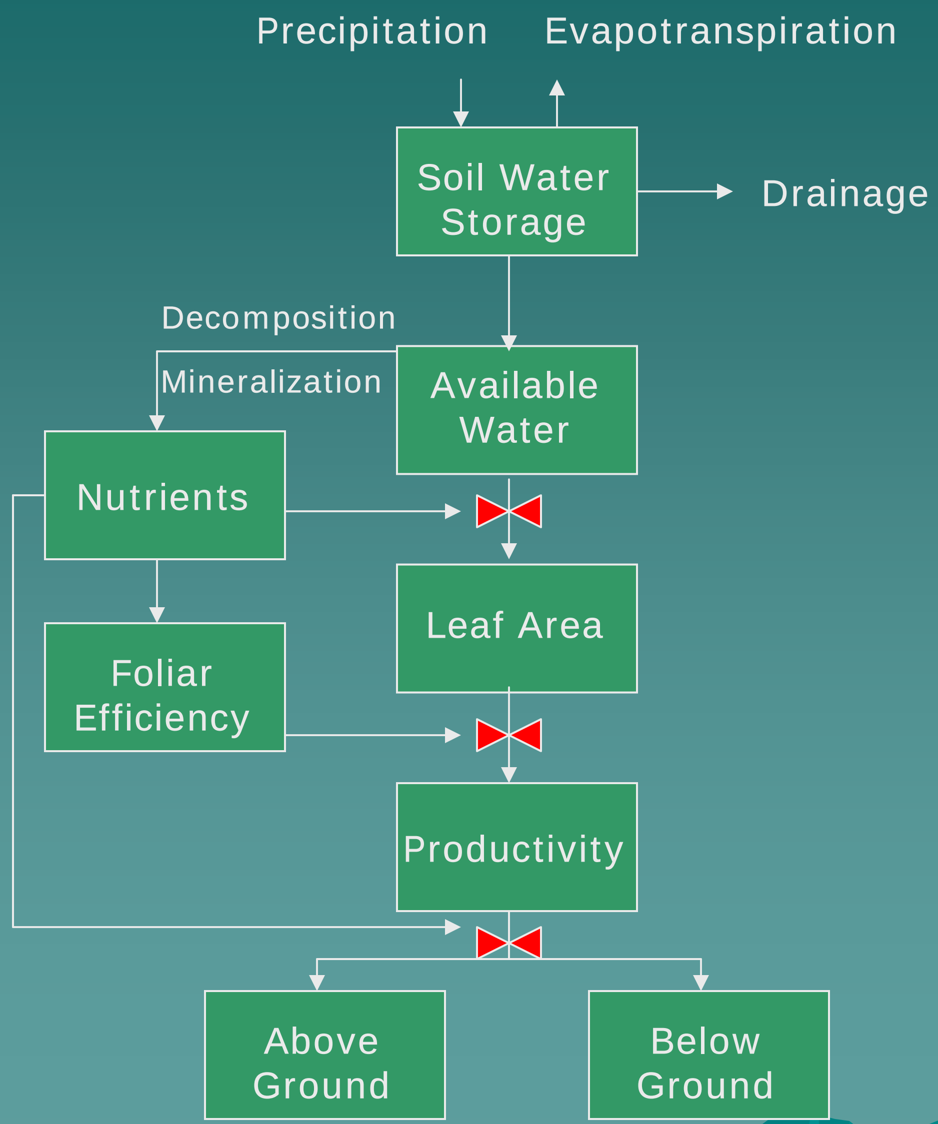
Fundamentals of Tree Nutrition

Paul Anderson
USDA Forest Service
PNW Research Station

Foliage, Production and the Availability of Water and Nutrients



Grier (1990)
Long et al. (2004)

Fundamentals of Tree Nutrition

- What is a nutrient?
- What are the essential nutrients elements?
- What are the mechanisms by which they are available?
- How are nutrients taken up by trees?
- What is the distribution of nutrients within trees?
- How do they influence growth and vigor?

What is a Nutrient?

- Any element or compound contributing to an organisms metabolism, growth, or other functioning

- *Essential nutrients* are those that can not be synthesized by the organism and therefore must be obtained from an external source

Macronutrients: >1000 ppm

Name	Symbol	Common Ionic Forms	Key Roles in Plants
Carbon	C	HCO_3^-	**Biomolecules**
Hydrogen	H	H^+	**Biomolecules**
Oxygen	O	O^{-2}	**Biomolecules, Respiration**
Phosphorus	P	PO_4^{-3}	**Bioenergetics – ATP**
Potassium	K	K^+	**Stomatal Aperture**
Nitrogen	N	NO_3^- NH_4^+	**Proteins, Amino Acids, DNA**
Sulfur	S	S^-	**Proteins, Amino Acids**
Calcium	Ca	Ca^{+2}	**Cell Walls, Regulation**
Magnesium	Mg	Mg^{+2}	**Pigmentation, Enzyme Cofactor**

