Nutrient Cycling in Land Vegetation and Soils

OCN 401 - Biogeochemical Systems

14 September 2017

Reading: Schlesinger & Bernhardt, Chapter 6

Outline

1. The annual Intrasystem Nutrient Cycle
2. Mass balance of the Intrasystem Nutrient Cycle
3. Nutrient-use efficiency
4. Microbial cycling in soils
5. Organic matter in soils

Annual Intrasystem Nutrient Cycle

- Although leaves and fine roots (short-lived tissue) are a small fraction of total plant biomass, they receive the vast majority of annual nutrient uptake
- New foliage has high concs of N, P and K – these decrease with time due to the accumulation of carbohydrates and cellulose during the growing season
- Nutrient concentrations in mature foliage is related to the rate of *photosynthesis* and *plant growth*, and (consequently) the *soil fertility*
- However, rainfall can leach nutrients from leaf surfaces -- this is especially true for K, which is highly water soluble
- Leaching rates generally increase as foliage *senesces* before *abscission.* Losses due to leaching follow the order:

  K >> P > N > Ca

- *Throughfall* - Rainfall that passes through a vegetation canopy
- *Stemflow* - Water that travels down the surface of stems and the trunk
  - Stemflow, although generally smaller than throughfall, is significant because it returns highly concentrated nutrient solutions to the soil at the base of the plant
- At the end of the growing season, nutrients are withdrawn (*reabsorbed*) from the leaves for reuse during the next year -- this is typically around 50% of the leaf N and P content
- *Litterfall* - Dead plant material (*e.g.*, leaves, bark, needles, twigs) that has fallen to the ground
  - Dominant pathway for nutrient return to the soil, especially for N and P

C/N ratio of plant litterfall:

- Varies by a factor of ~4 across environments
- Inversely related to the nutrient availability of the site

Low-nutrient environments:

- Plants tend to have low nutrient concs in mature leaves
- Generally reabsorb a larger *proportion* of nutrients in senescent leaves (compared to nutrient-rich environments)
- High *nutrient-use efficiency*

Nutrient-rich environments:

- Associated with high *productivity* and abundant *nutrient circulation* (next slide)
- Low nutrient-use efficiency

Mass Balance of the Intrasystem Cycle

Annual circulation of nutrients can be modeled using the mass-balance approach (assumes steady-state):

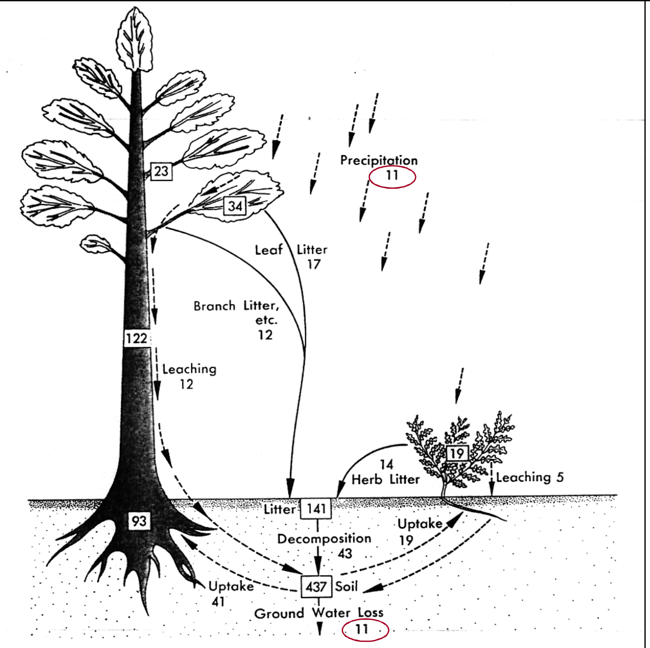

Figure 6.7 The intrasystem cycle for Ca in a forest ecosystem in Great Britain. Pools are shown in kg/ha and annual flux in kg ha^{-1} yr^{-1}. From Whittaker (1970).

