Biogeochemical cycles in Forest Ecosystem

evropský sociální fond v ČR
EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

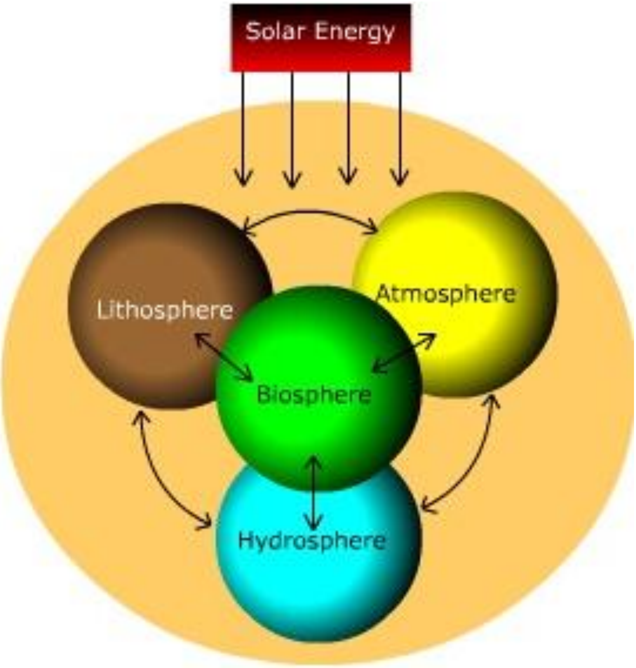
Tento projekt je spolufinancován Evropským sociálním fondem a Státním rozpočtem ČR InoBio – CZ.1.07/2.2.00/28.0018

Content

- Biogeochemical cycling, principles and definitions
- N-cycle in forest ecosystems
- Cycling of main mineral elements
- Acid deposition and forests
- Mineral nutrition
- Application in forestry

Biogeochemical Cycling, main principles

- **Biogeochemical cycles**: The chemical interactions (cycles) that exist between the atmosphere, hydrosphere, lithosphere, and biosphere.
- **Abiotic** (physio-chemical) and **biotic** processes drive these cycles
- We term this a **biogeochemical cycle** because ***bio*** pertains to life**, *geo*** pertains to Earth (atmosphere, water, rocks, and soils), and it is ***chemicals*** that are cycled.



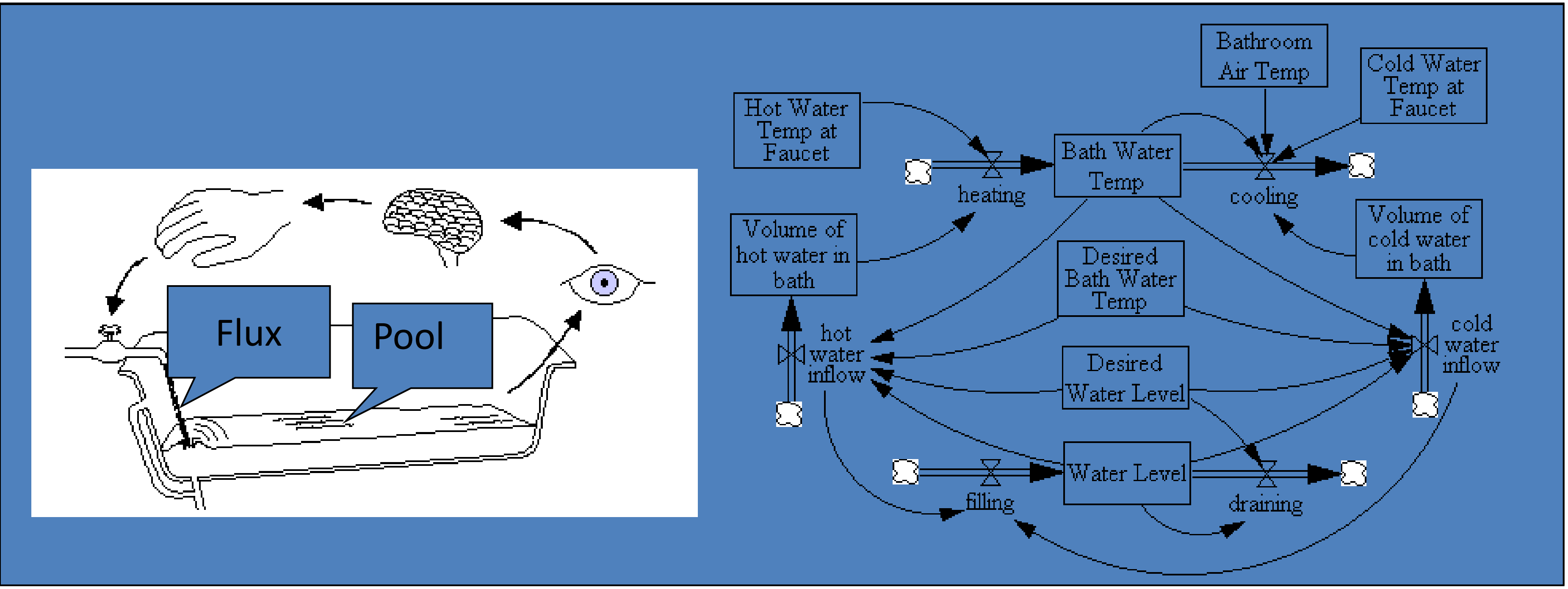
What is common amongst them?

- Each compound (water, carbon, nitrogen, other mineral elements) typically exists in all four parts of the Earth System
- There are
  - ‘Pools’
  - Fluxes in and out of pools
  - Chemical or biochemical transformations
- Transformations
  - are important
  - can lead to positive & negative consequences (e.g. Acidification)

What is a system?

- **System**: a collection of matter, parts, or components which are included inside a specified, often arbitrary, boundary. Example: **Ecosystem**

- Systems often have inputs and outputs.



Input - ouput system

Sources (fluxes - inputs)

- precipitation, throughfall (deposition), stemflow, weathering, undergound water, surface water, litter fall, decomposition of organic matter …

Losses (fluxes - outputs)

- soil gravimetrical water (leaching), harvesting, erossion, runoff, volatilization, fire (combustion)…

Storages (pools)

- Soil, total green biomass, leafs, needles, twigs, dead biomass,wood, roots…
- Belowground, undergound

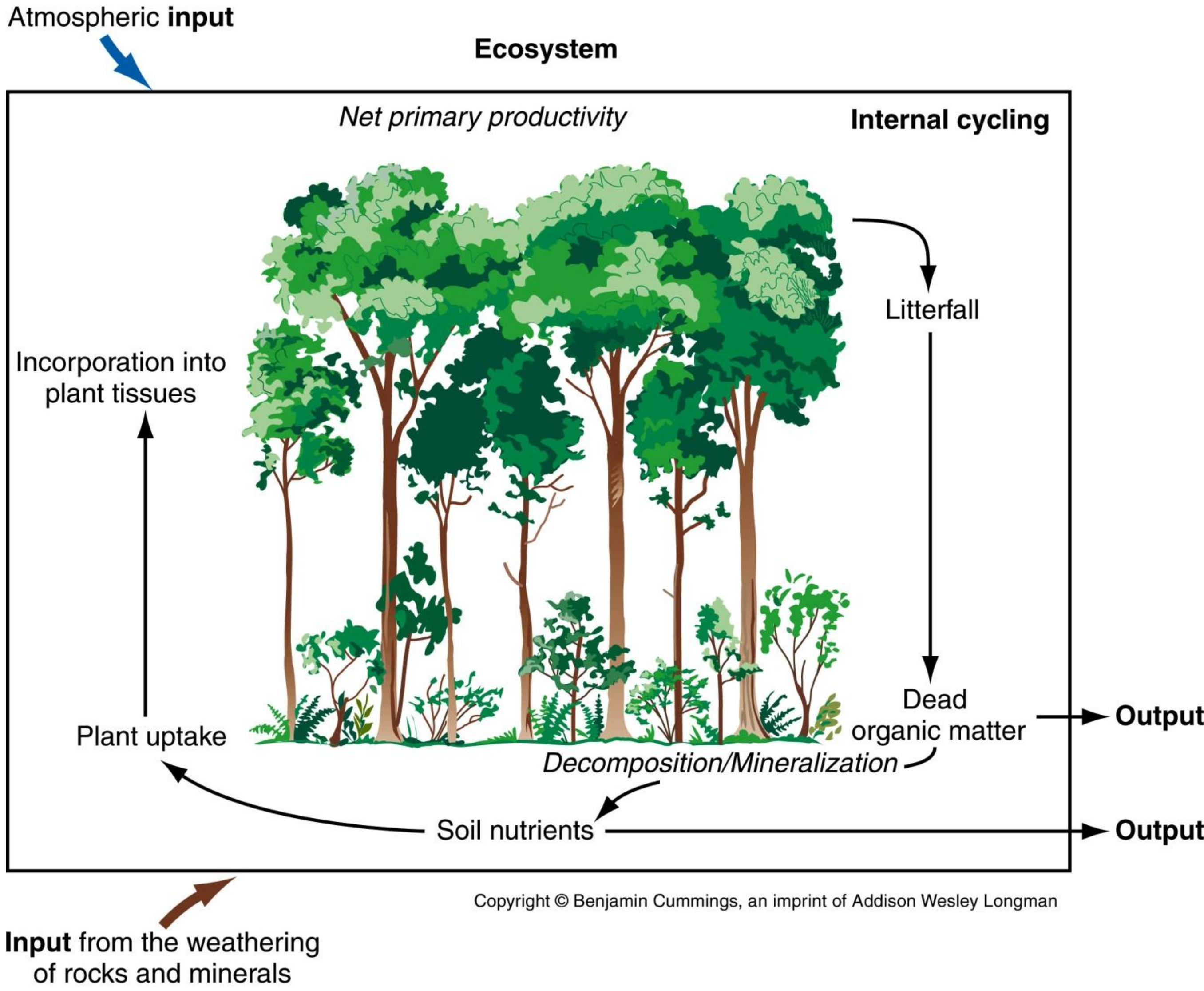
Plant processes

- Infrasystem cycling
- Recycling (organic , anorganic forms)

Litter processes, soil processes - (specific inner system)

Model of nutrient cycles

A generalized model of **nutrient cycling in a terrestrial ecosystem.** The three common components of **inputs, internal cycling and outputs** are shown in bold. The key ecosystem processes of **net productivity and decomposition** are *italicized.*



Nitrogen Cycle: Key Points

- Nitrogen is in the atmosphere as N_2 (78%)
- N_2 is an inert gas and cannot be used by plants or animals
- N_2 can be converted to a usable form via
  - Lightening
  - N-fixing plants and cyanobacteria
  - Industrial process (energy intensive)
- Nitrogen limits plant growth
- Nitrogen is easily lost from biological systems

Nitrogen Cycle

- Essential to life - important in forming amino acids >> proteins
- Most abundant in the atmosphere (79%)
- Flows continuously through the spheres
- **Reservoirs**: atmosphere and biosphere (soil)
- **Processes:** Nitrogen fixation, protein amonification, nitrification and denitrification
- Atmosphere => soil => plants => atmosphere (see figures)

Nitrogen Cycle

- **Nitrification/ nitrogen fixation**: converts N_2 to forms usable by plants (NH_3, and NO_3^-)
- **Denitrification**: is the conversion of NO_3^- back to N_2 in the atmosphere or in gases in the soil
- **Symbiotic relationship**: bacteria supply the plant with usable nitrogen and feed off the sugars and starches made by the plant

Nitrogen Cycle

- **Human activities** account for >50% of nitrogen fixation (fertilizers, cultivation of nitrogen fixing plants)
- **Denitrification -** done mainly by bacteria not by humans.
- Despite the huge size of the atmospheric reservoir of nitrogen, **human activites profoundly affect the nitrogen cycle**