Micronutrients: <1000 ppm

Name	Symbol	Common Forms	Key Roles in Plants
Iron	Fe	Fe(III)	**Enzyme Cofactor - Photosynthesis**
Molybdenum	Mo	MoO_2^{-4}	**Enzyme Cofactor – Amino Acid Synthesis**
Boron	B	$B(OH)_3$	**Sugar Transport, Cell Division, Enzyme Synthesis**
Copper	Cu	Cu^{+2}	**Photosynthesis**
Manganese	Mn	Mn^{+2}	**Chloroplasts**
Zinc	Zn	Zn^{+2}	**Enzyme Cofactor – Protein Synthesis**
Chlorine	Cl	Cl^-	**Photosynthesis**

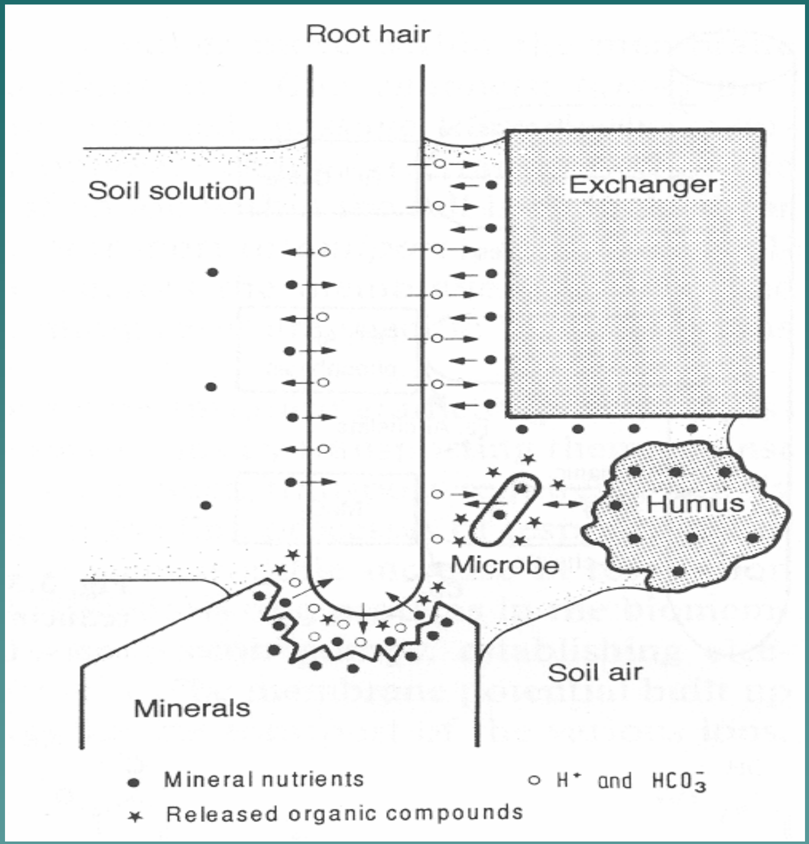
Mechanisms of Nutrient Supply to Roots

- Growth of roots into the soil to intercept exchangeable nutrients
- Mass flow of ions with the movement of soil water as a result of transpiration
- Diffusion of ions toward the root surface when uptake rate exceeds supply