A plant's annual nutrient *requirement* is equal to the peak nutrient content in *newly* produced tissue during the growing season:

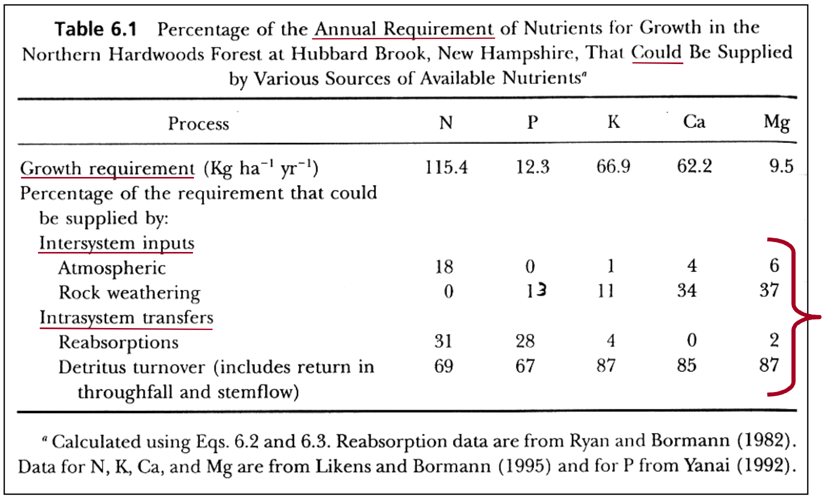

Table 6.1 Percentage of the Annual Requirement of Nutrients for Growth in the Northern Hardwoods Forest at Hubbard Brook, New Hampshire, That Could Be Supplied by Various Sources of Available Nutrients[a]

Process	N	P	K	Ca	Mg
Growth requirement (Kg ha^{-1} yr^{-1})	115.4	12.3	66.9	62.2	9.5
Percentage of the requirement that could be supplied by:					
Intersystem inputs					
Atmospheric	18	0	1	4	6
Rock weathering	0	13	11	34	37
Intrasystem transfers					
Reabsorptions	31	28	4	0	2
Detritus turnover (includes return in throughfall and stemflow)	69	67	87	85	87

[a] Calculated using Eqs. 6.2 and 6.3. Reabsorption data are from Ryan and Bormann (1982). Data for N, K, Ca, and Mg are from Likens and Bormann (1995) and for P from Yanai (1992).

These add to >100% because they are potential rates

What about Annual Budgets if you can't make the Steady-State Assumption?

- Nutrient *uptake* from soil cannot be measured directly
- But uptake must equal the increase in nutrients in perennial tissue (*e.g.*, stem wood) plus the loss of nutrient due to litterfall and leaching:

Uptake = Retained by plant + Returned to soil

- A plant's annual nutrient *requirement* is equal to uptake plus the amount reabsorbed during the previous autumn:

Requirement = Uptake + Reabsorption

Example: California shrubland system →

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Uptake = Retained + Returned