Nitrogen cycle

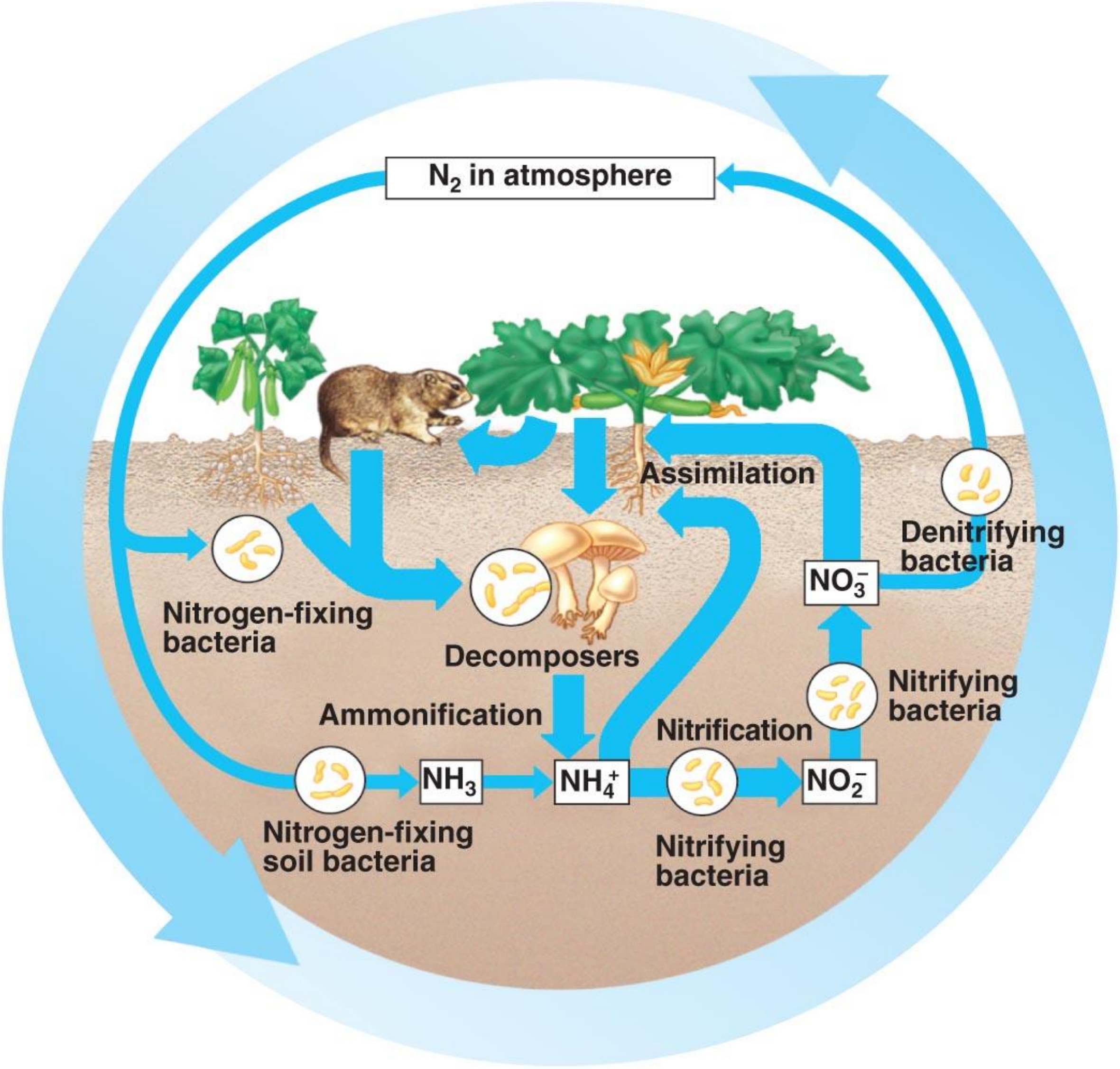
Main part of N-cycles

- Biomass uptake
- Litter decomposition
- Amonnification
- Nitrification
- Denitrification
- Nitrate leaching
- Volatilization
- N-fixation

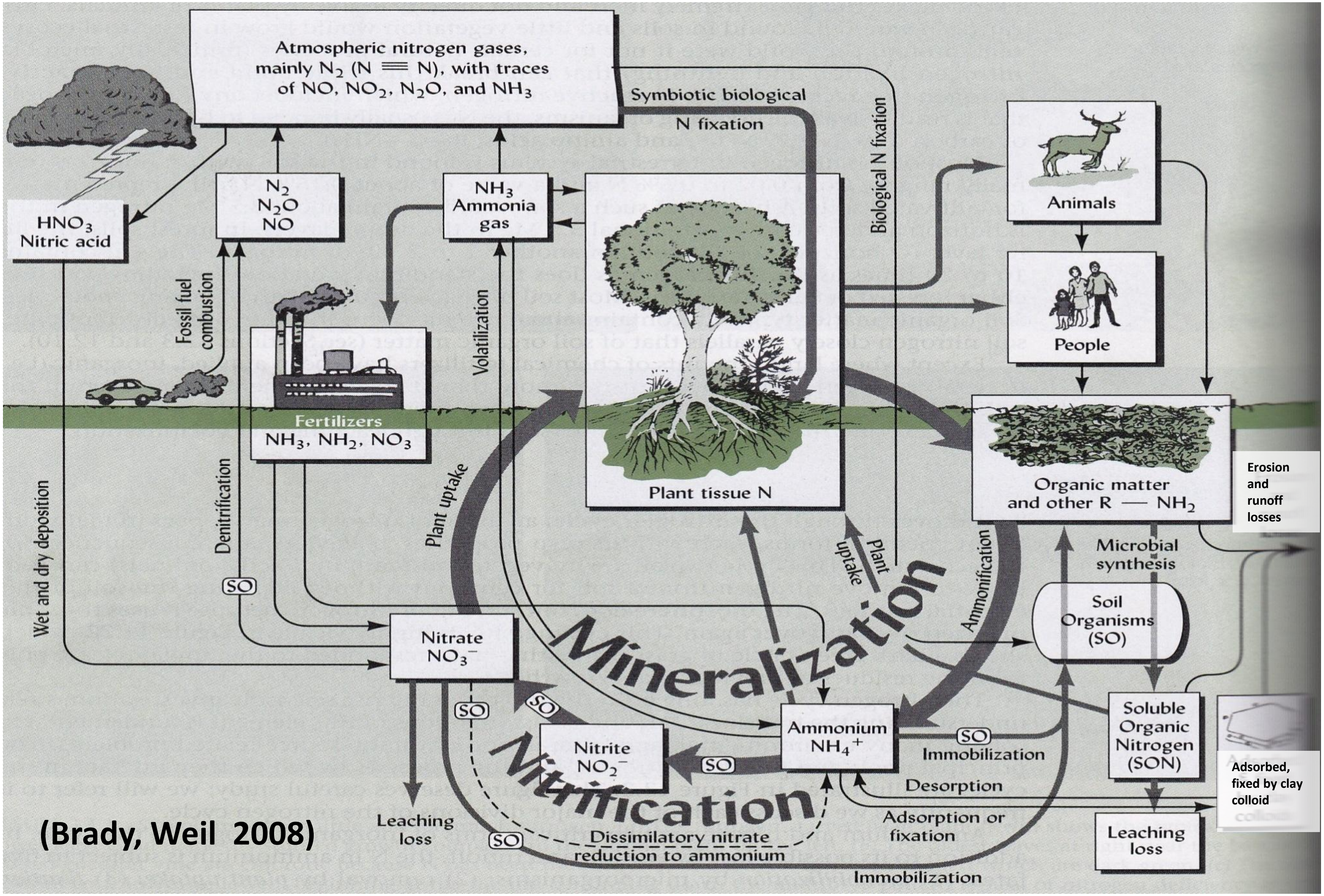
Forms of Nitrogen

1. N_2 - inert gas, 78% of the atmosphere
2. NO, N_20, NO_2 - other gases of nitrogen, not directly biologically important. Part of the gases found in smog.
3. NO_3^- (nitrate) and NH_4^+ (ammonium) - ionic forms of nitrogen that are biologically usable (available).

Simplified N- cycle



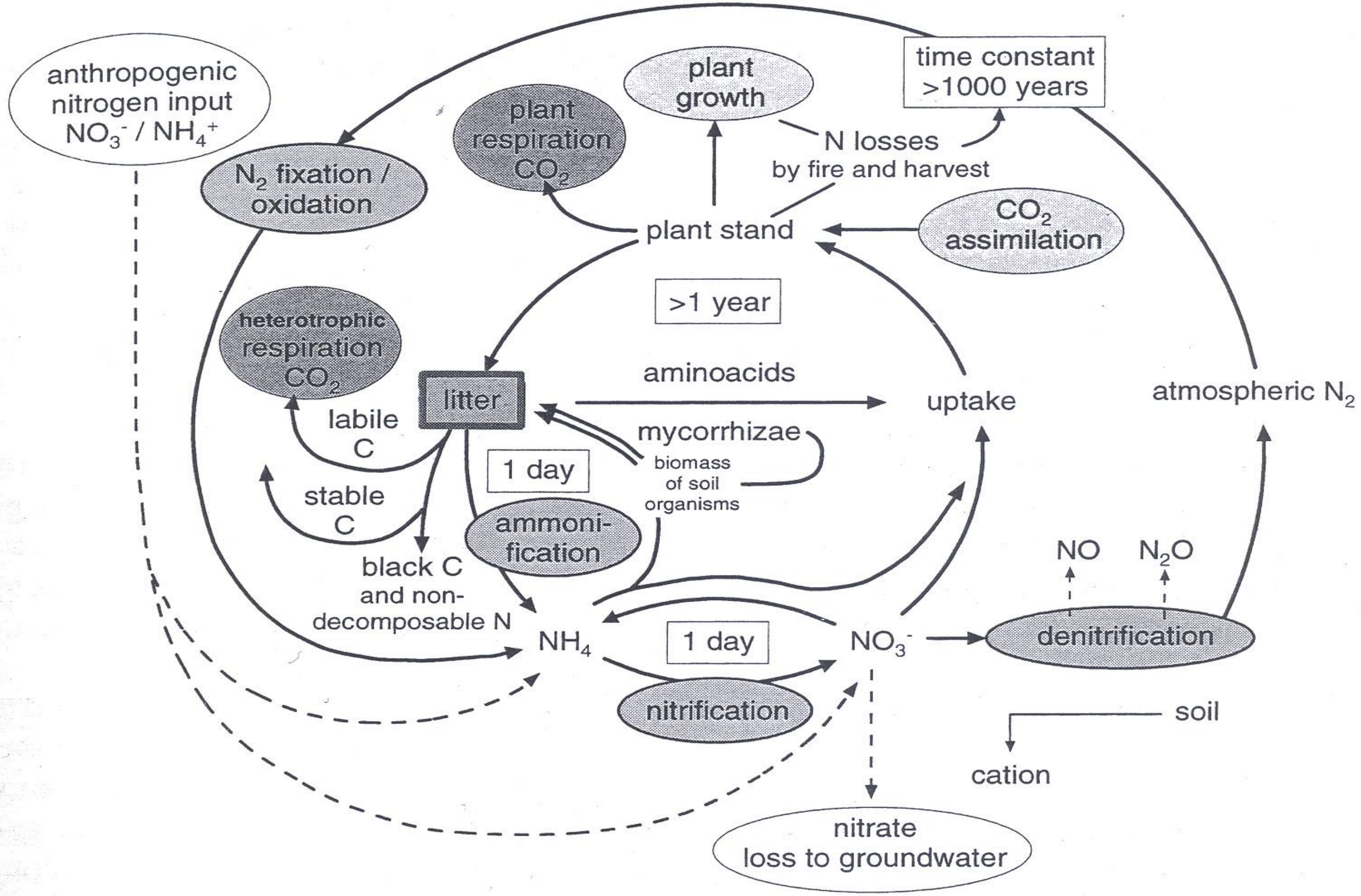
The Nitrogen Cycle



(Brady, Weil 2008)