Mechanisms of Nutrient Supply to Roots

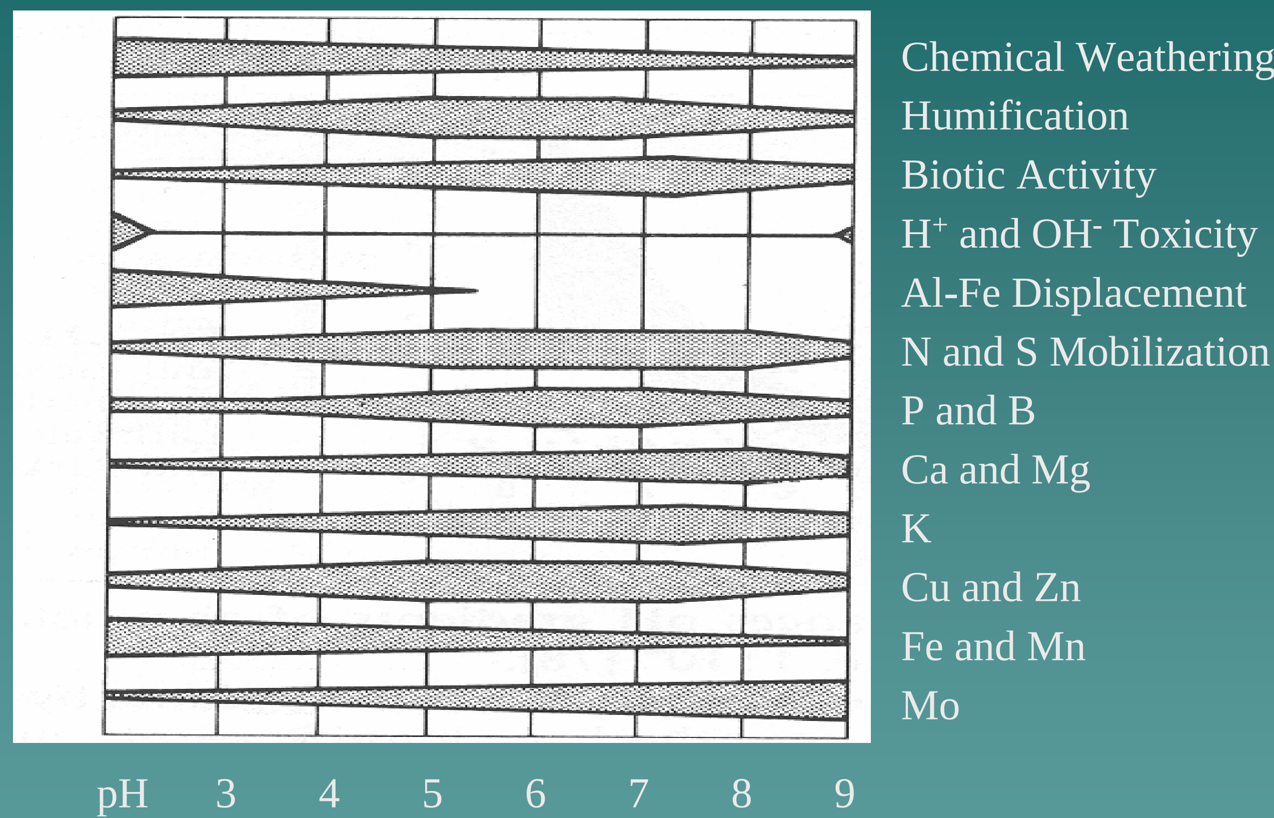
- Predominant mechanism depends on the relative mobility of the nutrient in question:
  - Growth interception important for Ca
  - Mass flow important for Mg, SO_4^- and Fe
  - Diffusion important when demand exceeds mass flow delivery
    - Often the case for N, P, and K
    - Relative to K^+, NH_4^+, and NO_3^-, Phosphate ion particularly immobile and diffusion rate strongly limits availability

