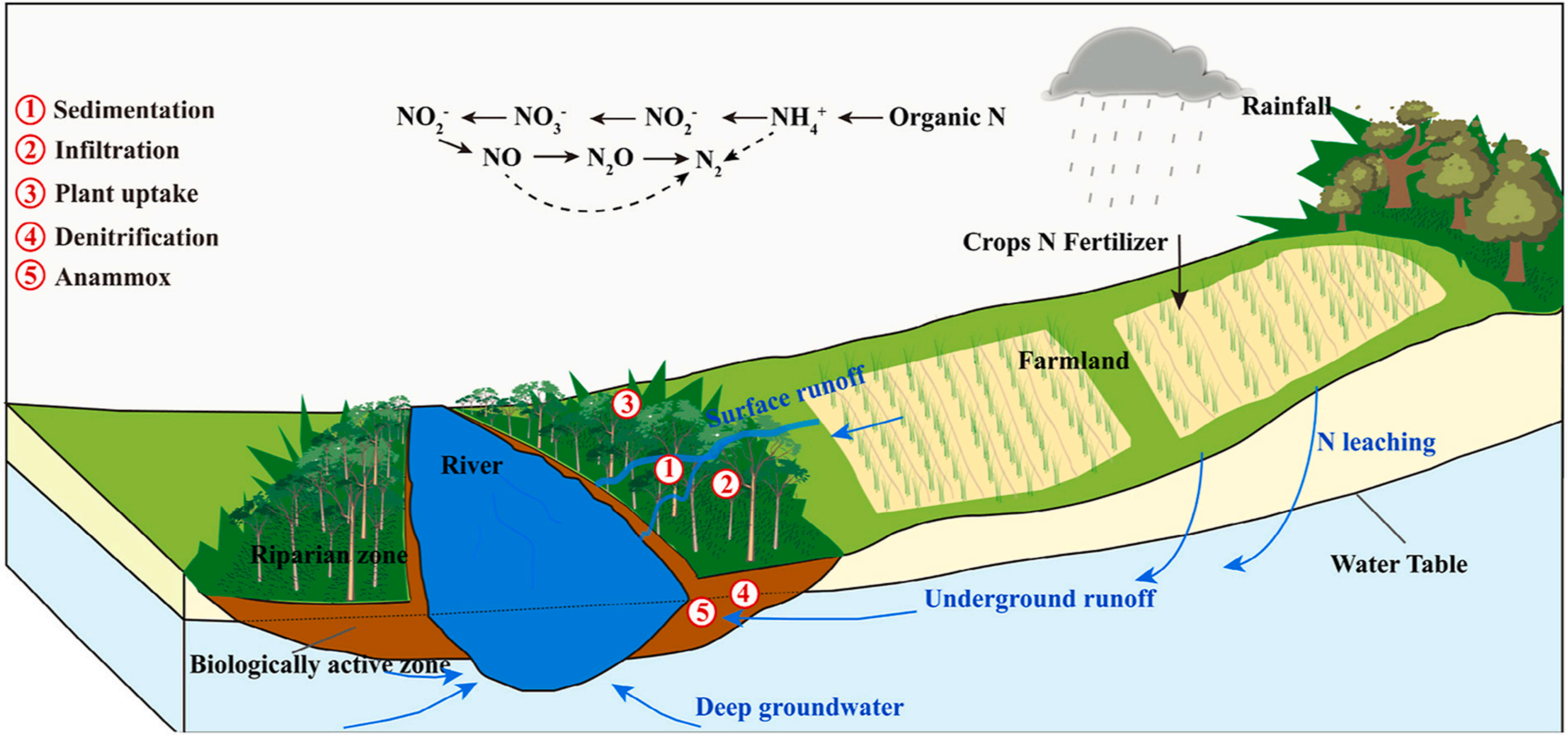
How does N & P get into our waters?

Nitrogen movement from land to water

- Nitrate is highly mobile
- Primarily lost via leaching to groundwater
  - Most drainage happens in fall and late-winter, early-spring