Carbon and Nitrogen Cycle in Forest Ecosystems

The Carbon and Nitrogen Cycle of Forest Ecosystems 7

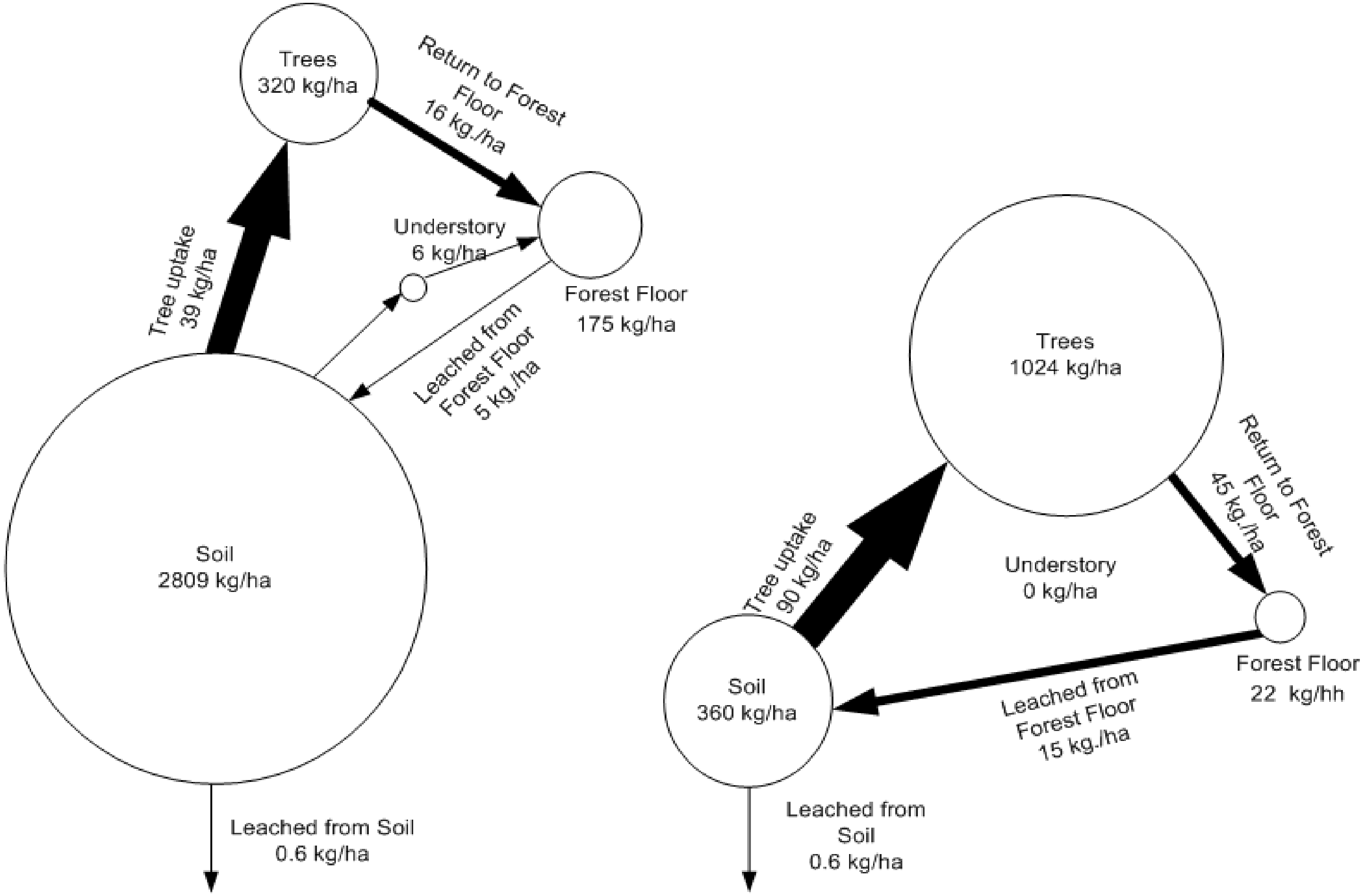


Nitrogen Cycle in Forest Ecosystem

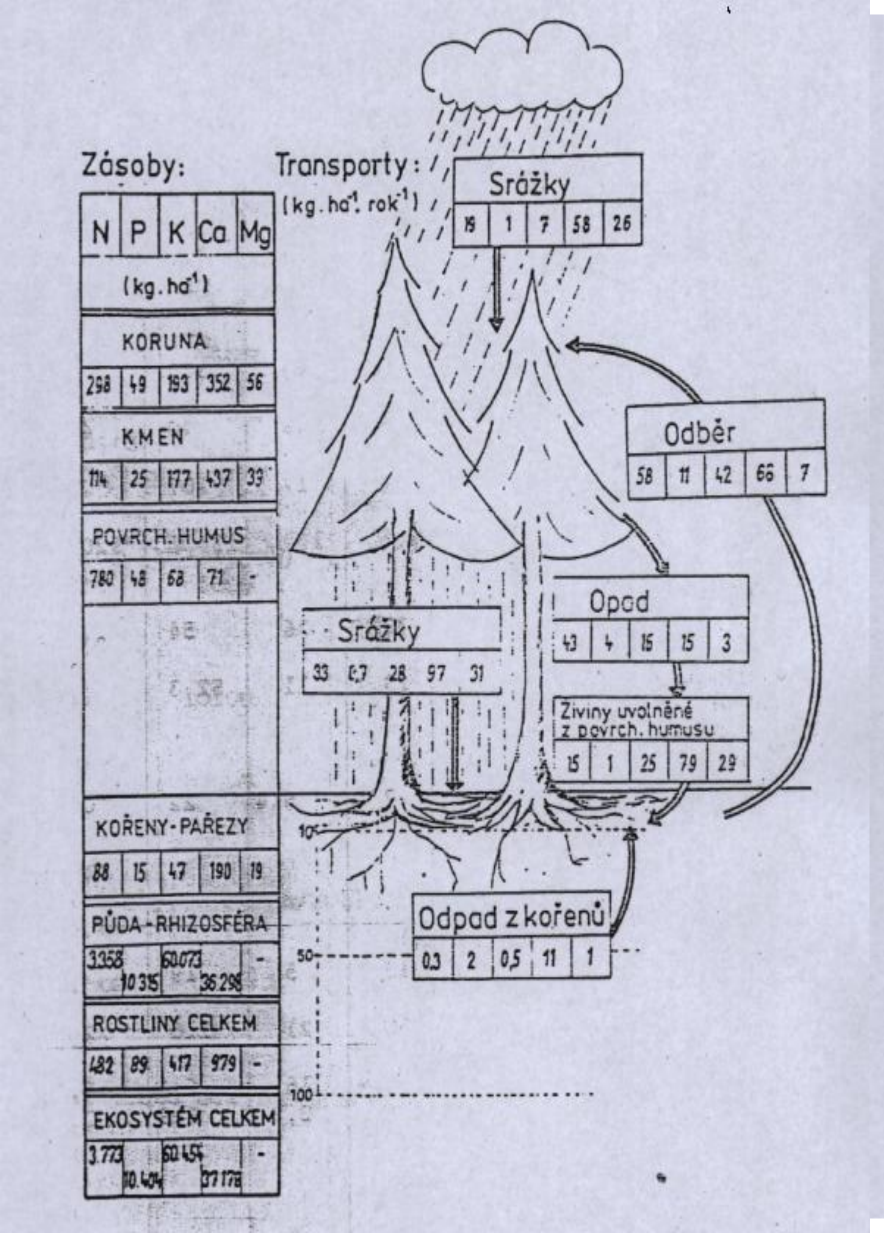
an example

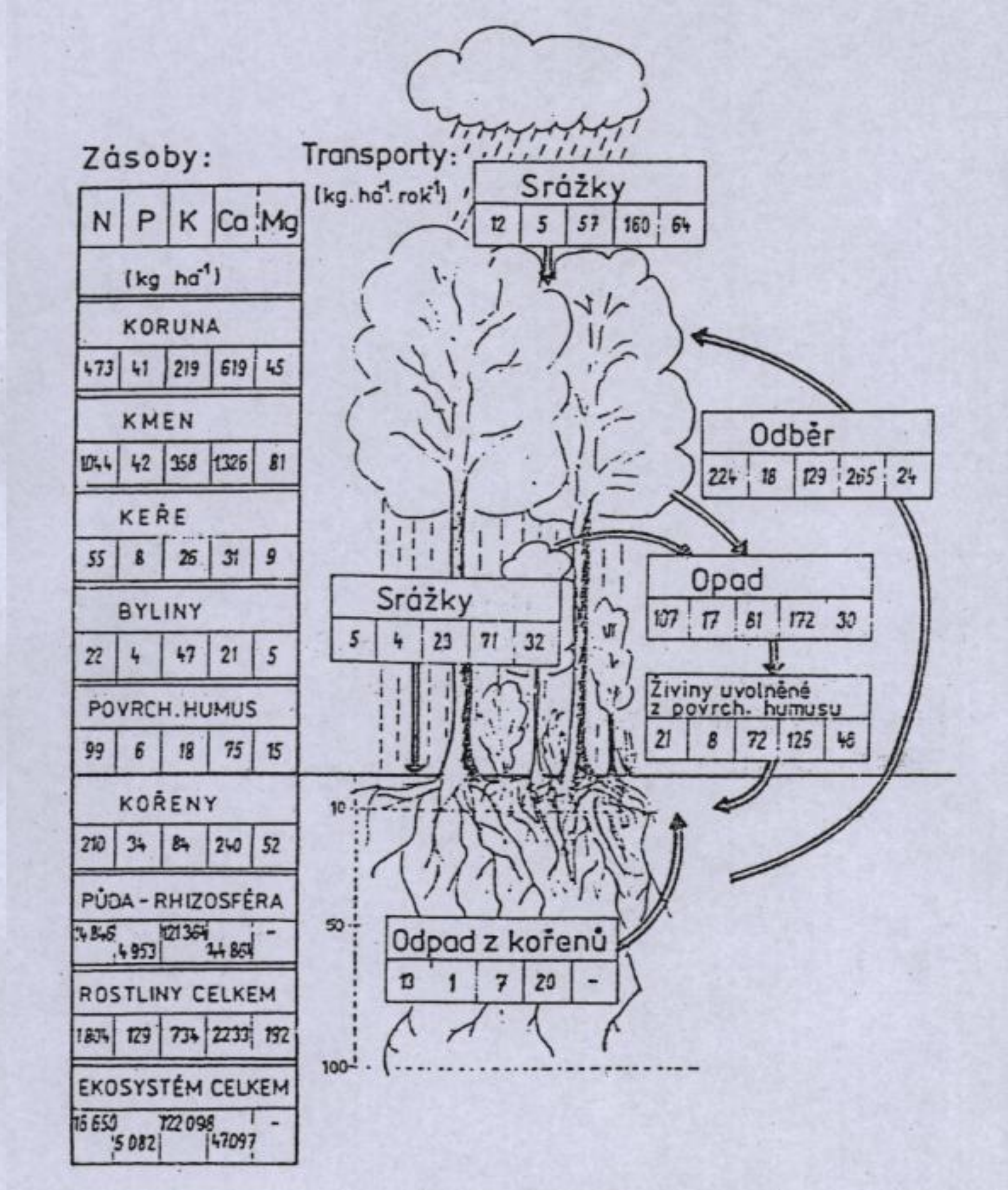
N Cycle of 60-year old Douglas-fir
Forest near Seattle, USA