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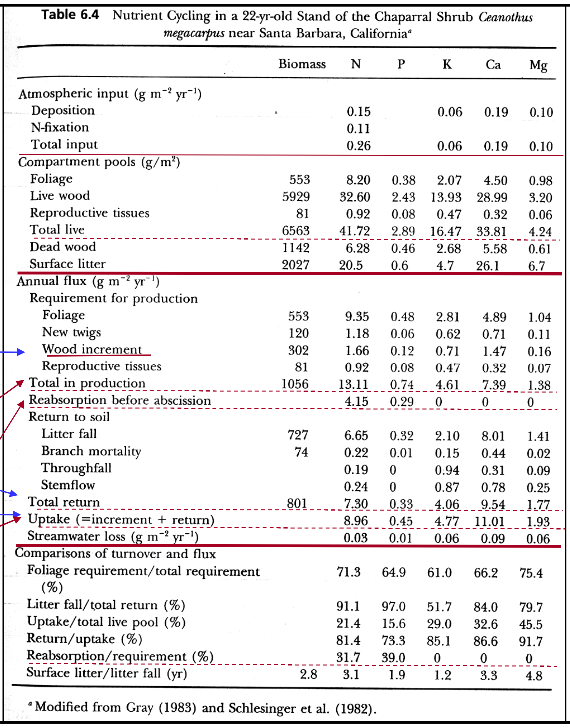
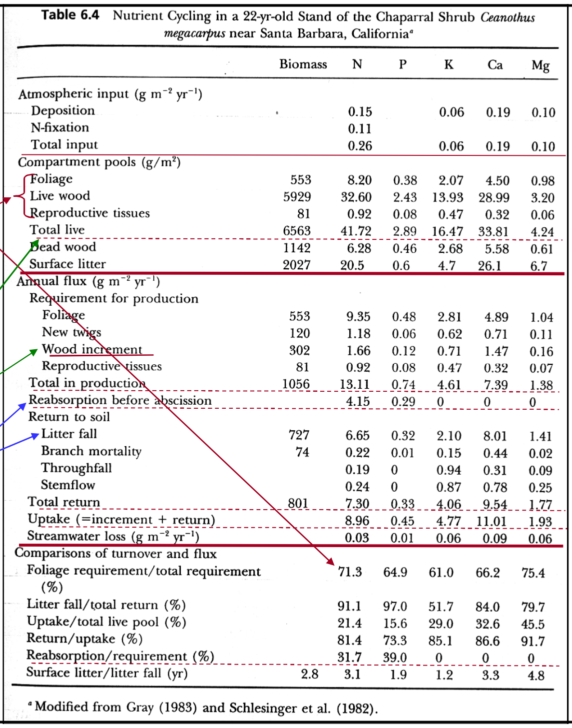


Table 6.4 Nutrient Cycling in a 22-yr-old Stand of the Chaparral Shrub *Ceanothus megacarpus* near Santa Barbara, California[a]

	Biomass	N	P	K	Ca	Mg
Atmospheric input (g m^{-2} yr^{-1})						
Deposition		0.15		0.06	0.19	0.10
N-fixation		0.11				
Total input		0.26		0.06	0.19	0.10
Compartment pools (g/m^2)						
Foliage	553	8.20	0.38	2.07	4.50	0.98
Live wood	5929	32.60	2.43	13.93	28.99	3.20
Reproductive tissues	81	0.92	0.08	0.47	0.32	0.06
Total live	6563	41.72	2.89	16.47	33.81	4.24
Dead wood	1142	6.28	0.46	2.68	5.58	0.61
Surface litter	2027	20.5	0.6	4.7	26.1	6.7
Annual flux (g m^{-2} yr^{-1})						
Requirement for production						
Foliage	553	9.35	0.48	2.81	4.89	1.04
New twigs	120	1.18	0.06	0.62	0.71	0.11
Wood increment	302	1.66	0.12	0.71	1.47	0.16
Reproductive tissues	81	0.92	0.08	0.47	0.32	0.07
Total in production	1056	13.11	0.74	4.61	7.39	1.38
Reabsorption before abscission		4.15	0.29	0	0	0
Return to soil						
Litter fall	727	6.65	0.32	2.10	8.01	1.41
Branch mortality	74	0.22	0.01	0.15	0.44	0.02
Throughfall		0.19	0	0.94	0.31	0.09
Stemflow		0.24	0	0.87	0.78	0.25
Total return	801	7.30	0.33	4.06	9.54	1.77
Uptake (=increment + return)		8.96	0.45	4.77	11.01	1.93
Streamwater loss (g m^{-2} yr^{-1})		0.03	0.01	0.06	0.09	0.06
Comparisons of turnover and flux						
Foliage requirement/total requirement (%)		71.3	64.9	61.0	66.2	75.4
Litter fall/total return (%)		91.1	97.0	51.7	84.0	79.7
Uptake/total live pool (%)		21.4	15.6	29.0	32.6	45.5
Return/uptake (%)		81.4	73.3	85.1	86.6	91.7
Reabsorption/requirement (%)		31.7	39.0	0	0	0
Surface litter/litter fall (yr)	2.8	3.1	1.9	1.2	3.3	4.8

[a] Modified from Gray (1983) and Schlesinger et al. (1982).