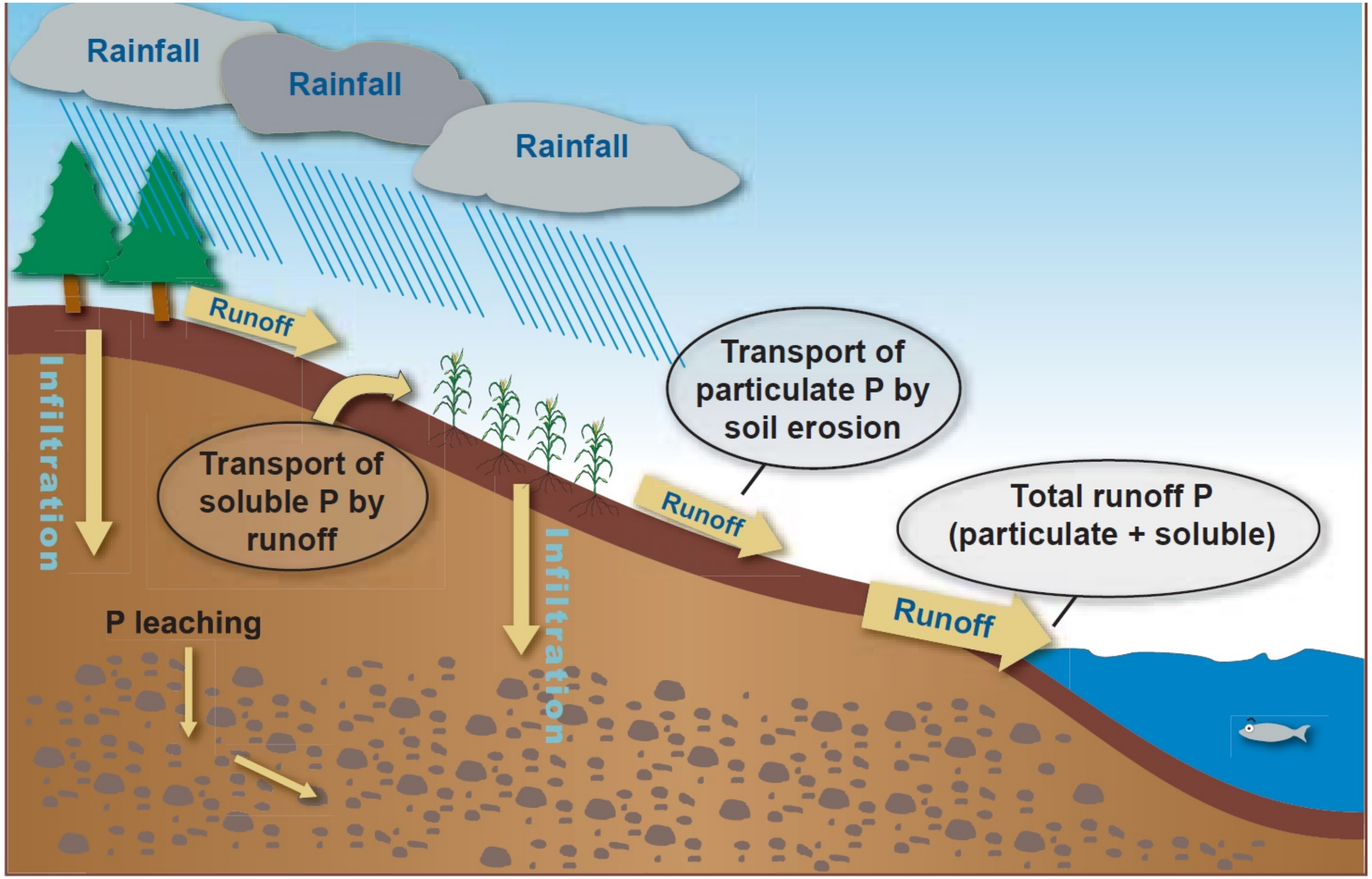


Nitrogen movement from land to water



Lyu et al. 2021

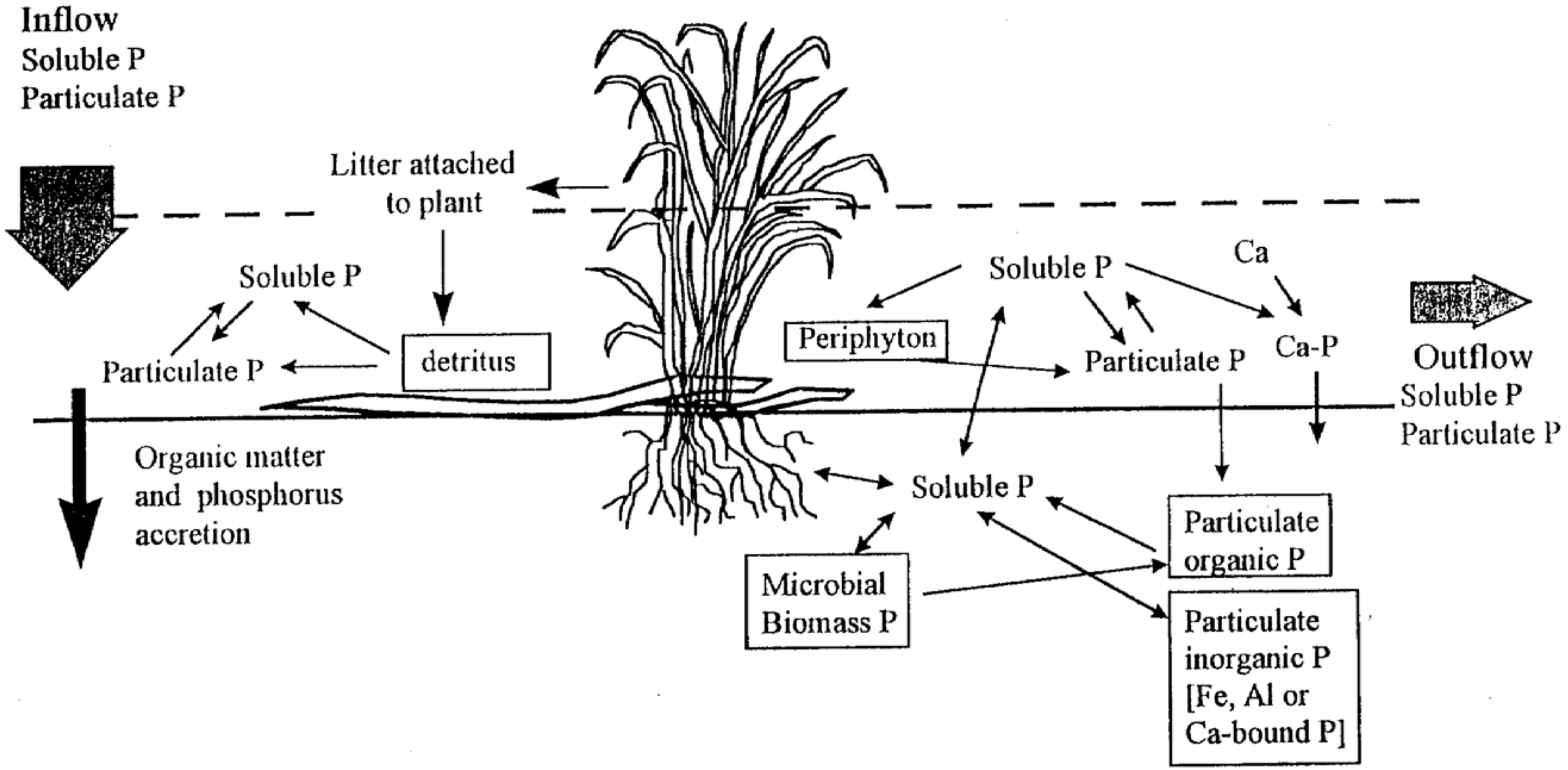
Phosphorus movement from land to water