N Cycle of 22-year old Eucalyptus
Forest in Sao Paulo State, Brazil



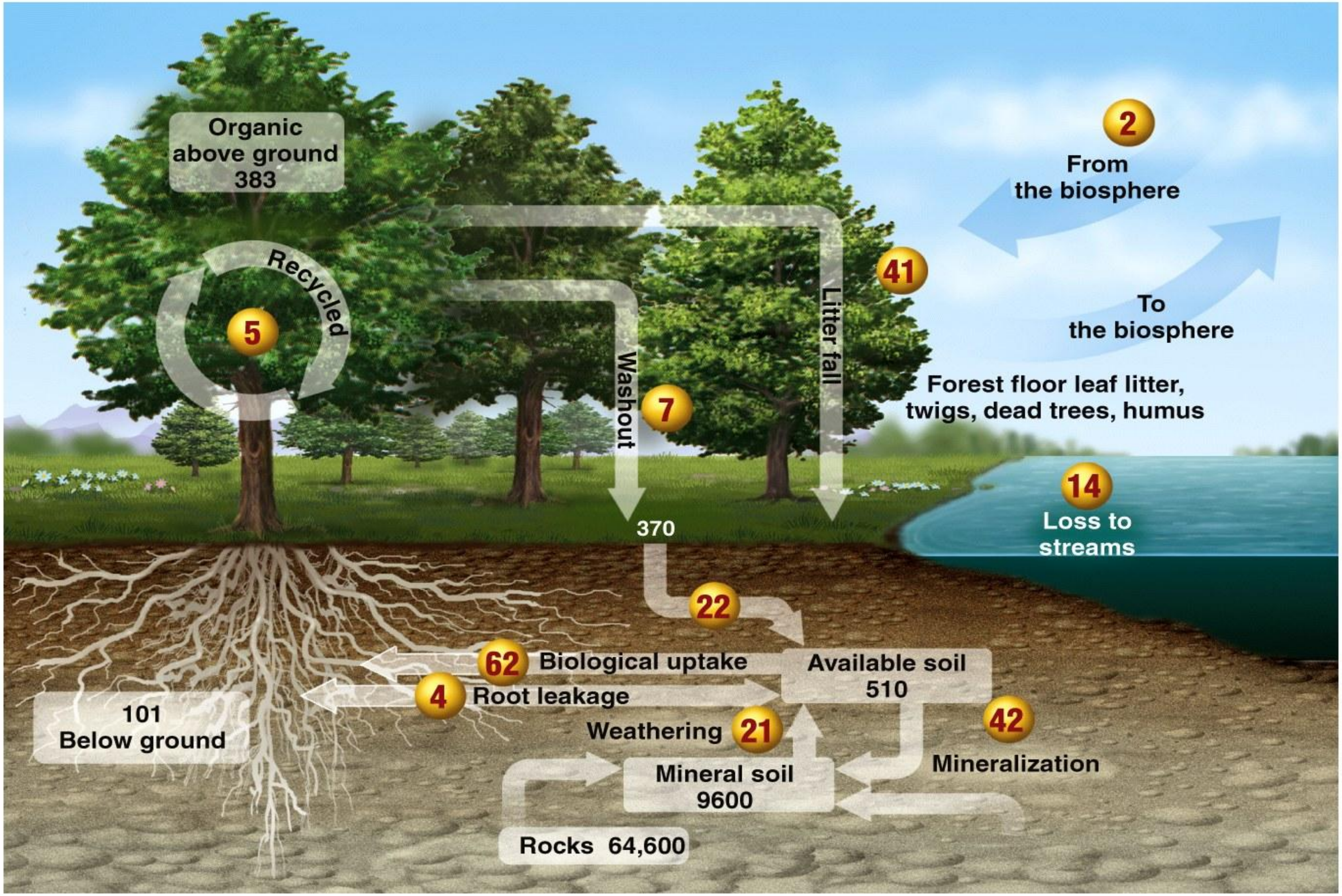
Cycling in elements in forest ecosystems (The Czech Republic)



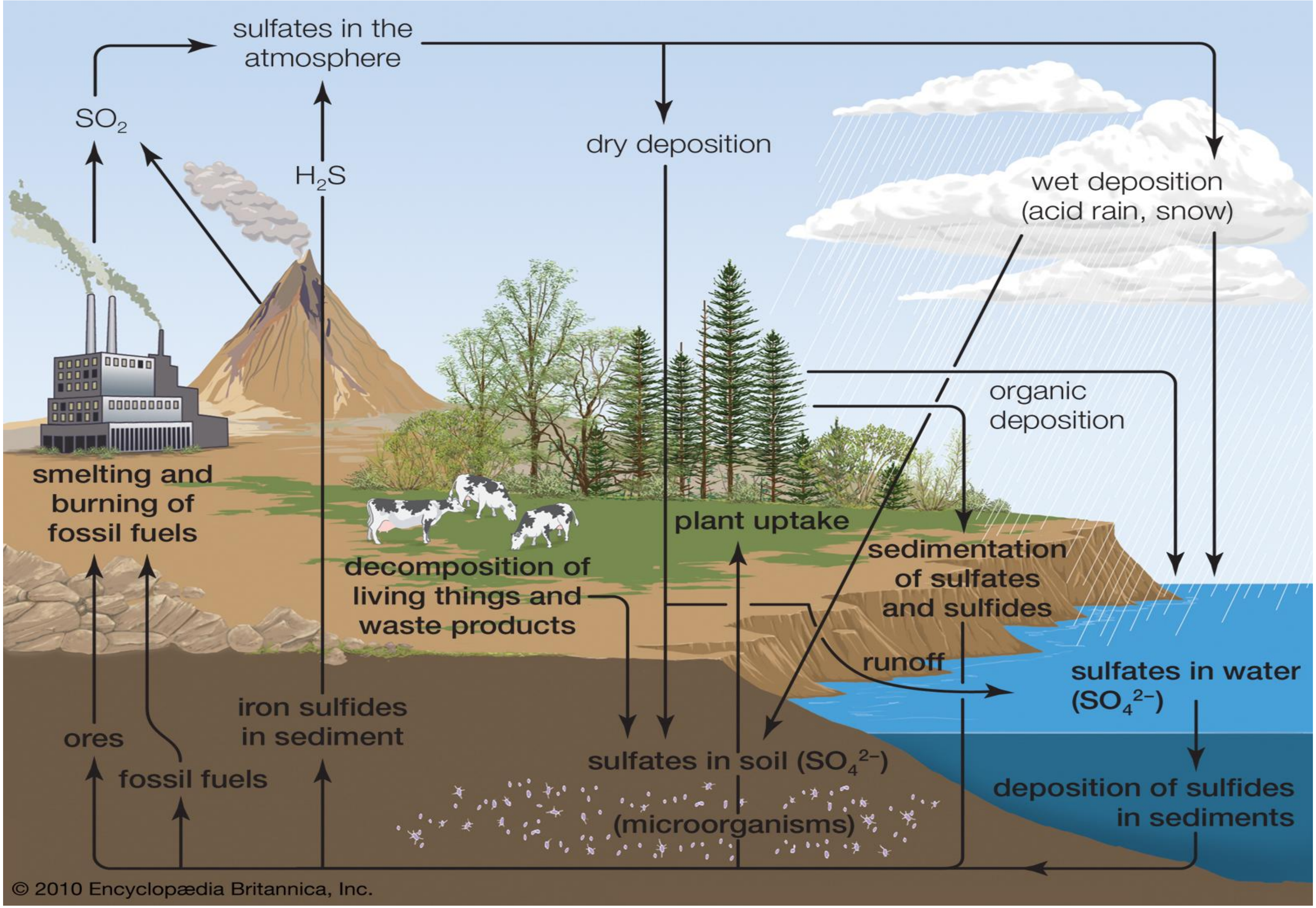


Biogeochemical Cycle of Ca in Forest Ecosystem

- see also special PP in DS



Sulphur Cycle



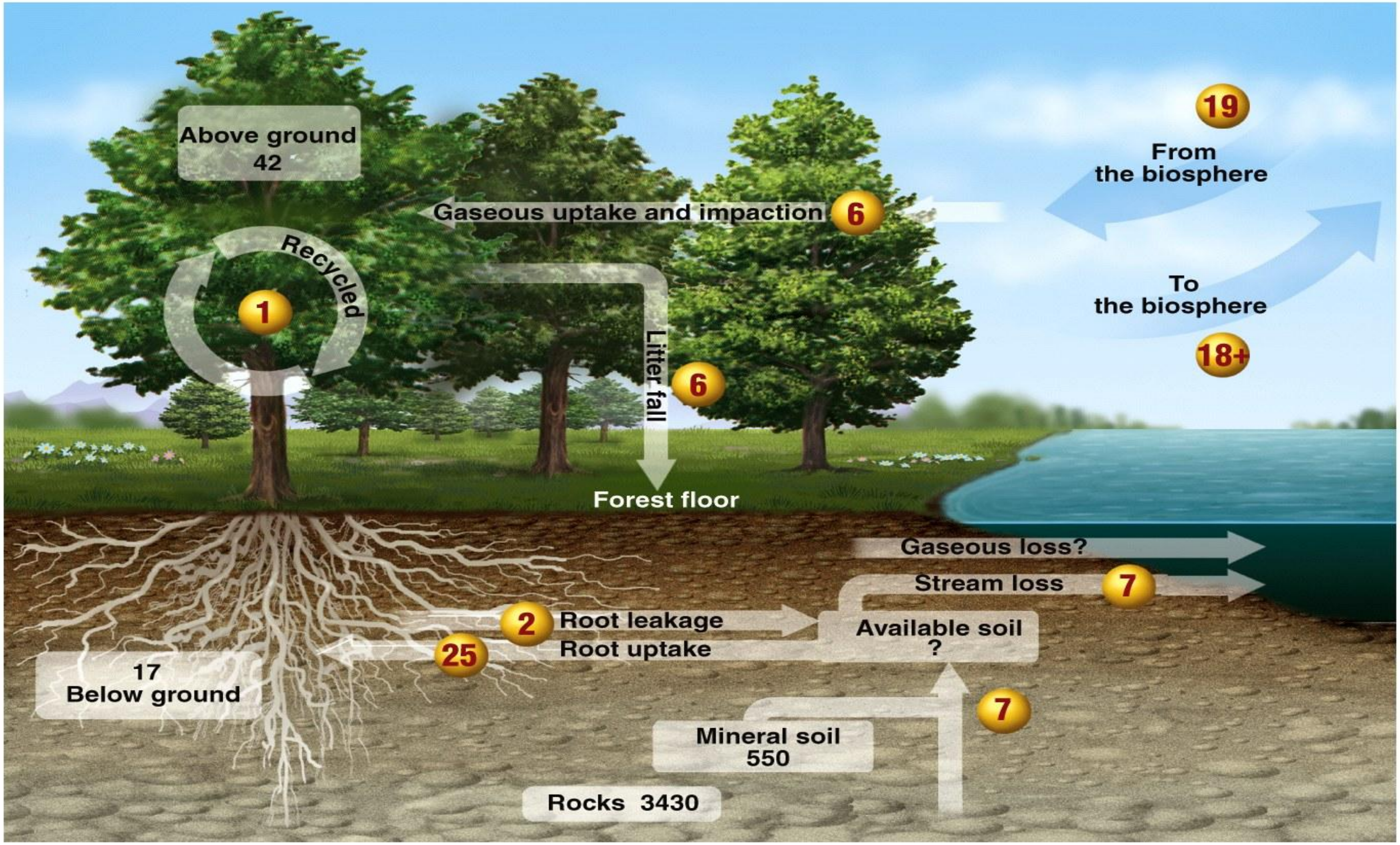
Sulfur Cycle

- Essential for organic material (protein)
- Found in coal, petroleum, and plants
  - Gas released to atm. when burned
- Common with metallic ores
  - Gas released to atm when smelted
- Important component of urban SMOG
- Important source of aerosols (cloud formation, albedo, acidrain)