Uptake of Mineral Nutrients from Soil

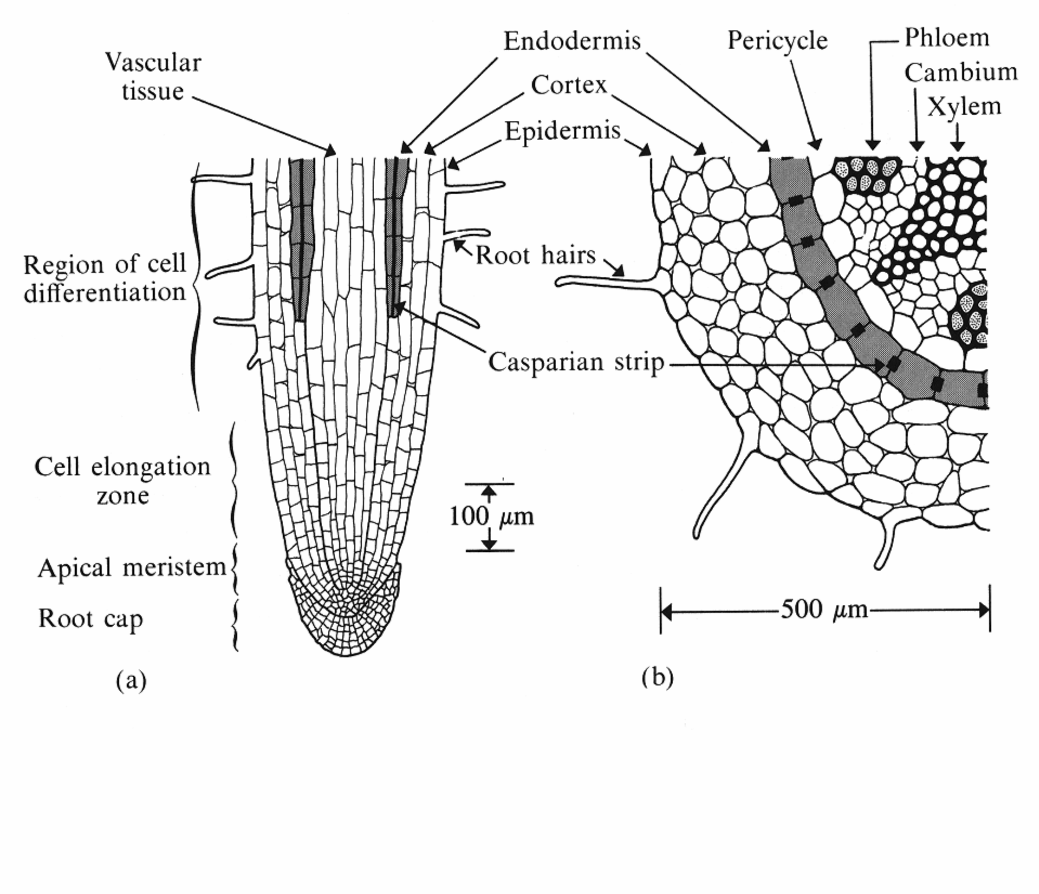


1. **Exchange absorption of adsorbed nutrient ions**
2. **Absorption from the nutrient solution**
3. **Mobilization of chemically bound nutrients**

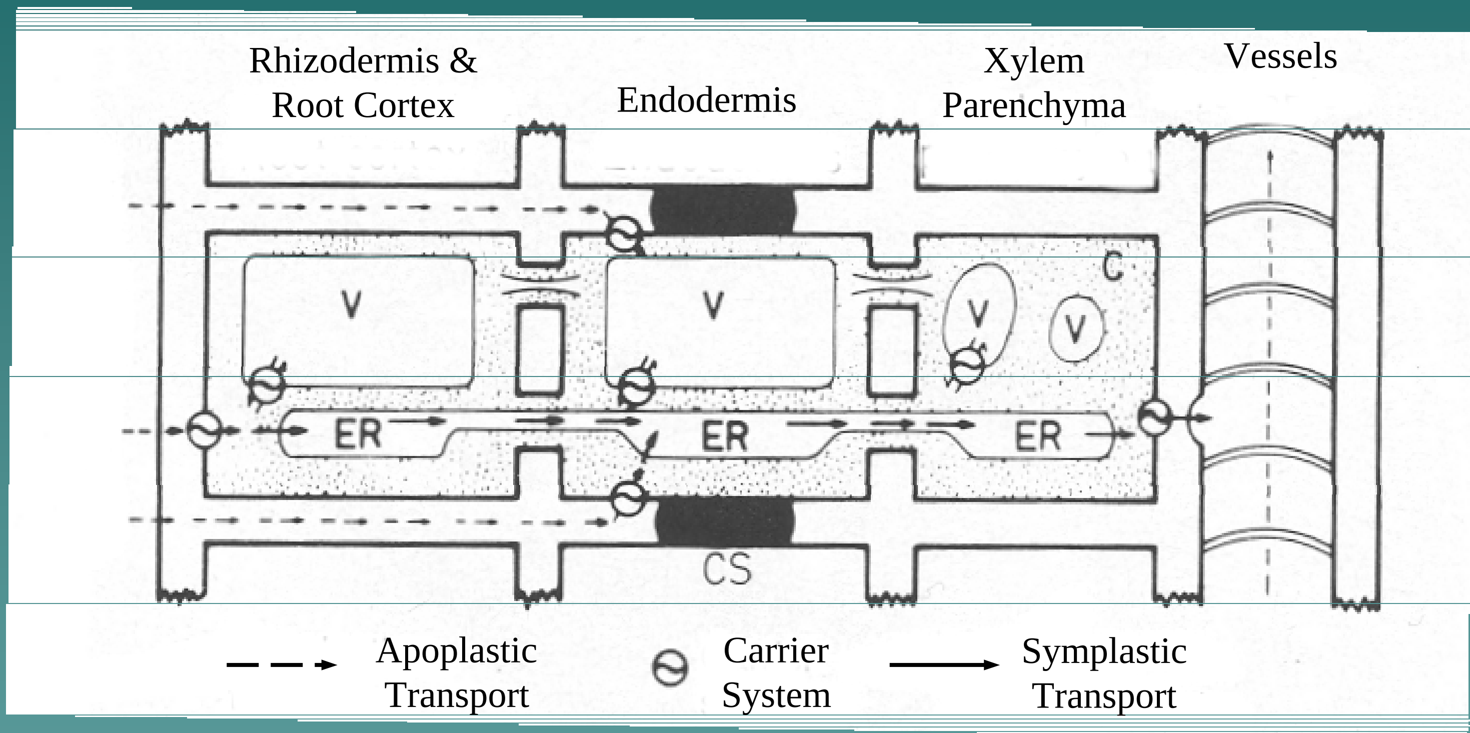
Influence of pH on Soil Formation, Nutrient Mobilization and Availability