Bundy & Sturgul, 2004

Phosphorus movement from land to water

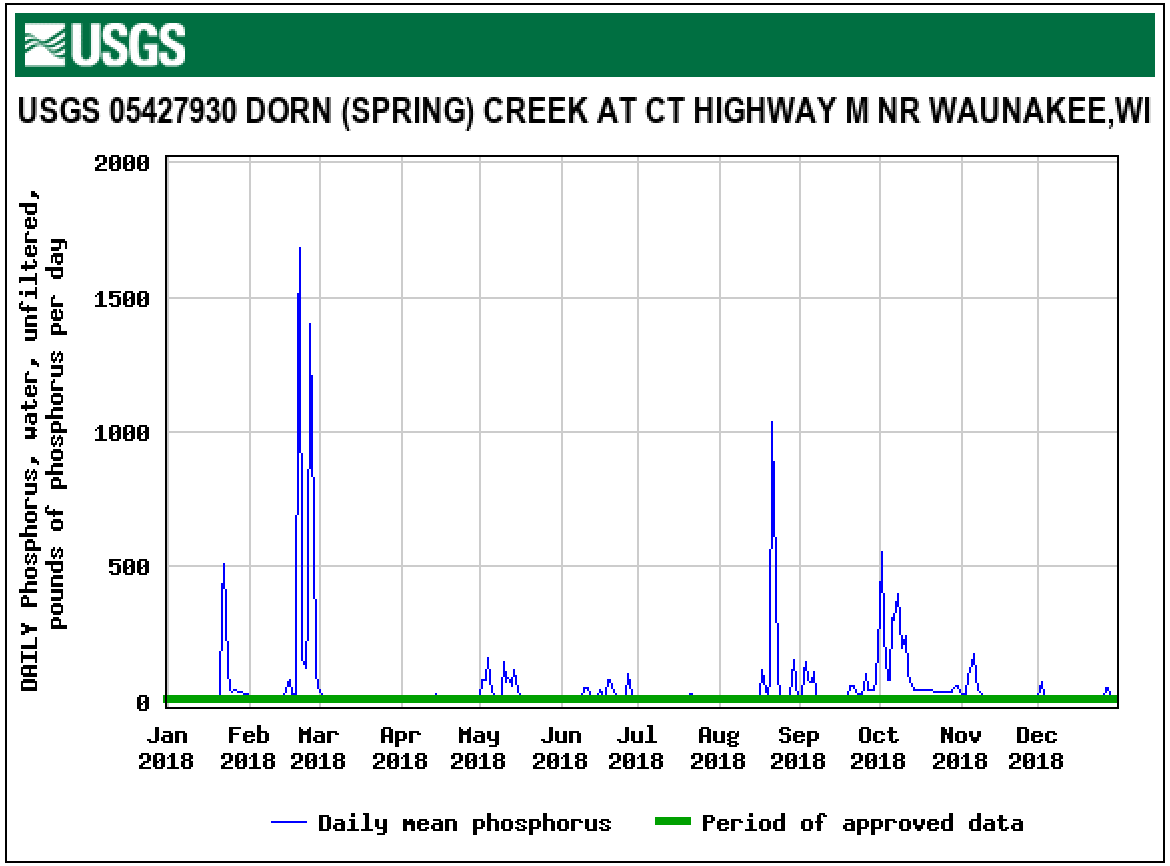
- Retention, recycling, and release in streams, wetlands