Sulfur Cycle

- Reservoirs: Lithosphere (sulfide, sulfate), hydrosphere (sulfate 7.8 % in ocean)
- Processes: Bacteria plays an important role in reducing sulfate to sulfide and in early photosynthesis- use of H_2S instead of H_2O
- Formation of sulfide; burial; weathering
- Volcanic activity
- Combustion of fossil fuels

Biogeochemical Cycle of Sulfur in Forest EcosystemEcosystem



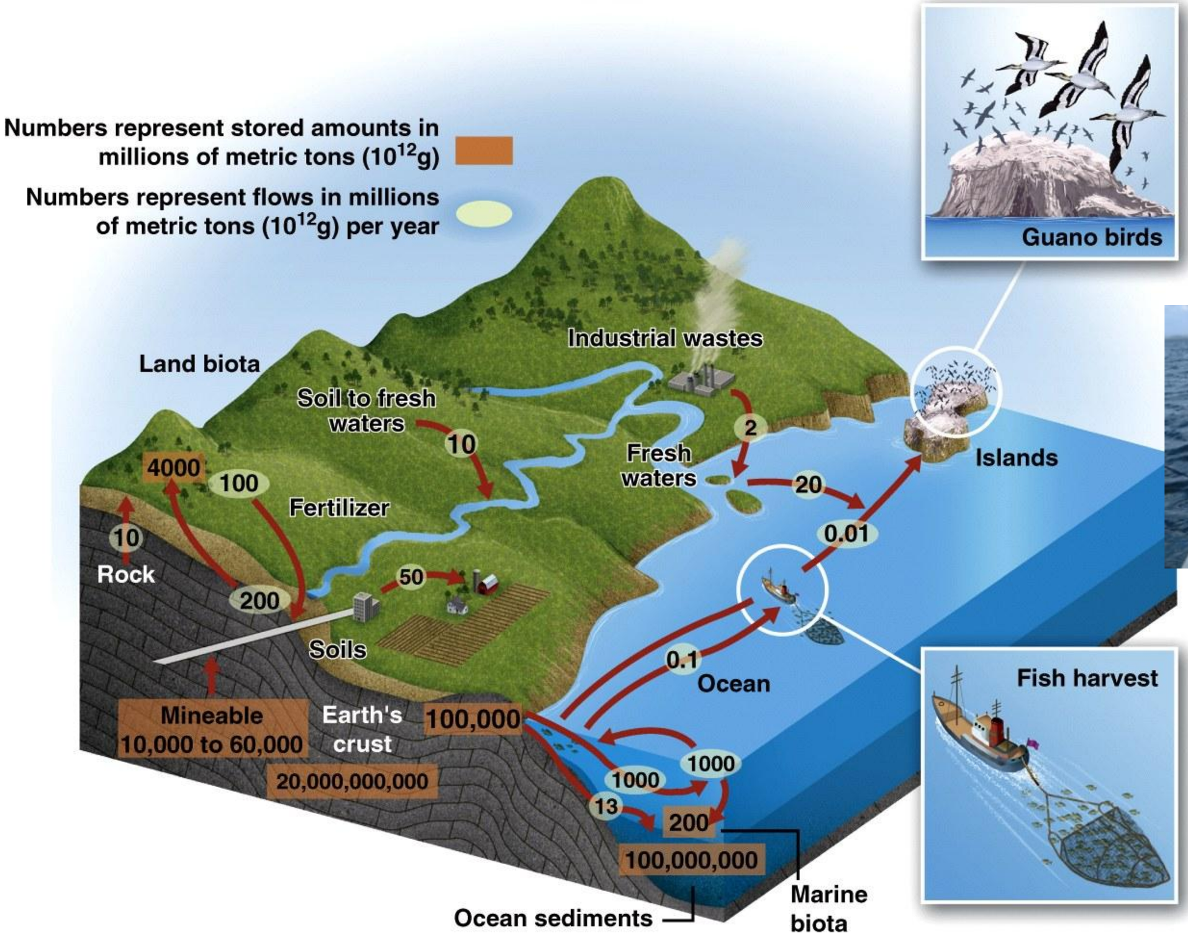
Phosphorus Cycle

- Reservoirs: Hydrosphere (as phosphate ion), lithosphere (phosphate minerals), and biosphere (bones, teeth, shells)
- Short-term cycle: PO_4^{3-} in soil or ocean => assimilation by plants => consumption by animals => decay or excretion => recycled to soil or ocean, residence time 100s of yrs

Phosphorus Cycle

- Long-term cycle - Residence time ~10^8 yrs
- Extraction (mining) short-circuits the long-term cycle
- Component of DNA, RNA, ATP, proteins and enzymes
- Soluble in H2O as phosphate (PO4)- plant availability
- Atmosphere is not a source
- As with nitrate, humans are doubling the rate of transport of phosphate into the environment through the application of fertilizers (eutrophication)

Global Phosphorus Cycle



Mineral Nutrition - plants

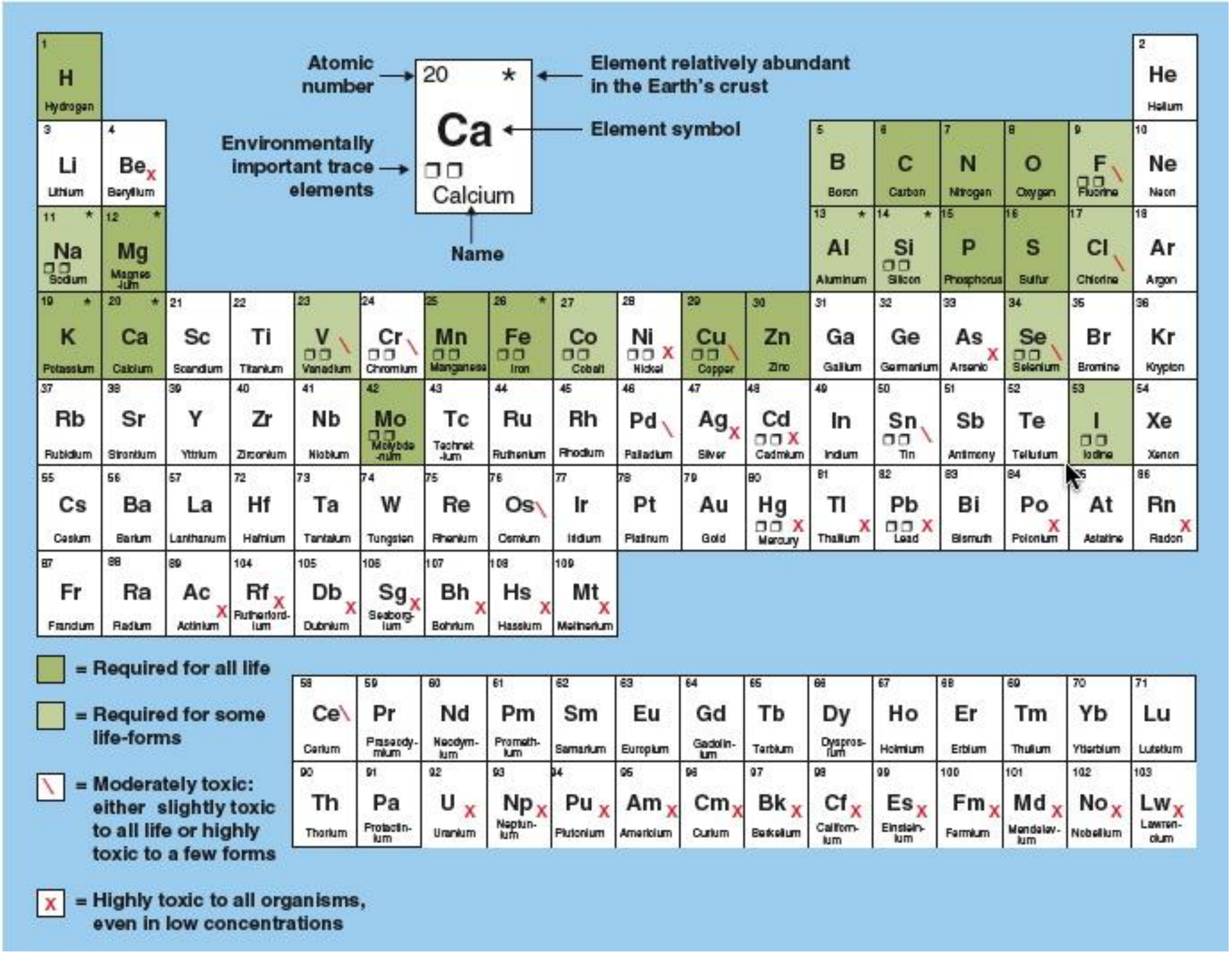
24 elements are required for life

Macronutrients are required in large quantities

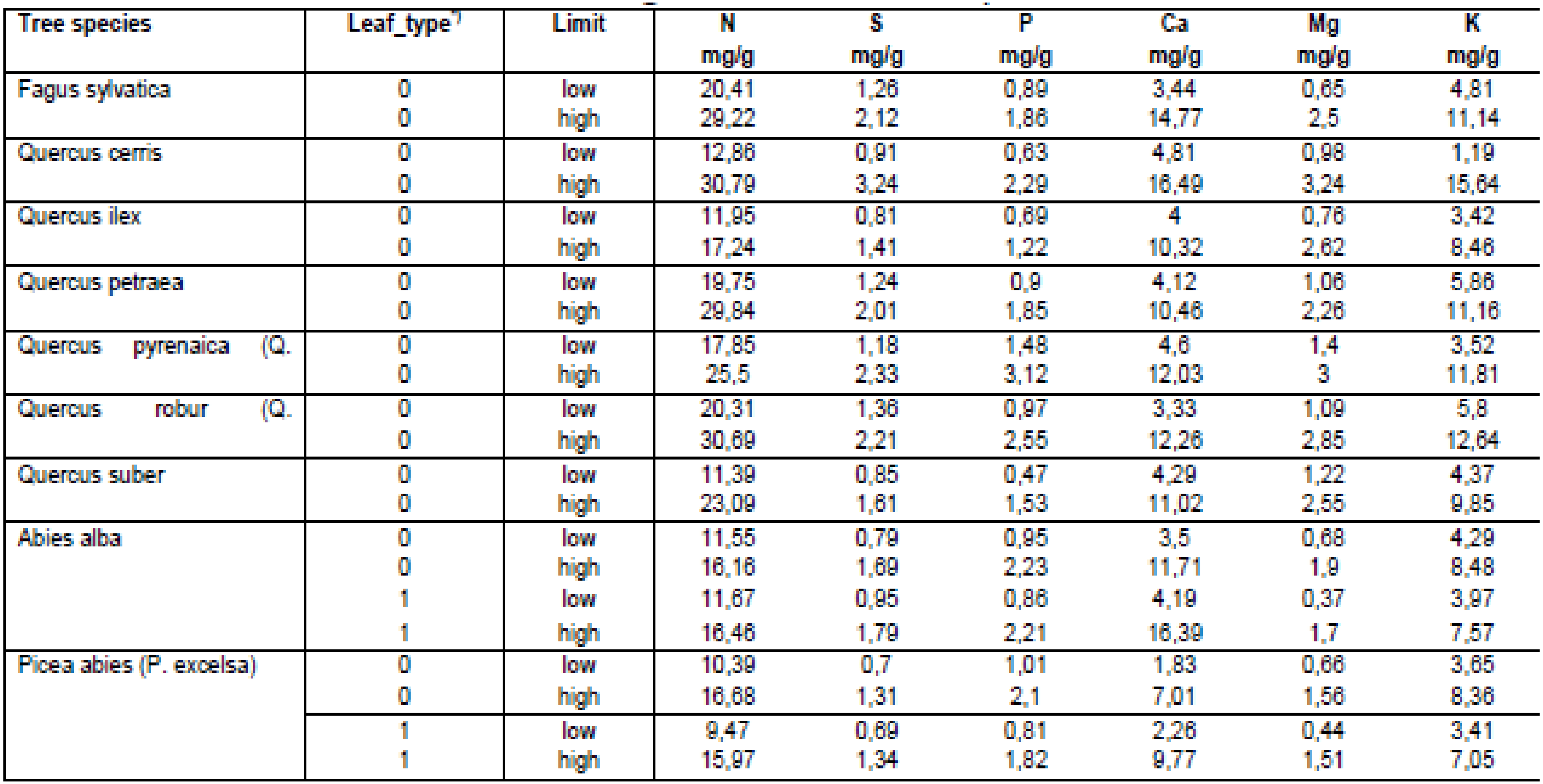
- carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur