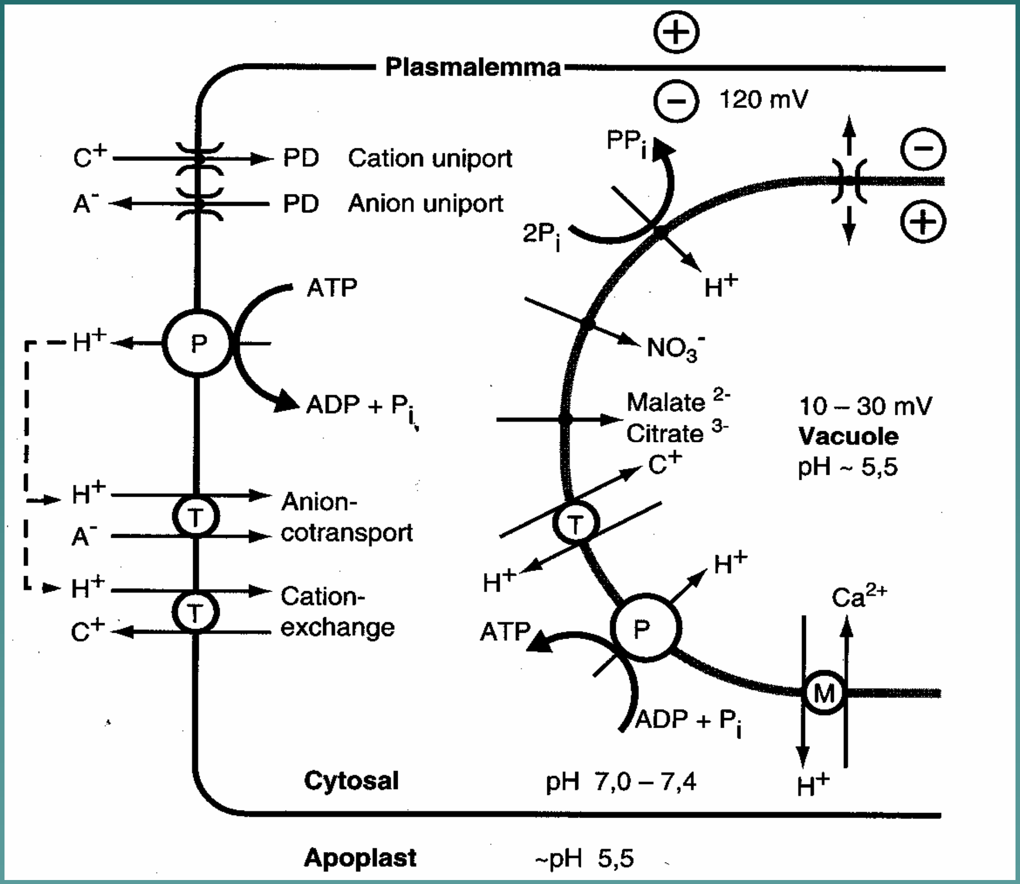
Primary Root Anatomy



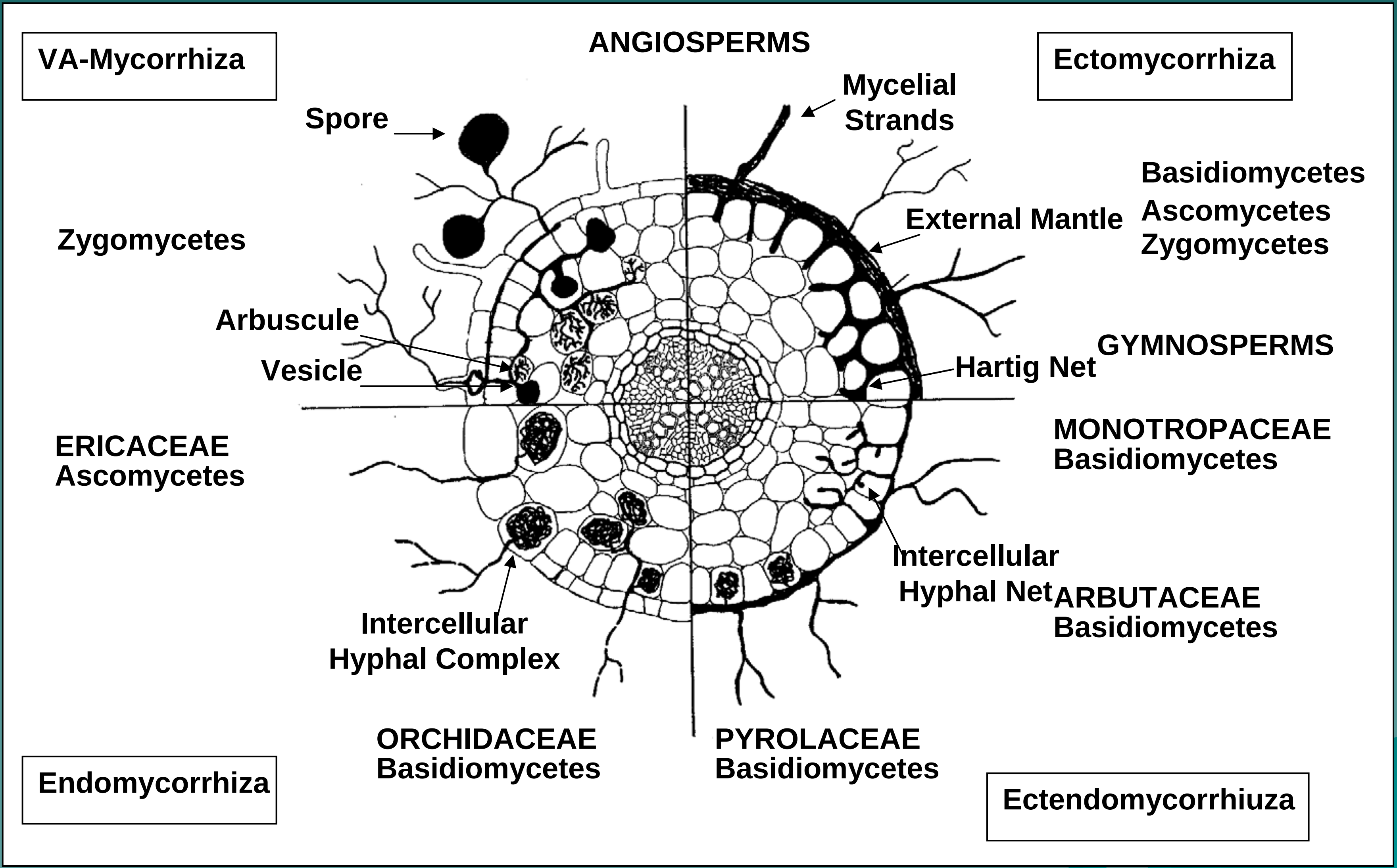
Transport of Ions in Roots



Mechanisms of Ion Transport Across Cellular Membranes