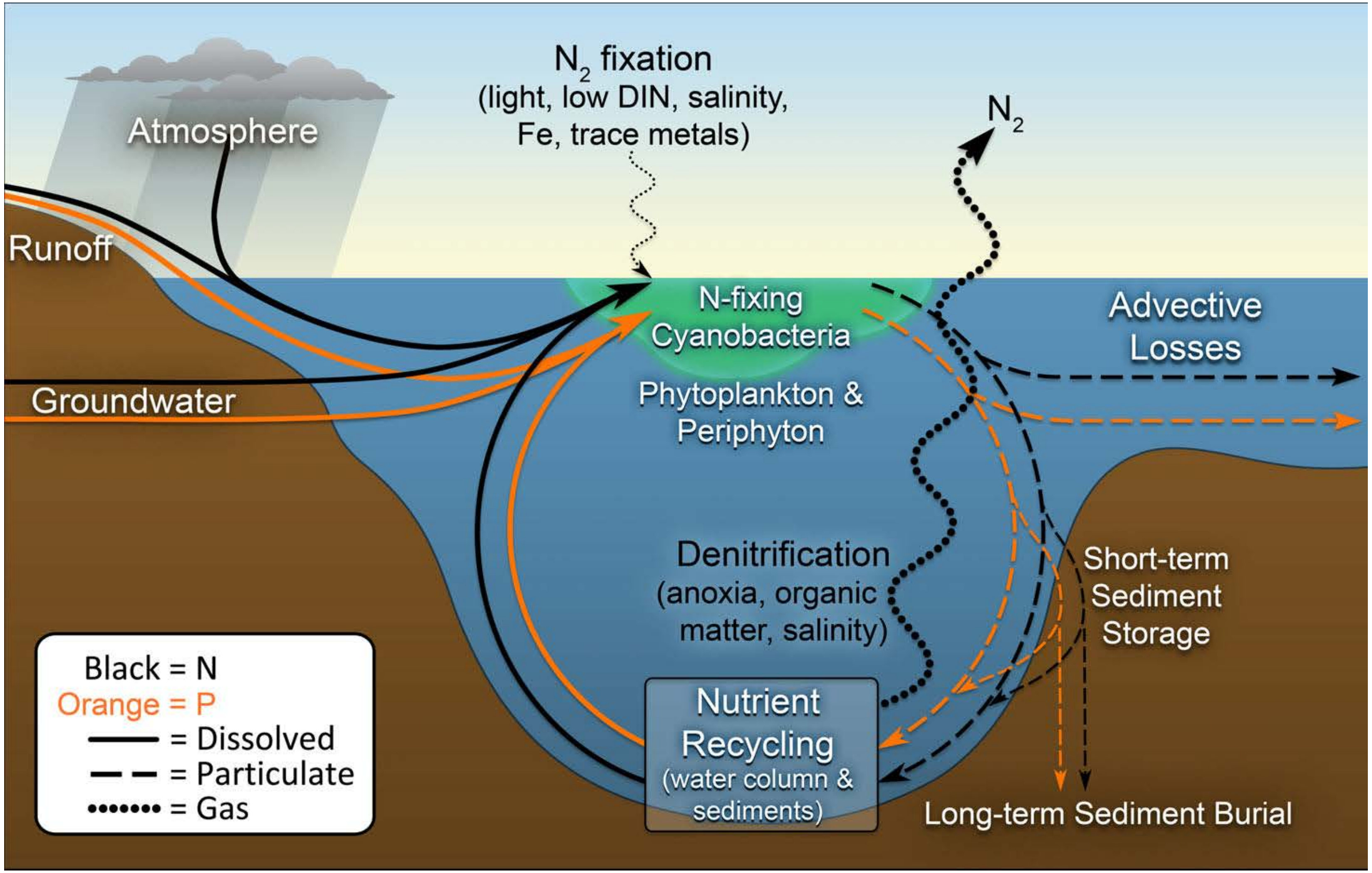
Reddy 1998

movement – Daily scale

- Driven by rainfall / runoff



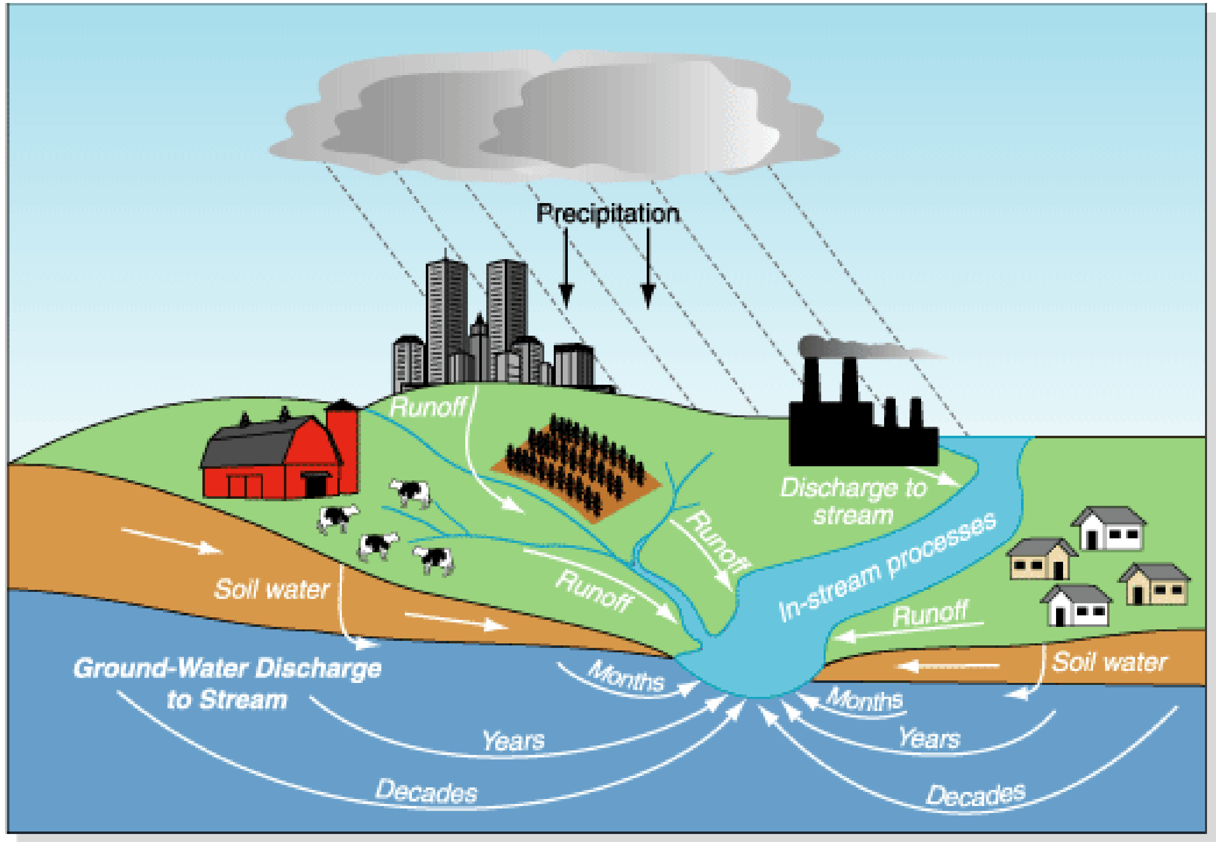
Nutrient processing within water bodies



Wurtsbaugh et al. 2019

Legacy nutrients and time lags

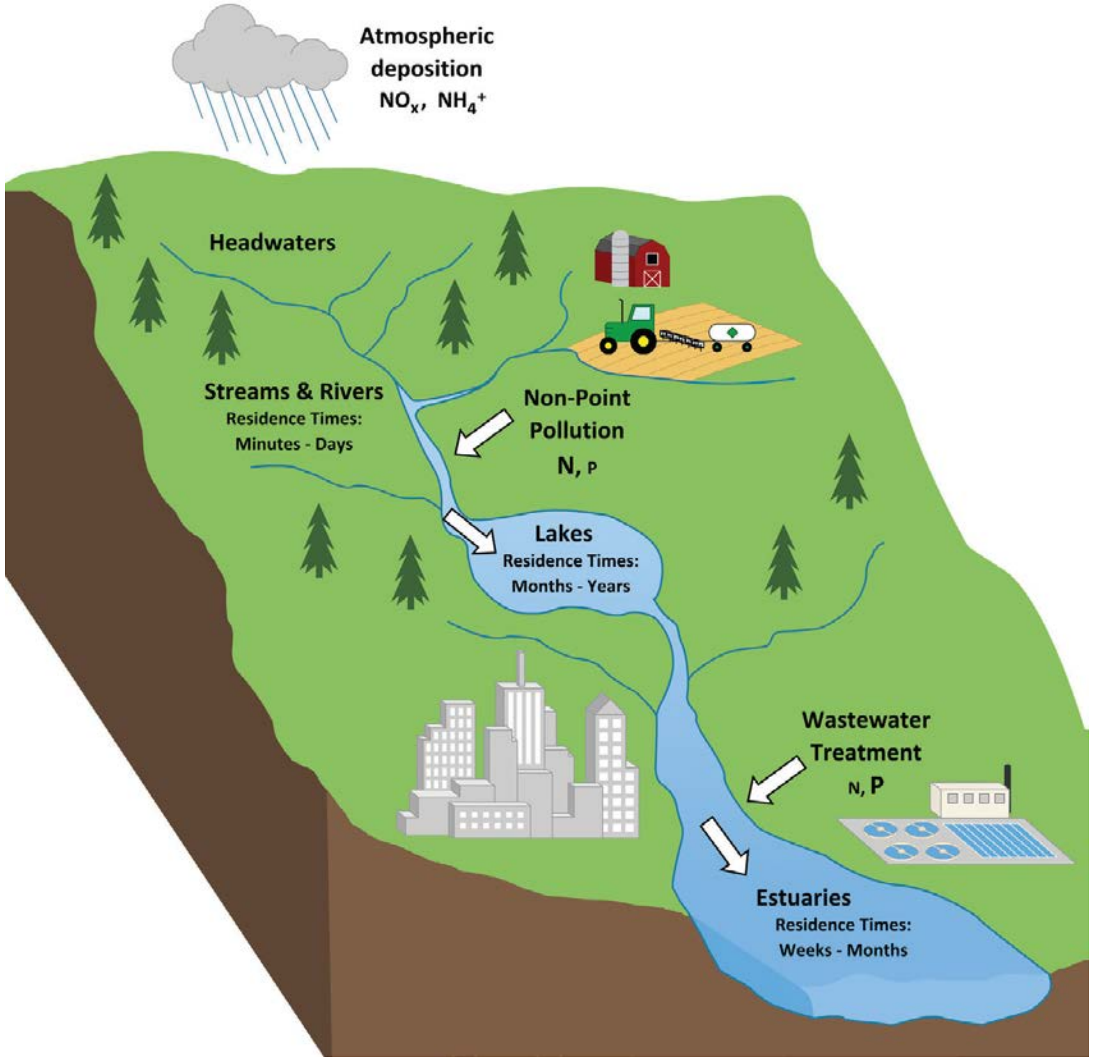
- Agricultural soils store a lot of excess P and organic N
- Nitrogen: groundwater flow paths are long and slow