Micronutrients are required in small/medium quantities, or not at all in some organisms

- copper, sodium, iodine, …


Atomic number
Element relatively abundant in the Earth's crust
Element symbol
Environmentally important trace elements
Name
20 * Ca ☐☐ Calcium
1 H Hydrogen
2 He Helium
3 Li Lithium
4 Be X Beryllium
5 B Boron
6 C Carbon
7 N Nitrogen
8 O Oxygen
9 F ☐☐ \ Fluorine
10 Ne Neon
11 * Na ☐☐ Sodium
12 * Mg Magnesium
13 * Al Aluminum
14 * Si ☐☐ Silicon
15 P Phosphorus
16 S Sulfur
17 Cl \ Chlorine
18 Ar Argon
19 * K Potassium
20 * Ca Calcium
21 Sc Scandium
22 Ti Titanium
23 V ☐☐ \ Vanadium
24 Cr ☐☐ \ Chromium
25 Mn ☐☐ Manganese
26 * Fe ☐☐ Iron
27 Co ☐☐ Cobalt
28 Ni ☐☐ X Nickel
29 Cu ☐☐ \ Copper
30 Zn Zinc
31 Ga Gallium
32 Ge Germanium
33 As X Arsenic
34 Se ☐☐ \ Selenium
35 Br Bromine
36 Kr Krypton
37 Rb Rubidium
38 Sr Strontium
39 Y Yttrium
40 Zr Zirconium
41 Nb Niobium
42 Mo ☐☐ Molybdenum
43 Tc Technetium
44 Ru Ruthenium
45 Rh Rhodium
46 Pd \ Palladium
47 Ag X Silver
48 Cd ☐☐ X Cadmium
49 In Indium
50 Sn ☐☐ \ Tin
51 Sb Antimony
52 Te Tellurium
53 I ☐☐ Iodine
54 Xe Xenon
55 Cs Cesium
56 Ba Barium
57 La Lanthanum
72 Hf Hafnium
73 Ta Tantalum
74 W Tungsten
75 Re Rhenium
76 Os \ Osmium
77 Ir Iridium
78 Pt Platinum
79 Au Gold
80 Hg ☐☐ X Mercury
81 Tl X Thallium
82 Pb ☐☐ X Lead
83 Bi Bismuth
84 Po X Polonium
85 At Astatine
86 Rn X Radon
87 Fr Francium
88 Ra Radium
89 Ac X Actinium
104 Rf X Rutherfordium
105 Db X Dubnium
106 Sg X Seaborgium
107 Bh X Bohrium
108 Hs X Hassium
109 Mt X Meitnerium
58 Ce \ Cerium
59 Pr Praseodymium
60 Nd Neodymium
61 Pm Promethium
62 Sm Samarium
63 Eu Europium
64 Gd Gadolinium
65 Tb Terbium
66 Dy Dysprosium
67 Ho Holmium
68 Er Erbium
69 Tm Thulium
70 Yb Ytterbium
71 Lu Lutetium
90 Th Thorium
91 Pa Protactinium
92 U X Uranium
93 Np X Neptunium
94 Pu X Plutonium
95 Am X Americium
96 Cm X Curium
97 Bk X Berkelium
98 Cf X Californium
99 Es X Einsteinium
100 Fm X Fermium
101 Md X Mendelevium
102 No X Nobelium
103 Lw X Lawrencium
= Required for all life
= Required for some life-forms
\ = Moderately toxic: either slightly toxic to all life or highly toxic to a few forms
X = Highly toxic to all organisms, even in low concentrations

Element concentrations in the foliage of different tree species calculated from the ICP Level II data sets



Tree species	Leaf_type[7]	Limit	N mg/g	S mg/g	P mg/g	Ca mg/g	Mg mg/g	K mg/g
Fagus sylvatica	0	low	20,41	1,26	0,89	3,44	0,65	4,81
	0	high	29,22	2,12	1,86	14,77	2,5	11,14
Quercus cerris	0	low	12,86	0,91	0,63	4,81	0,98	1,19
	0	high	30,79	3,24	2,29	16,49	3,24	15,64
Quercus ilex	0	low	11,95	0,81	0,69	4	0,76	3,42
	0	high	17,24	1,41	1,22	10,32	2,62	8,46
Quercus petraea	0	low	19,75	1,24	0,9	4,12	1,06	5,86
	0	high	29,84	2,01	1,85	10,46	2,26	11,16
Quercus pyrenaica (Q.	0	low	17,85	1,18	1,48	4,6	1,4	3,52
	0	high	25,5	2,33	3,12	12,03	3	11,81
Quercus robur (Q.	0	low	20,31	1,36	0,97	3,33	1,09	5,8
	0	high	30,69	2,21	2,55	12,26	2,85	12,64
Quercus suber	0	low	11,39	0,85	0,47	4,29	1,22	4,37
	0	high	23,09	1,61	1,53	11,02	2,55	9,85
Abies alba	0	low	11,55	0,79	0,95	3,5	0,68	4,29
	0	high	16,16	1,69	2,23	11,71	1,9	8,48
	1	low	11,67	0,95	0,86	4,19	0,37	3,97
	1	high	16,46	1,79	2,21	16,39	1,7	7,57
Picea abies (P. excelsa)	0	low	10,39	0,7	1,01	1,83	0,66	3,65
	0	high	16,68	1,31	2,1	7,01	1,56	8,36
	1	low	9,47	0,69	0,81	2,26	0,44	3,41
	1	high	15,97	1,34	1,82	9,77	1,51	7,05

ICP Forest - http://www.icp-forests.org/pdf/FINAL_Foliage.pdf

Limits for mineral nutritions - soil available nutrients

Content mg/kg	**in solution 1 % citric acid**		
	P	**K**	**Mg**
Very low	to 40	to 55	to 45
Low	40 – 80	55 – 90	45 – 70
Medium	81 – 110	91 – 130	71 – 100
Good	Up 110	Up 130	Up 100

Content mg/kg	**in solution 1 N ammonium chloride**		
	P	**K**	**Mg**
Very low	to 30	to 30	to 20
Low	30 – 70	30 – 50	20 – 40
Medium	71 – 120	51 – 80	41 – 60
Good	Up 120	Up 80	Up 60

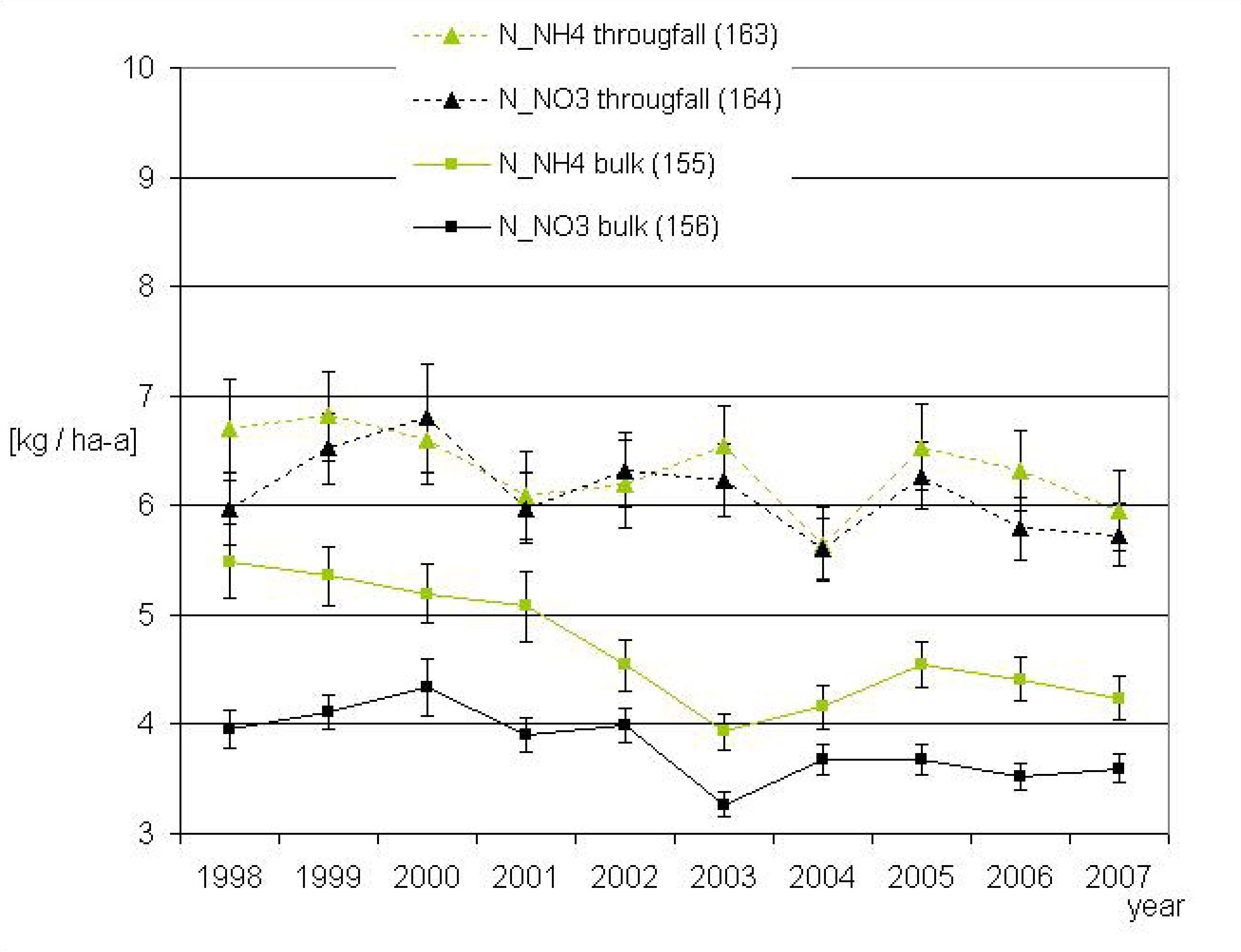
Nitrogen content in soil

Content	**%**
Very poor	to 0,03
Poor	0,03 - 0,06
Medium	0,06 - 0,2
Good	0,2 - 0,3
Rich	Up 0,3