Mycorrhizae



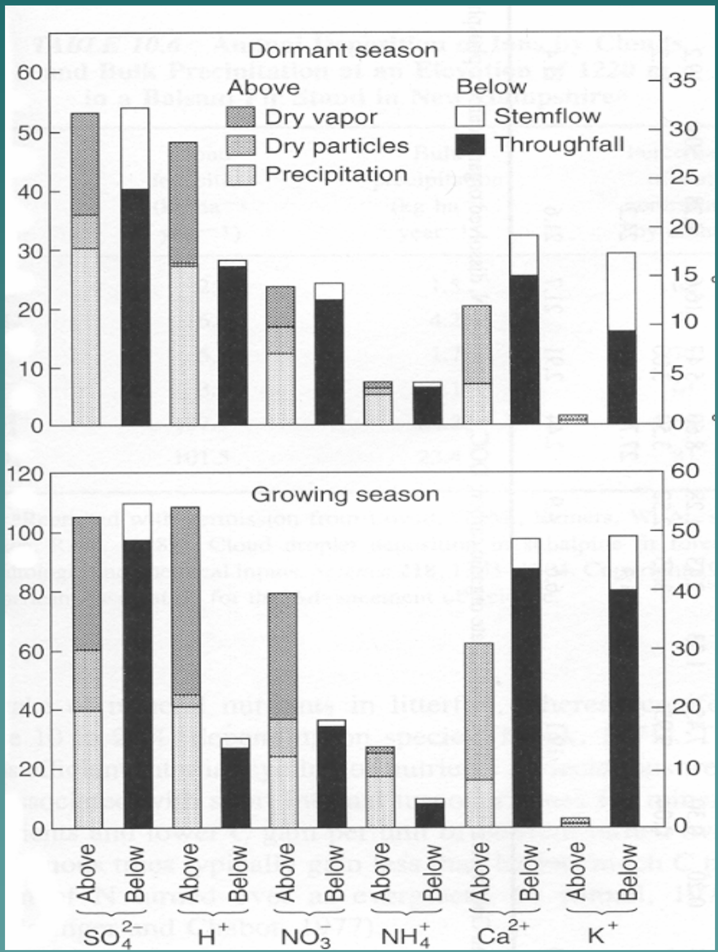
Characteristics of Mycorrhizal and Non-mycorrhizal Roots of Eastern White Pine Seedlings