- Phosphorus: P-bound sediment moves very slowly (and episodically through stream-lake-river networks)



Phillips and Lindsey 2003

Legacy nutrients and time lags

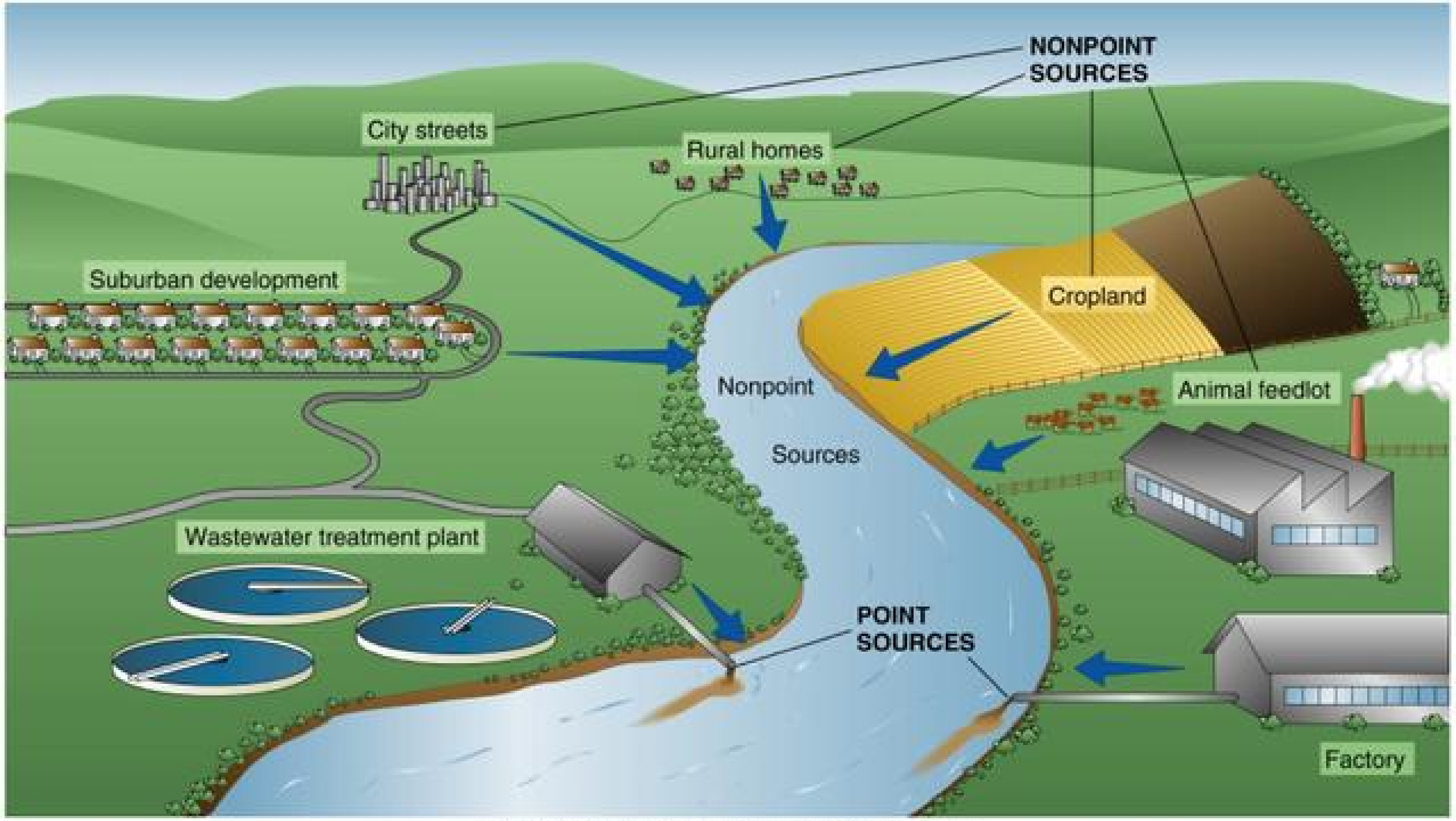
- Agricultural soils store a lot of excess P and organic N
- Nitrogen: groundwater flow paths are long and slow
- Phosphorus: P-bound sediment moves very slowly (and episodically through stream-lake-river networks)