Acid deposition and acidification

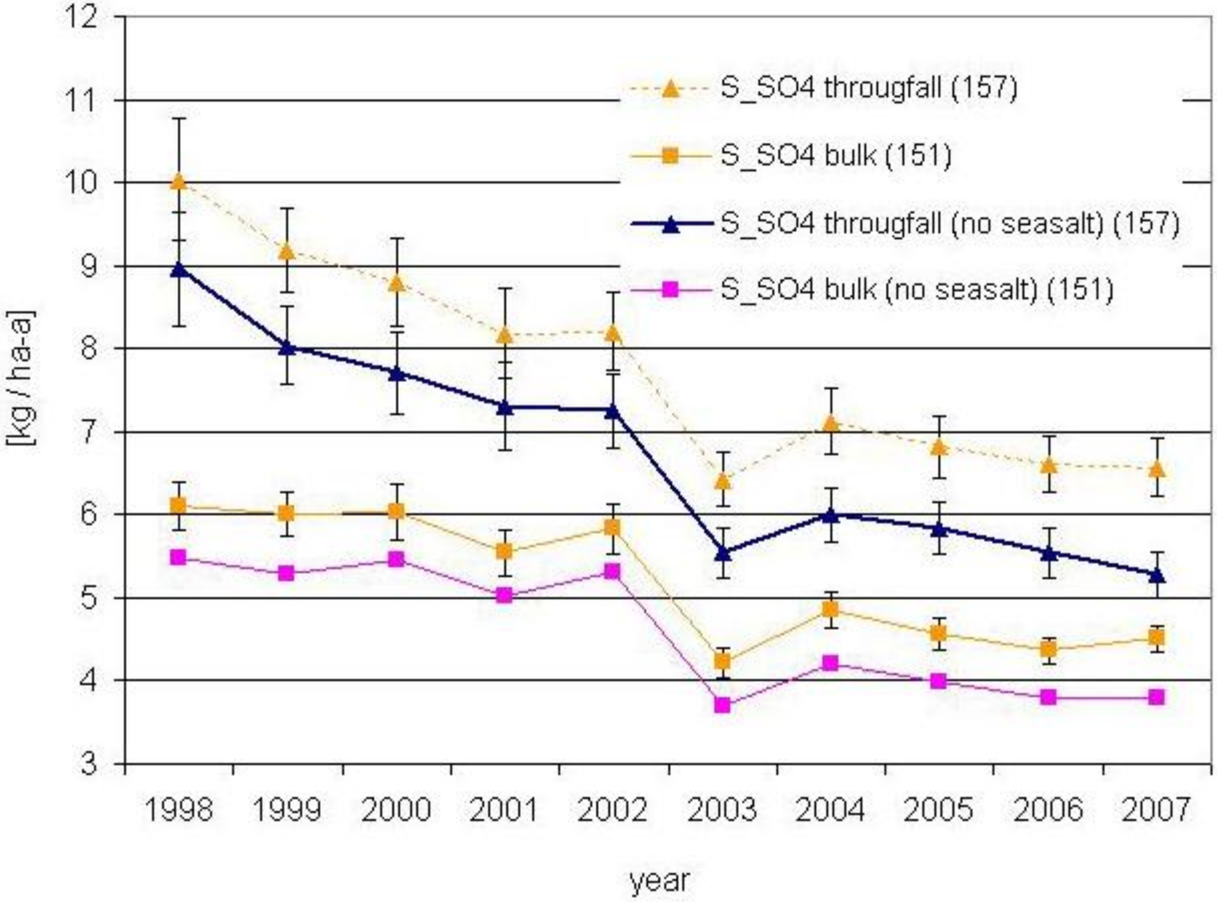
Nitrogen deposition 1998-2007 in Europe

See the lectures 5C, 5D (Document server UIS)



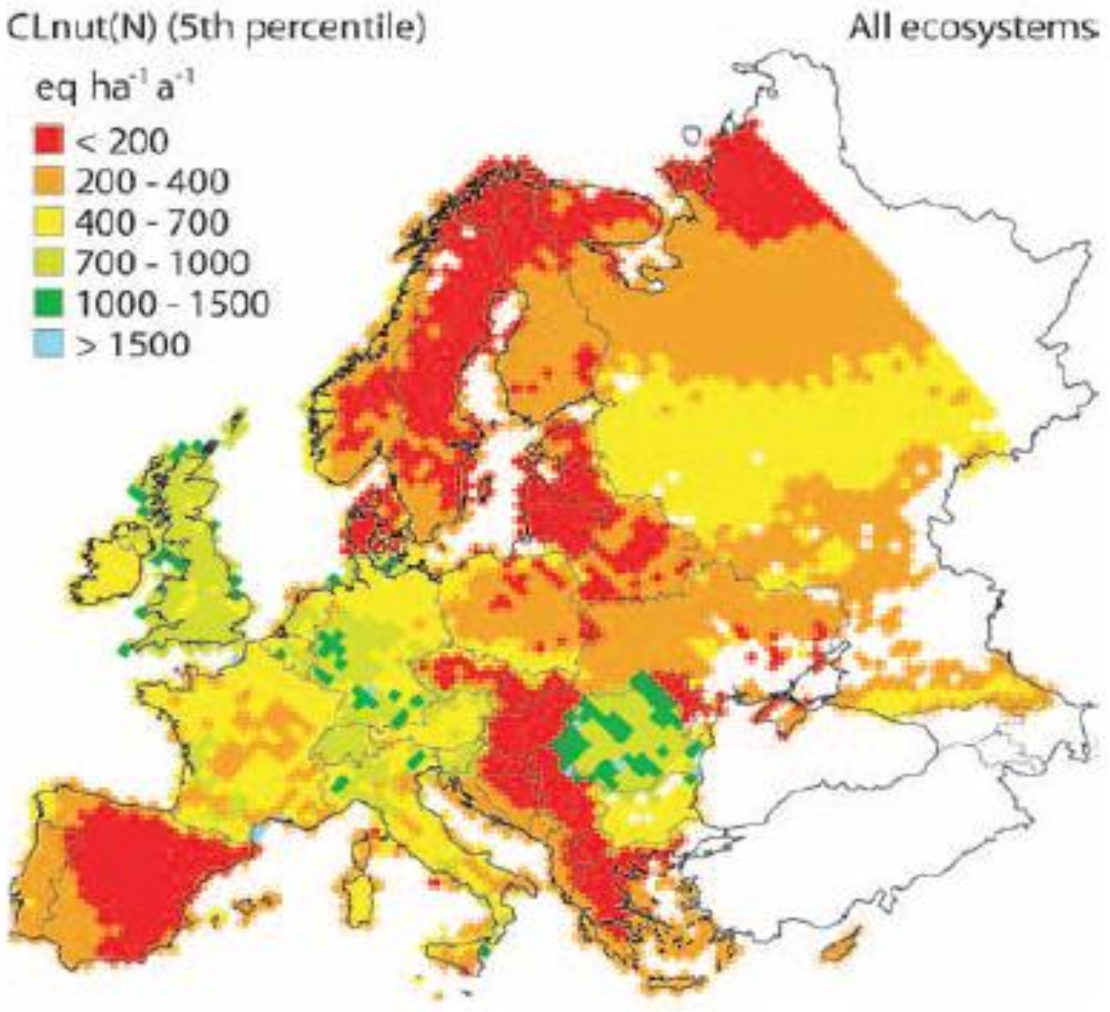
(FutMon 2011)

Mean annual sulphate deposition 1998-2007 in Europe



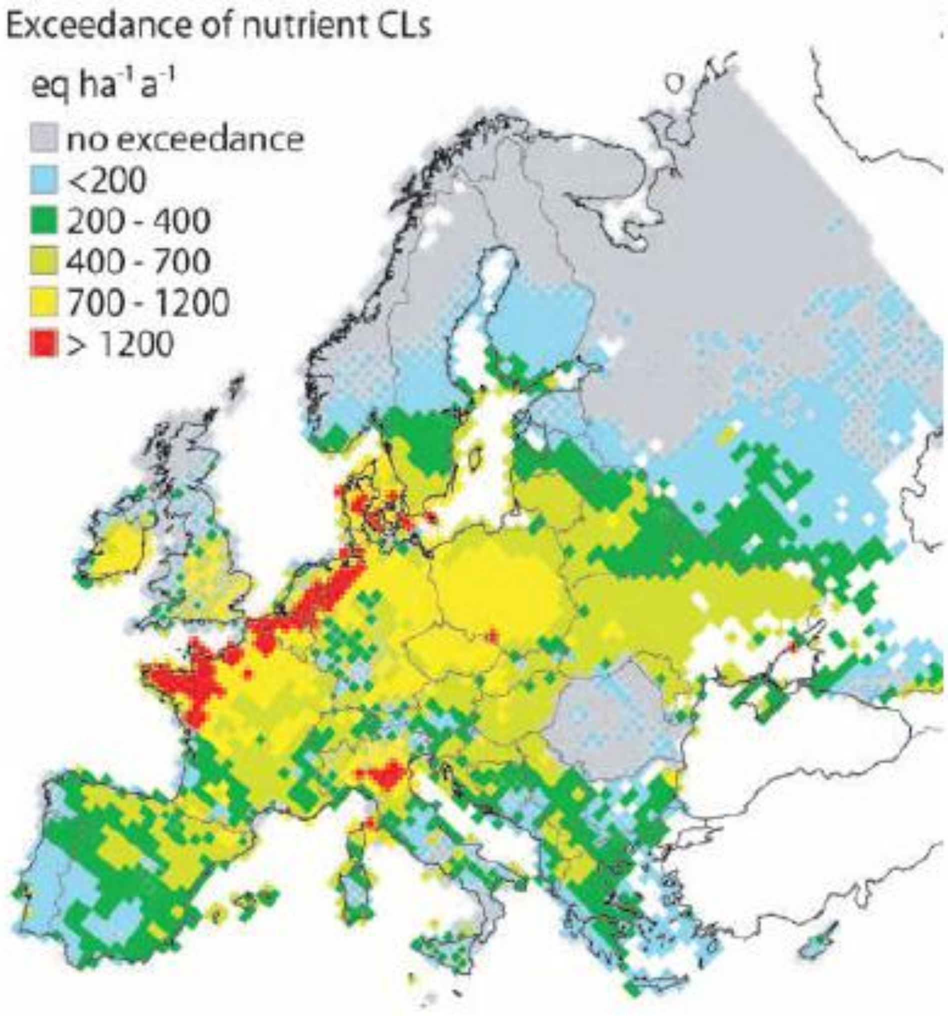
(FutMon 2011)

Acid Deposition and Critical Loads



Critical loads for nutrient nitrogen in Europe (ÅGREN 2009)

Exceedance of Critical Loads



Areas where the critical loads nitrogen were exceeded in 2000 (Ågren 2009)

Forest diabeck

Krušné hory Mts.

Krkonoše – National Park

Review questions

1. Main definition and principles of cycling of elements
2. Identifiy and describe the flow of nutrients in each biogeochemical cycle
4. N-cycle in forest ecosystems, main parts and evaluation
5. Cycling of other mineral elements, mineral nutrition
6. Acid deposition in forest ecosystems
7. Explain the impact that humans have on the biogeochemical cycles.

Literature

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Examples

Actual case studies in Europe

esf evropský sociální fond v ČR
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Ecological Studies 142

Ernst-Detlef Schulze (Ed.)

Carbon and Nitrogen Cycling in European Forest Ecosystems

Springer

with CD-ROM

Book: Carbon and Nitrogen Cycling … (Schulze et al. 2000) - http://books.google.cz/books?id=ku6QwSTDsvEC&printsec=frontcover&hl=cs&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false

1.3 The NIPHYS/CANIF Project

The present book is based on two projects of the European Community (NIPHYS: NItrogen PHYSiology of Forest Plants and Soils and CANIF: Carbon and Nitrogen Cycling in Forest Ecosystems) aimed at studying key processes of the C and N cycle in coniferous (*Picea abies*) and deciduous (*Fagus sylvatica*) forest ecosystems along a north-south transect through Europe. *Picea abies* and *Fagus sylvatica* dominate about 60% of the European forests (Stanners and Bourdeau 1995).