		Mycorrhizal	Non-mycorrhizal
Seedling	Dry Weight (g)	405	321
	Root/Shoot Ratio	0.78	1.14
Leaf (% O.D. Wt.)	N	1.24	0.85
	P	0.20	0.07
	K	0.74	0.43

From Hatch (1973)

Atmospheric Nutrient Deposition to a Mixed-Deciduous Forest

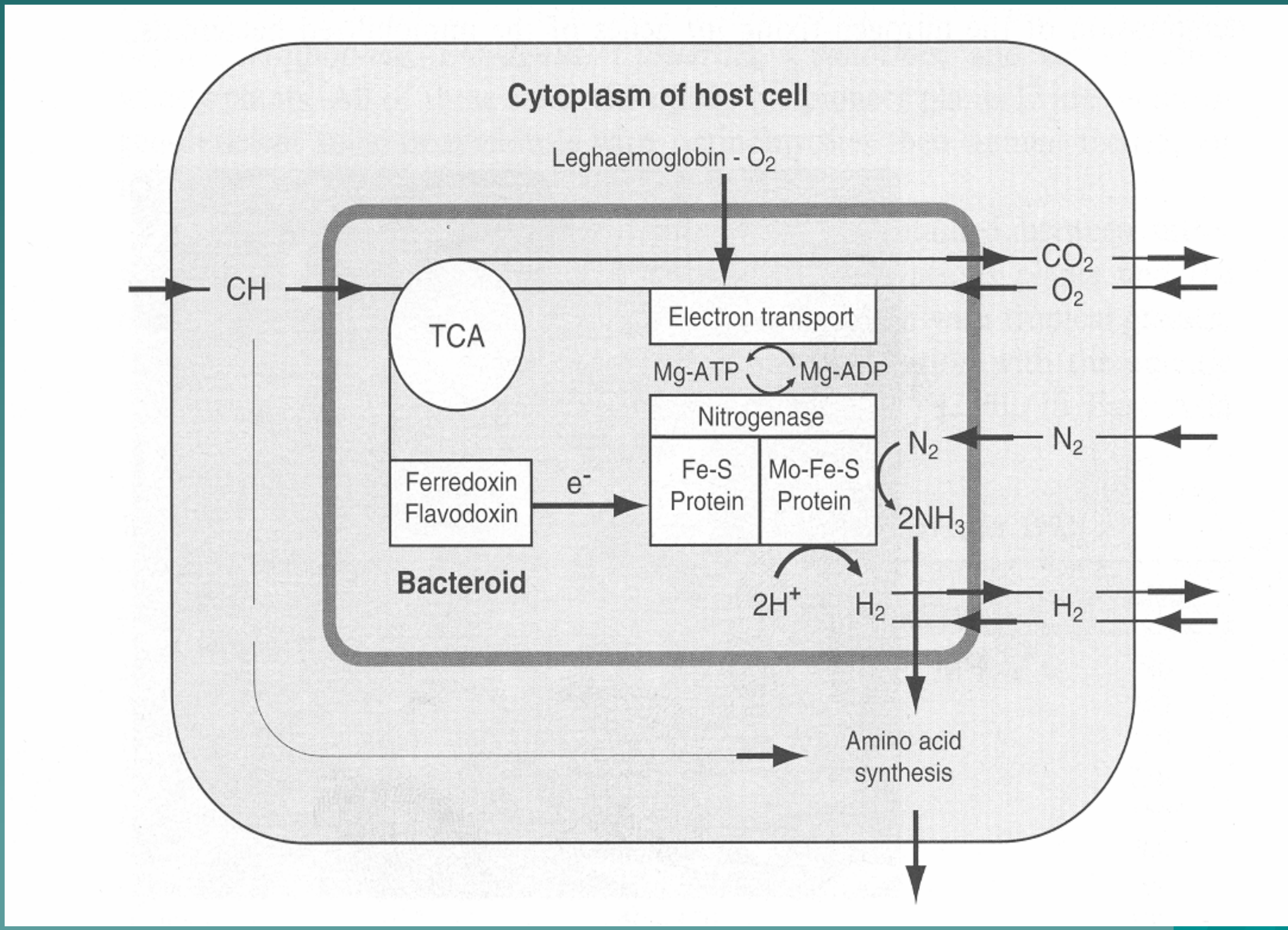
Deposition (SO_4^{2-}, H^+) (mEq/m^2)



Deposition (NO_3^-, NH_4^+, Ca_2^+, K^+) (mEq/m^2)

From Ralston and Prince (1965)