Wurtsbaugh et al. 2019

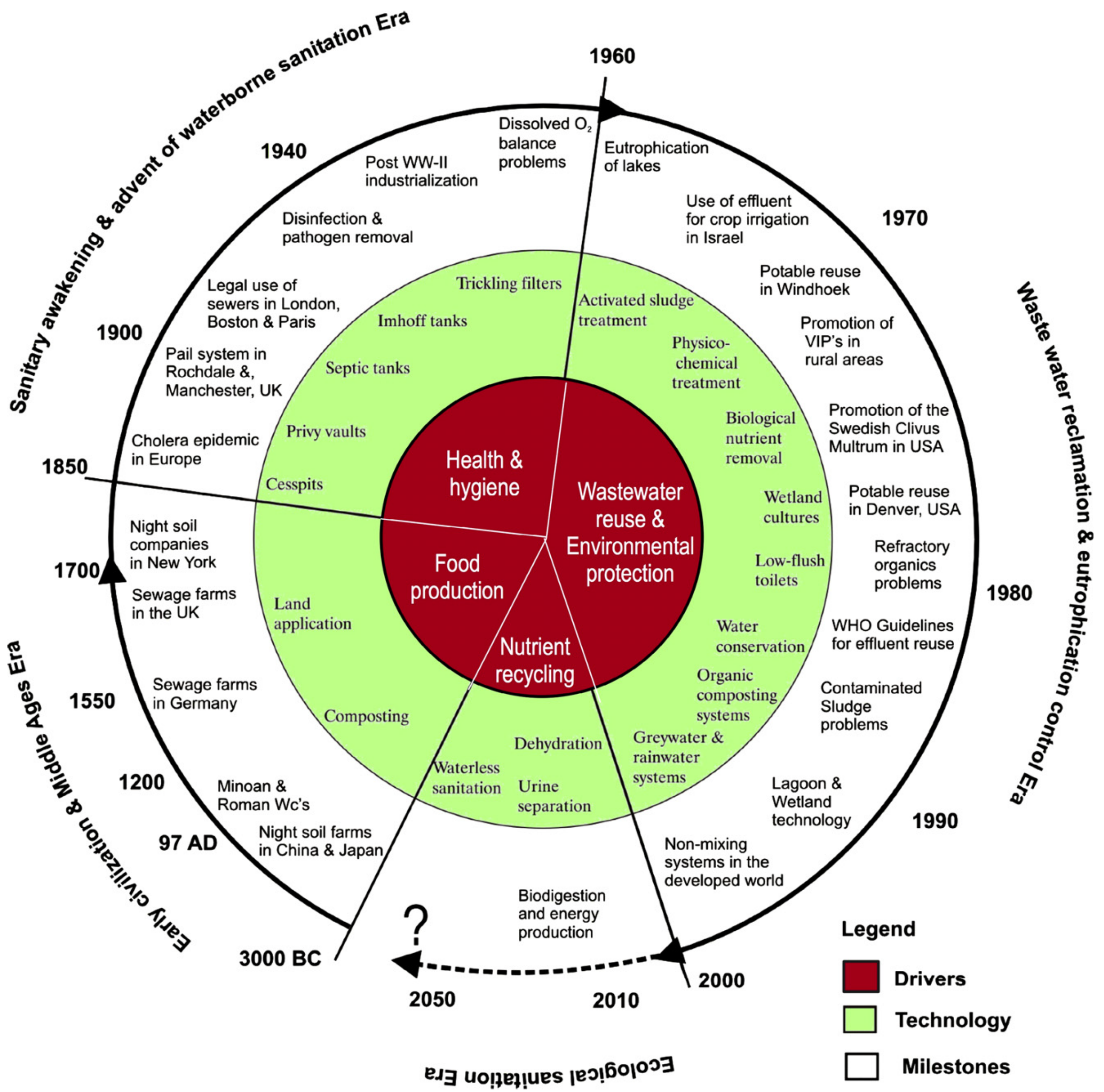
How have we tried to keep excess N & P out of our waters?

- Wastewater treatment
- Agricultural nonpoint sources



Wastewater treatment

- Leveraging the knowledge of nutrient cycling
  - Biological nutrient removal
    - Manipulate oxygen levels
    - Encourage denitrification
  - Chemical treatment
    - Encourage P precipitation
- New technologies but expensive
- Movement towards nutrient recycling (circularity)