- 71% of annual N requirement is allocated to foliage, whereas much less is allocated to stem wood (the remainder). Nevertheless, total nutrient storage in short-lived tissue is small compared to storage in wood (the latter reflects 22 years of accumulation).
- For most nutrients, the storage in wood increases ~5% / year
- Despite substantial reabsorption of N and P, litterfall is the dominant pathway of reusing nutrients
  - Note: Table does not accurately reflect belowground transfers!



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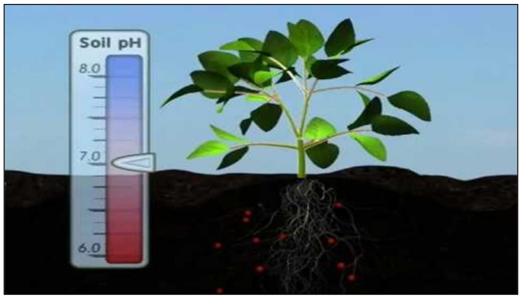
- Nutrients tend to accumulate most rapidly during the early development of a woody plant (due to the greater percentage of leaf biomass), then slow to a steady state value

- Thus C/N and C/P ratios for the whole-plant biomass increase with time as the vegetation becomes increasingly dominated by structural biomass

And now for a short commercial announcement….

Plant Nutrition: Mineral Absorption

https://www.youtube.com/watch?v=6aC-WTAWgOg



Nutrient-Use Efficiency

- Mass balance allow us to calculate *nutrient-use efficiency*:
  - *NUE = NPP / nutrient uptake*
- Nutrient-use efficiency reflects factors such as:
  - Rate of photosyn per leaf nutrient supply rate
  - Uptake per root growth rate (Fig. 6.2)
  - Leaching rate
  - Reabsorption rate
- In temperate systems, nutrient-use efficiency in coniferous forest is greater than in deciduous forests -- due to conifers having:
  - Lower nutrient circulation (mostly due to lower leaf turnover)
  - Lower leaching losses
  - Greater photosynthesis per unit of leaf N
- May explain the dominance of conifers in low-nutrient environments and in boreal climates (where soil nutrient turnover is low)

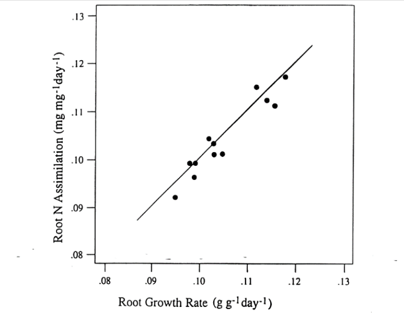


Figure 6.2 The rate of N uptake in tobacco as a function of the relative growth rate of roots. From Raper et al. (1978).

However, the effects of temperature and rainfall are the primary determinants of NPP rates:

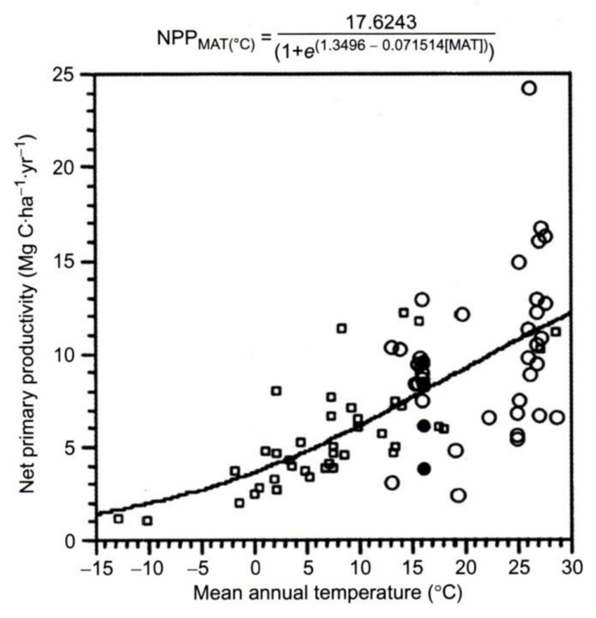


Figure 5.13 NPP in world forests vs. mean annual temperature

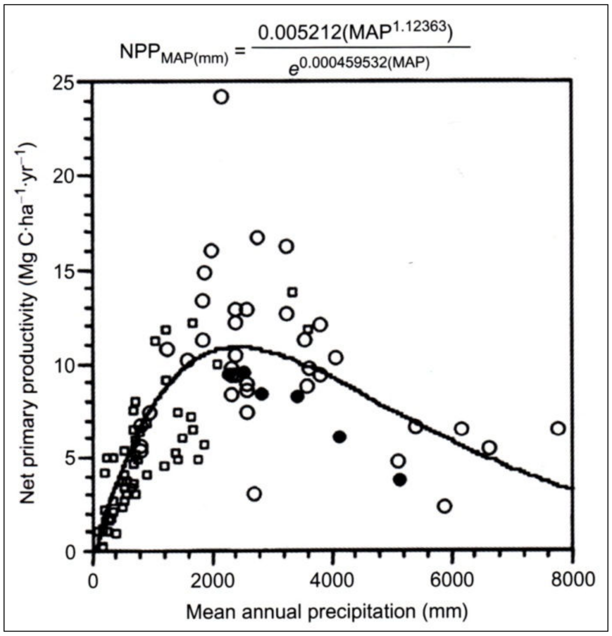
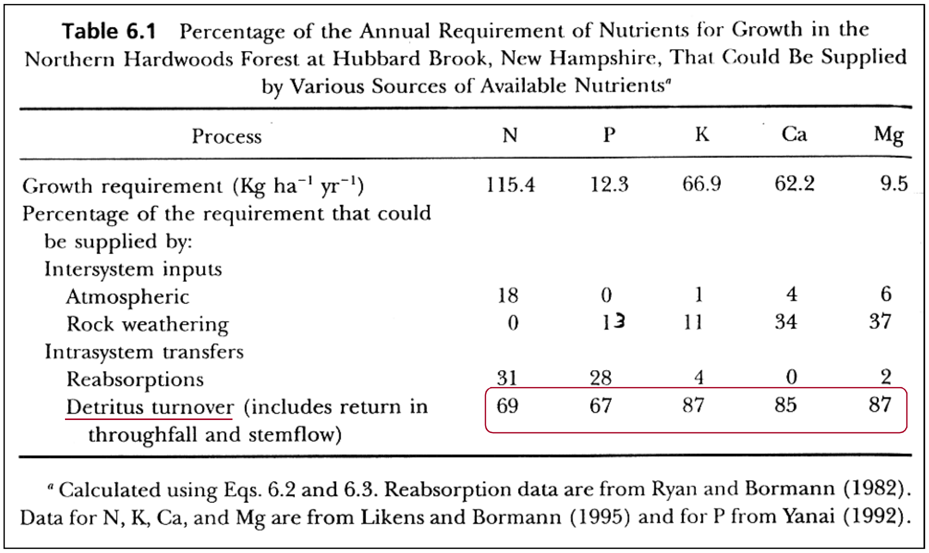


Figure 5.14 NPP in world forests vs. mean annual precipitation

Microbial Cycling in Soils

Most of the land plant nutrients come from decomposition of dead material in the soil:



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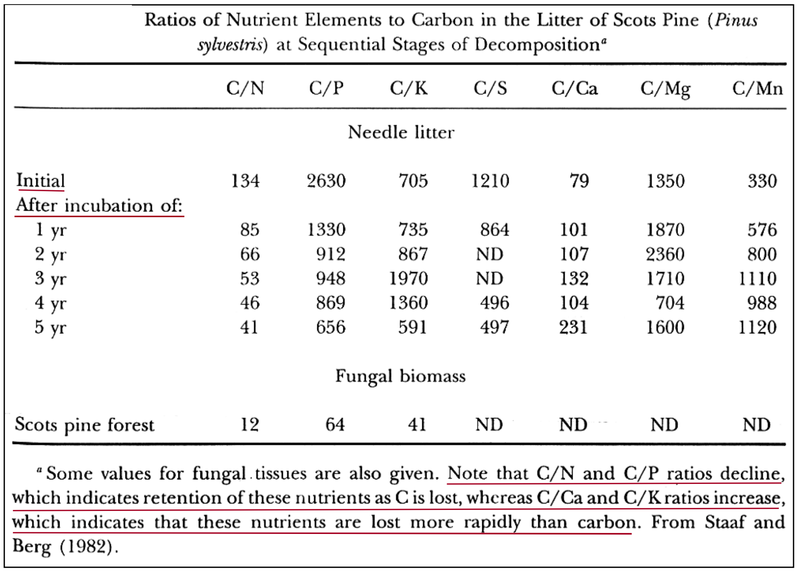
- Decomposition includes *remineralization*, the process that releases CO_2 and inorganic nutrients (*e.g.*, N as NH_4^+ or NO_3^-)
  - Mainly performed by bacteria and fungi via extracellular enzymes, although larger organisms (*e.g.*, earthworms) fragment and mix fresh litterfall
- Microbial biomass typically composes <3% of the soil organic matter (OM) -- higher levels are found in forest soils, and lower levels in deserts
- Accumulation of nutrients into the solid-phase of soil is known as *immobilization* -- most important for N and P
- Immobilization is due to:
  - Accumulation of nutrients into soil microbes (see Fig. 6.9)
  - Chemical adsorption onto mineral surfaces (esp. important for P)
  - Chemical precipitation of solid minerals

The effect of immobilization is displayed in litterbag experiments:



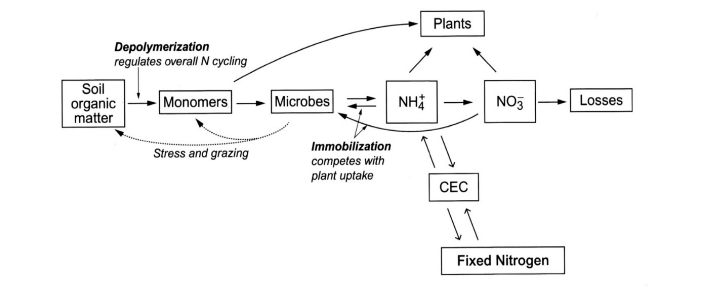
Ratios of Nutrient Elements to Carbon in the Litter of Scots Pine (*Pinus sylvestris*) at Sequential Stages of Decomposition[a]

	C/N	C/P	C/K	C/S	C/Ca	C/Mg	C/Mn
Needle litter							
Initial	134	2630	705	1210	79	1350	330
After incubation of:							
1 yr	85	1330	735	864	101	1870	576
2 yr	66	912	867	ND	107	2360	800
3 yr	53	948	1970	ND	132	1710	1110
4 yr	46	869	1360	496	104	704	988
5 yr	41	656	591	497	231	1600	1120
Fungal biomass							
Scots pine forest	12	64	41	ND	ND	ND	ND

[a] Some values for fungal tissues are also given. Note that C/N and C/P ratios decline, which indicates retention of these nutrients as C is lost, whereas C/Ca and C/K ratios increase, which indicates that these nutrients are lost more rapidly than carbon. From Staaf and Berg (1982).

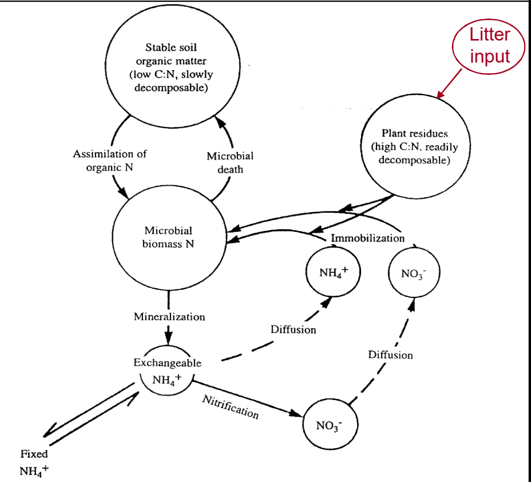
Decomposition also leads to formation of *fulvic* and *humic* compounds with high N content and high stability -- called *geopolymers* because they are random compounds formed abiotically

Models of N Cycling in Soils



A conceptual model for the soil nitrogen cycle. *Source: Modified from Schimel and Bennett (2004)*

CEC = Cation Exchange Capacity of soil particles



A conceptual model of the soil nitrogen cycle. From Drury et al. (1991).