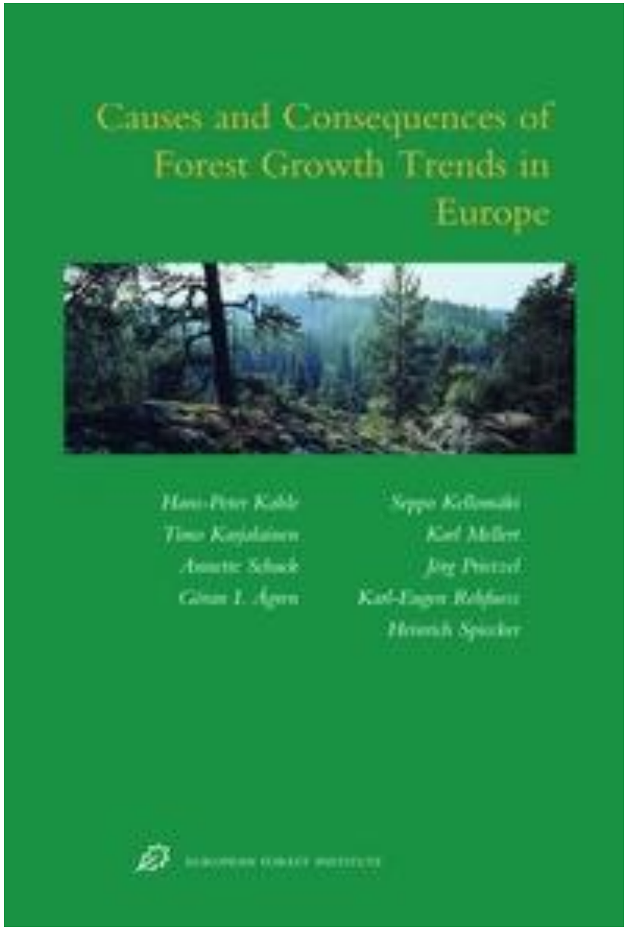
NIPHYS and CANIF were experimental investigations of the processes involved in the contribution of C and N to the overall biogeochemical cycles and of the functional significance of biodiversity in the biogeochemical cycles in forest ecosystems. Thus, CANIF is an investigation of the present effects of climate, and soil-borne and deposited N on C and N assimilation as well as on forest organism functioning along a climatic transect through Europe. The study was based on the idea that acid and N deposition has changed forest ecosystems dynamics in Central Europe (Schulze and Ulrich 1991), but it remained difficult to quantify these effects because all habitats and regions of central Europe are affected (Teller et al. 1992). Therefore, this study had the following major objectives:

1. To investigate effects of N deposition on ecosystem processes, particularly the C cycle, by extending the range of study to the northern and southern limit of spruce and beech forests where N deposition was reported by the European Environmental Agency to be lower (Fig. 1.3; Stanners and Bourdeau 1995). Since climate and N deposition changed over the geographic range of this study, the specific effects of N deposition were expected to become apparent by studying low deposition in the north and in the south. In order to separate effects of climate and N deposition, the attempt was made to maintain soil conditions as constant as possible by selecting acidic bedrock and soils for as many sites as possible. We hypothesised that a number of ecosystem parameters would reach a specific maximum or minimum in central Europe when compared with the south or the north. Thus, a main emphasis of this study was to identify the interactions between the forest C and N cycle and their effect on forests being C sources or sinks.
2. In contrast to studies of the biogeochemical cycles per se, it was the specific aim of this study to investigate the significance of soil organisms and their associated C and N transformations and C and N fluxes. There was an evident lack in knowledge to what extent soil organisms regulate the biogeochemical cycles and affect the soil conditions, and to what extent the decomposer community responds to the climatic and edaphic conditions. In this case, ecosystem processes may be maintained constant due to a compensatory effect of a change in the organism

assembly (Schulze 1984). The role of biodiversity would be to contain a reservoir of organisms that is able to maintain ecosystem function under conditions of variable climate and N deposition. It is important to know if soil organisms adjust to or change their environment and maintain their specific function in the process of element cycling. It also remains unclear if ecosystem processes depend on keystone species, a balance of many species or a variable minimum number of species, and what is the role of the heterogeneity in soil processes. We hypothesise that certain products (e.g. soil organic matter) would accumulate if the capacity for compensatory response of the soil biota were overstressed.

3. Given the fact that there are a number of nested cycles in the pathway of N through the ecosystem, it was unclear if certain thresholds exist, where one or the other pathway dominates in the transformation of N, and if such thresholds would relate to N deposition. If the decomposer chain was C-limited and delivers N, and C assimilation of plants was N-limited but delivers C for the decomposer community, then thresholds should occur under conditions of N deposition, such as the loss of nitrate to groundwater. We hypothesised that the soil solution chemistry and the output of dissolved organic C and N, as well as the loss of nitrate, would be indicators for such thresholds. However, before such interpretation is possible, a careful assessment of the pathway in the soil is necessary.

4. It is quite clear that soil processes determine NEP in a time-lapse manner (Melillo et al. 1996), i.e. pools of C and N compounds may serve as sources for CO_2 asynchronously to the plant production process. It is very difficult to decide if soils are C sinks or sources because their net balance is determined by litter inputs and by respiration, and both processes may not be in phase, resulting in SOM accumulation or losses. Since changes in C and N pools are difficult to quantify due to small fluxes and large pools in soils, this study intended to quantify the underlying processes and predict SOM turnover using a whole range of approaches. We hypothesised that a hierarchical approach of predictions (extrapolations) from the lower level of C transformations (bottom-up prediction) and verifications from whole ecosystem measurements (top-down verifications) would make it possible to quantify changes in SOM.



Causes and Consequences of
Forest Growth Trends in
Europe

Hans-Peter Kahle
Timo Karjalainen
Annette Schuck
Göran I. Ågren

Seppo Kellomäki
Karl Mellert
Jörg Prietzel
Karl-Eugen Rehfuess
Heinrich Spiecker

EUROPEAN FOREST INSTITUTE

Book: Causes and Consequences of Forest Growth Trends in Europe (Kahle et al. 2008)
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http://books.google.cz/books?id=gSFKtxtv1kEC&printsec=frontcover&dq=Causes+and+Consequences+of+Forest+Growth&hl=cs&sa=X&ei=avg_Ura7DojesgbnuICoAw&ved=0CDEQ6AEwAA#v=onepage&q=Causes%20and%20Consequences%20of%20Forest%20Growth&f=false

Forest growth in Europe has been increasing during the last decades. The possible causes suggested to explain this phenomenon have been elevated atmospheric carbon dioxide concentration, temperature and precipitation climate beneficial to tree growth, increasing nitrogen deposition and better management. In this book complementary approaches are adopted to discriminate between the levels of importance of these factors. Investigations over large geographical areas are used to separate current spatial variability while studies of the growth of individual trees allow time trends to be evaluated. Four different mechanistic forest ecosystem models supplement the empirical investigations.

This study gives empirical evidence for the prominent role of increasing nitrogen supply as the key driver of the observed forest site productivity increases. However, to which part increased nitrogen availability is driven by recovery of soil from former often devastative land use, and to which extent it is attributed to anthropogenically increased nitrogen deposition has not been unequivocally clarified. The process-based modelling gives clear evidence that nitrogen played the most important role for forest site productivity changes in the past, but in the future, climate change and especially CO_2 fertilization will be of increasing importance.

The Recognition project:

Together with 24 partners from across Europe, the European Forest Institute launched in April 1999 with financial support from the European Union the EC-FAIR project “Relationships Between Recent Changes of Growth and Nutrition of Norway Spruce, Scots Pine, and European Beech Forests in Europe – Recognition”.

The objectives of the research project were:

- to identify potential causes of recent growth trends in European forests;
- to investigate the relative importance of nutrients, climate, and land-use changes; and
- to analyse the long-term consequences and risks of observed changes for sustainability and to assess the implications for future forest management.

Main results achieved by the Historical Development Investigation:

- During recent decades most Scots pine stands in Central Europe showed significantly faster height growth as compared to previous decades.
- This increase was predominantly caused by improved nitrogen nutrition which is the combined result of a recovery of sites from former devastative land-use practices and anthropogenically increased atmospheric nitrogen deposition.
- Nitrogen nutrition played a prominent role on sites where nitrogen deposition was high. On the sites in Northern Europe and Great Britain, increased nitrogen supply was less important for long-term growth changes of Scots pine stands than in Central Europe.
- Precipitation and thus water availability are key factors for the short-term fluctuations of growth, but not for the long-term growth trends.
- No significant direct effect of changes in air temperature on growth changes of Scots pine and Norway spruce stands could be detected.
- It is likely that increased atmospheric CO_2 concentration has only been of secondary importance for the tree growth changes in the past.

Main results achieved by the Present State Analysis:

- During the period 1960–2000 average annual height growth increased by +23% for spruce, and by +25% both for pine and beech.
- During the first 50 years of their lifetime the average annual diameter growth of trees with germination dates in the 1940s and 1950s was on average increased by +16 % for spruce, +13 % for pine, and +27 % for beech as compared to trees which started to grow between 1900 and the 1920s. This indicates that the stand management adapted to the growth increases through earlier and more frequent and/or intensive thinnings.
- Based on species specific functional relations between stand height and total wood volume production potential validated for German conditions the observed changes in height growth gave rise to increases in total wood volume production over the period 1960–2000 of +56 % for spruce, +45 % for pine, and +74 % for beech, which is equivalent to average annual productivity increases of +1.4 %, +1.1 %, and + 1.8 % for spruce, pine and beech respectively.
- Pine and beech sample trees with high foliar nitrogen nutrition at the end of the observation period showed a significantly lager increase in height growth than those with low nitrogen nutrition.
- Pine and beech sample trees from sites with low initial site fertility showed a significantly larger increase in height growth than those from sites with high initial site fertility.
- Confounding of the analysed causative factors (i) change in seasonal air temperature, (ii) change in seasonal precipitation, and (iii) level of foliar nitrogen nutrition complicated identification of the independent effects these variables have on growth change.

Main results achieved by the mechanistic modelling approach:

- All four process-based models identified increasing nitrogen supply as the major cause of observed changes in European forest growth during the 20th century. This finding is mainly the result of the large increase in nitrogen deposition rates during that period.
- The process-based model simulations showed that the relative importance of the different changing environmental factors might change over time: Further changes in forest growth (i.e. in the simulation time-periods 1960–2040 and 2000–2080) are more likely to be caused by increasing atmospheric CO_2 concentration and, especially in northern latitudes, by increasing temperature.
- In the model simulations, the effects of the environmental factors air temperature, moisture availability, availability of nitrogen and CO_2 were largely additive.
- Uncertainties regarding the response of nitrogen uptake and nitrogen use efficiency to environmental change evident in diverging model results need to be resolved in experiments and models.

Implications and consequences of the growth changes for sustainability of European forests:

- There are no indications from the project, at least in the short term, that the growth changes themselves represent any major threat to the sustainability of the forest ecosystems, and their provision of services. In a longer time perspective, the situation might be different and increased water stress and deficiencies of nutrients other than nitrogen might occur.
- Increased growth and accumulating wood volume in the forests indicate that if the structure of the forests should be maintained, changes in the intensity of management practices, e.g. more frequent and/or intensive thinnings, are needed. This also refers to ensuring the stability of the stands, e.g. with respect to storm.
- The model simulations indicate that the time for timber production can be shortened; a finding which especially refers to Central Europe where increases in forest site productivity have been largest during recent decades, whereas in the future tree growth and consequent profitability of forestry may increase most in Northern Europe.
- Sustainable forest management in the future may require more attention to the nutritional budget of forest ecosystems. The Pan-European EC-UN/ECE Programme for Intensive and Continuous Monitoring of Forest Ecosystems is one of the tools that can provide early-warning signals if large-scale changes in European forests are occurring.