Strategies to reduce excess losses of N & P from agricultural land

- <u>TRANSPORT</u>: reduce transport of existing N & P in soil & watershed

LAND

WATER

- <u>SUPPLY</u>: reduce supply of existing N & P in soil & watershed

P Transport Management

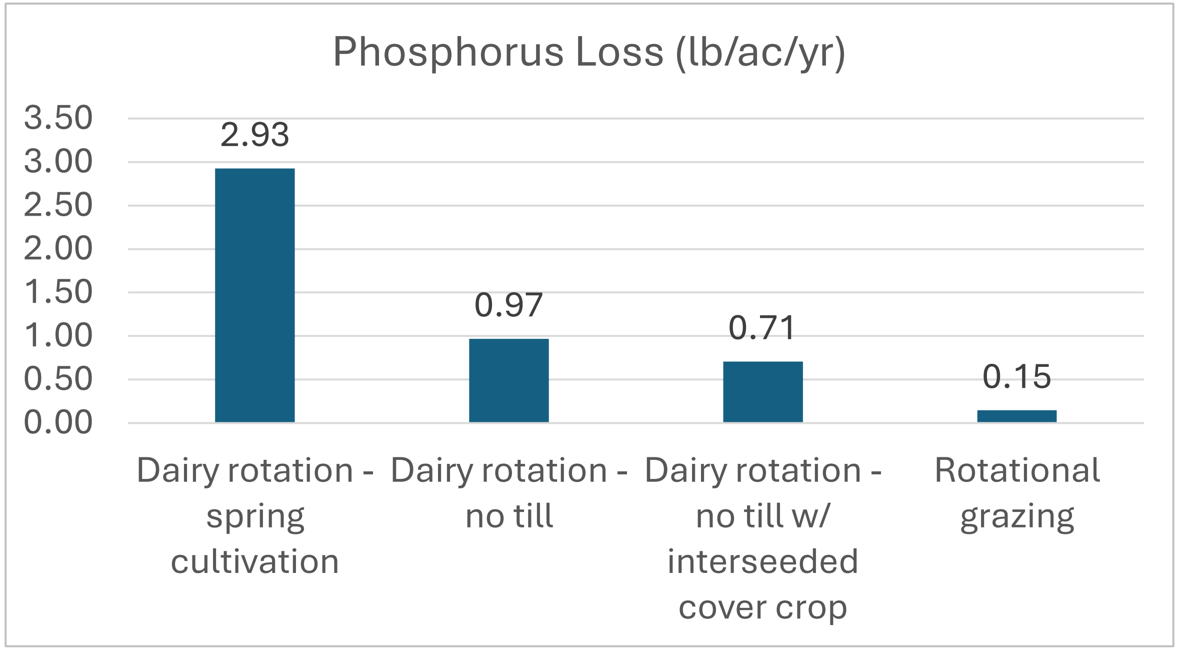
- Reduce erosion and runoff
  - Reduce disturbance
  - Increase ground cover
  - Promote infiltration
  - Target susceptible areas (high slope, shallow water table)
  - Avoid applications at susceptible times
  - Anticipate more extreme rainfall in warming climate


UW-Extension


Finn Ryan


Gregg Sanford

Variation in performance



MORE PERENNIAL COVER

SnapPlus results for Plano Silt Loam (4% slope) in Dane Co.
Dairy rotation = corn grain, corn silage, alfalfa (3 yrs)

N Transport Management

- Reduce leaching
  - Slow-release of nitrate to plants when needed
  - Design system to hang on to nitrogen longer (e.g., cover crops)