Release rates from soil OM differ for different nutrients (some faster, others slower):

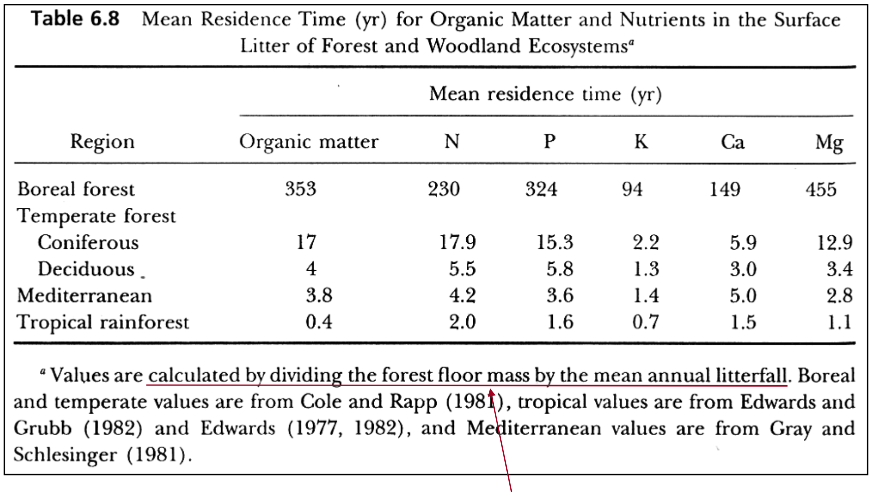


Table 6.8 Mean Residence Time (yr) for Organic Matter and Nutrients in the Surface Litter of Forest and Woodland Ecosystems[a]

	Mean residence time (yr)					
Region	Organic matter	N	P	K	Ca	Mg
Boreal forest	353	230	324	94	149	455
Temperate forest						
Coniferous	17	17.9	15.3	2.2	5.9	12.9
Deciduous	4	5.5	5.8	1.3	3.0	3.4
Mediterranean	3.8	4.2	3.6	1.4	5.0	2.8
Tropical rainforest	0.4	2.0	1.6	0.7	1.5	1.1

[a] Values are calculated by dividing the forest floor mass by the mean annual litterfall. Boreal and temperate values are from Cole and Rapp (1981), tropical values are from Edwards and Grubb (1982) and Edwards (1977, 1982), and Mediterranean values are from Gray and Schlesinger (1981).

litter

Turnover

Slow

Fast

Organic Matter in Soils

- In most ecosystems, the pool of soil organic matter greatly exceeds the mass of live biomass
- Typically, less than 5% of soils is composed of organic matter -- the organic matter content of some agricultural soil is <1%
- *Humus*: Soil organic matter which has reached a point of stability
- Because of its high nutrient content, the humus fraction dominates the storage of biogeochemically elements in most systems

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Soil organic matter provides numerous ecosystem services:

- Provides carbon, nitrogen, and energy for soil bacteria and fungi
- Supplies nutrients for plants
- Acts as a “glue” to bind soil particles together to stabilize soils
- Serves as a reservoir for plant nutrients
- Serves as a sink for CO_2, thus reducing greenhouse gases
- Contributes to high soil biodiversity
- Binds pesticides and heavy metals, thus reducing water pollution
- Enhances water- and nutrient-holding capacity of soils, thus improving plant productivity

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Several factors affect the amount of soil organic matter, including:

- Climate – the rate of decomposition doubles for every 8-9ºC increase in mean annual temperature
- Soil type – clay soils retain more organic matter than sandy soils
- Vegetation – the more vegetation and litter produced, the more organic matter in the soil; also, high C:N ratios of vegetation slow down decomposition
- Topography – organic matter can accumulate in soils with poor drainage
- Tillage – tilling soil causes a decrease in organic matter by facilitating its decomposition

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Next class:

“Cycling and Biogeochemical Transformations of N, P and S”

We will look in more detail at the

microbial and geochemical transformations involved in

N, P and S cycles