N & P Supply Management

FEED & MANURE

FERTILIZER

Nutrient Inputs

SOIL

OR

WATERSHED

Productive Outputs

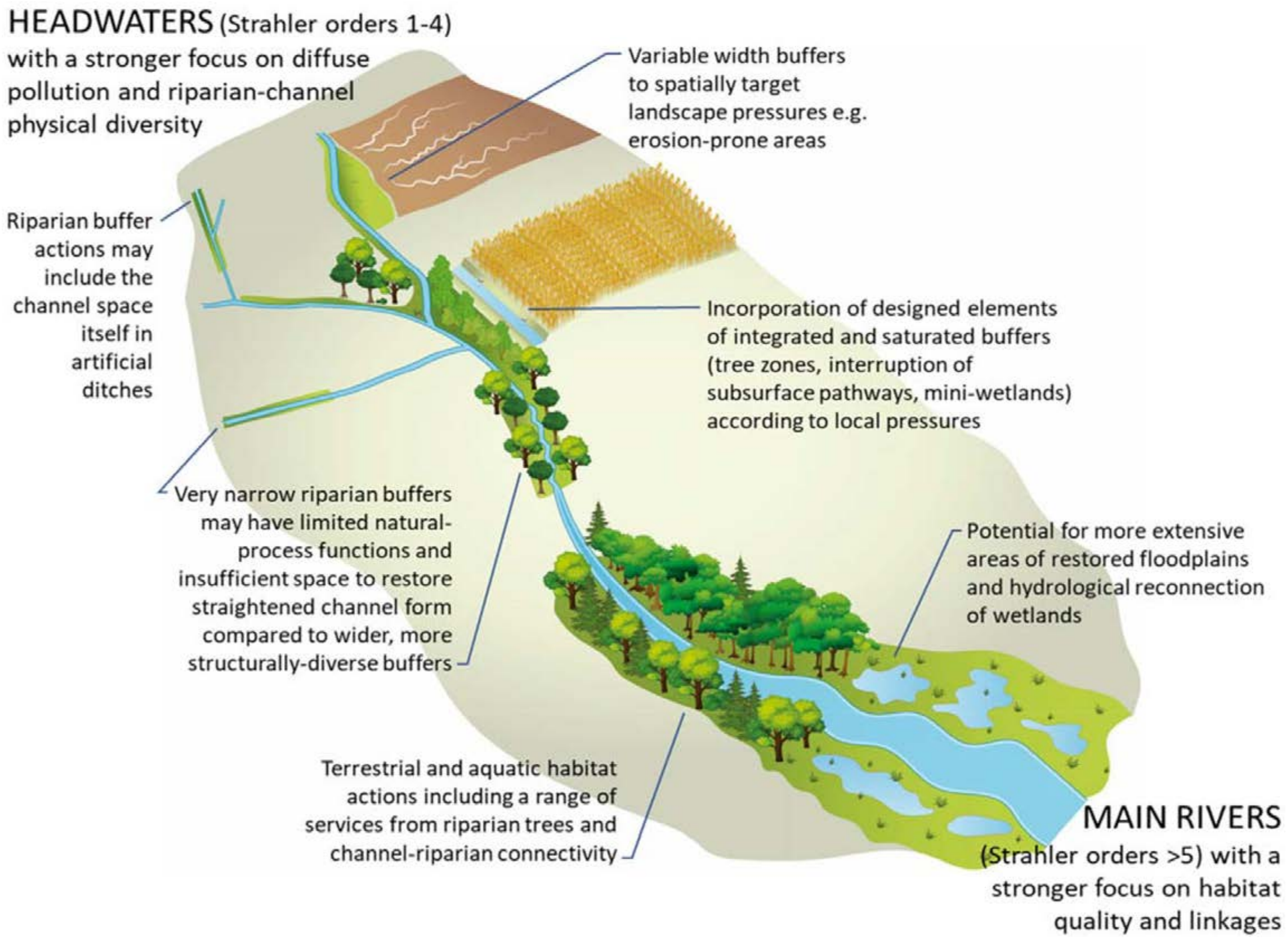
Nutrient Losses

- How do we better balance nutrient inputs and outputs?
  - Increasing productive outputs is one way
  - But cropping systems are inherently leaky (↑ inputs, ↑ losses)
    - Especially nitrate
  - Low input systems lead to less losses

Source: Zhang et al. 2020

Opportunities to reduce N and P along flow path

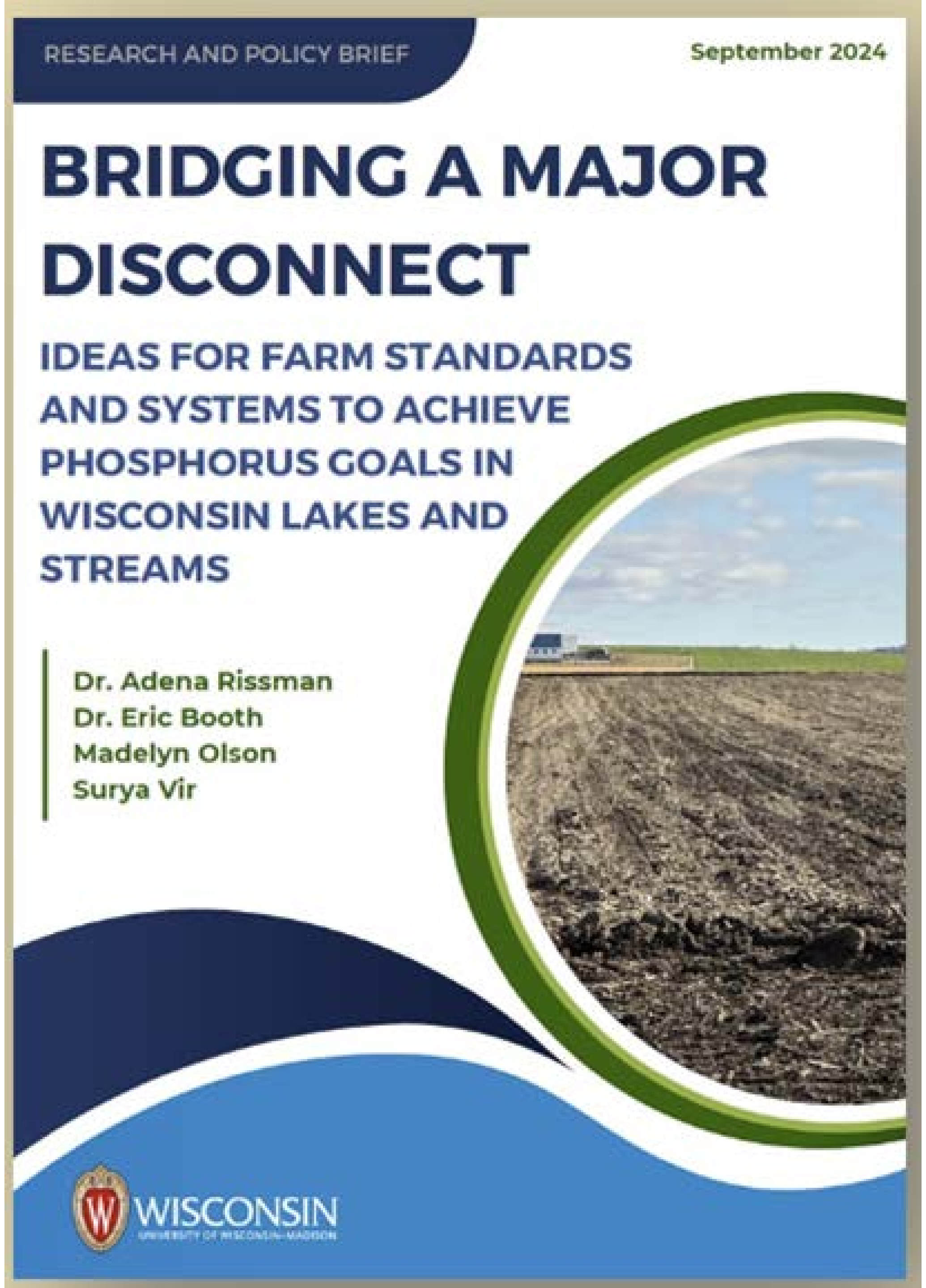
- Encouraging denitrification (wetlands, floodplains, buffers) and plant uptake
- Encouraging sediment P deposition and retaining / harvesting (?)



Collaborative Landscape Design

- Generating sufficient nutrient credits is a system-level challenge
  - Food, energy, water, ecosystems, society
- Requires engaging with a community of farmers (renters and landowners) and residents
  - Finding solutions for multiple objectives (profitability, keeping a farm)
- Need to normalize high-performance perennial systems
  - Managed grazing, agroforestry
  - Can be profitable with good management

grassLAND 2.0



"If we're serious about water quality, we need to take a look at where our rules are in relation to water quality, and relate the fields to the water, and not have this huge disconnect."

\- County conservationist

Acknowledgments

- Fellow researchers, land/water managers
- Good quality data and research depends on public funding
  - USDA-NIFA, NSF

Contact: Eric Booth, egbooth@wisc.edu