Nitrogen Fixation by Symbiotic Bacteria



Nutrient Distribution Within Trees of Five Species

Species	Age (years)	Foliage (%)	Branches (%)	Bole bark (%)	Bole wood (%)	Roots (%)	Total (kg ha^{-1})
				N			
Pinus sylvestris	45	30	20	11	20	19	186
Picea glauca	40	34	28	10	13	15	449
Pseudotsuga menziesii	36	32	19	15	24	10	320
Betula verrucosa	55	14	31	—	27	28	543
Quercus alba	150	9	23	—	36	22	631
				P			
Pinus sylvestris	45	27	19	14	11	29	21
Picea glauca	40	42	27	13	8	10	64
Pseudotsuga menziesii	36	44	19	14	14	9	66
Betula verrucosa	55	12	35	—	32	21	34
Quercus alba	150	10	19	—	30	35	41
				K			
Pinus sylvestris	45	27	17	13	19	24	96
Picea glauca	40	34	31	12	13	10	254
Pseudotsuga menziesii	36	28	17	20	24	11	220
Betula verrucosa	55	22	23	—	32	23	200
Quercus alba	150	14	31	—	27	26	419
				Ca			
Pinus sylvestris	45	13	19	21	28	19	123
Picea glauca	40	32	27	20	10	11	809
Pseudotsuga menziesii	36	22	32	21	14	11	333
Betula verrucosa	55	6	28	—	42	24	651
Quercus alba	150	3	33	—	39	20	2,029
				Biomass (tons ha^{-1})			
Pinus sylvestris	45	4.4	10.6	5.3	55.6	19.3	95.2
Picea glauca	40	17.4	34.6	10.8	88.0	34.0	184.8
Pseudotsuga menziesii	36	9.1	22.0	18.7	121.7	33.0	204.5
Betula verrucosa	55	2.5	28.7	—	134.5	49.8	215.5
Quercus alba	150	5.4	52.8	—	129.0	95.6	282.8

From Van den Driessche (1984)

Nutrient Distributions within Hardwood and Conifer Species

Species	Age (yr)	Foliage (%)	Branches (%)	Bole Bark (%)	Bole Wood (%)	Roots (%)	Total (kg ha^{-1})
Nitrogen							
Doug-fir	36	32	19	15	24	10	320
White oak	150	9	23	- - -	36	22	631
Phosphorus							
Doug-fir	36	44	19	14	14	9	66
White oak	150	10	19	- - -	30	35	41
Potassium							
Doug-fir	36	28	17	20	24	11	220
White oak	150	14	31	- - -	27	26	419
Calcium							
Doug-fir	36	22	32	21	14	11	333
White oak	150	3	33	- - -	39	20	2029
Biomass (tons ha^{-1})							
Doug-fir	36	9.1	22.0	18.7	121.7	33.0	204.5
White oak	150	5.4	52.8	- - -	129.0	95.6	282.8

Nutrient Distributions within Two Conifer Species

Species	Age (yr)	Foliage (%)	Branches (%)	Bole Bark (%)	Bole Wood (%)	Roots (%)	Total (kg ha^{-1})
Nitrogen							
Doug-fir	36	32	19	15	24	10	320
Loblolly Pine	16	26	19	11	25	20	321
Phosphorus							
Doug-fir	36	44	19	14	14	9	66
Loblolly	16	22	12	9	22	35	48
Potassium							
Doug-fir	36	28	17	20	24	11	220
Loblolly	16	21	13	11	29	27	226
Calcium							
Doug-fir	36	22	32	21	14	11	333
Loblolly	16	12	13	10	33	32	68
Biomass (tons ha^{-1})							
Doug-fir	36	9.1	22.0	18.7	121.7	33.0	204.5
Loblolly	16	- - -	- - -	- - -	- - -	- - -	- - -

Nutrient Profiles: Douglas-fir 1-yr Foliage

Percentile class	Wt[a] (g)	N (%)	P (ppm)	Ca (%)	Mg (%)	K (%)	Na (%)	Mn (ppm)	Fe (ppm)	Zn (ppm)
0	0.01	0.446	475	0.101	0.048	0.073	0.001	11	54	4
1	0.02	0.602	568	0.125	0.051	0.209	0.001	21	58	4
5	0.02	0.727	695	0.160	0.057	0.307	0.001	44	69	5
10	0.02	0.810	796	0.189	0.063	0.372	0.001	67	81	7
15	0.03	0.872	878	0.213	0.069	0.418	0.001	87	94	8
20	0.03	0.924	952	0.235	0.075	0.457	0.001	107	106	10
30	0.03	1.012	1086	0.275	0.087	0.523	0.002	146	133	14
40	0.04	1.091	1213	0.313	0.100	0.581	0.002	187	161	18
50	0.04	1.166	1342	0.352	0.114	0.635	0.003	231	193	24
60	0.05	1.243	1479	0.394	0.130	0.691	0.004	281	231	31
70	0.05	1.325	1635	0.442	0.150	0.750	0.007	341	279	40
80	0.06	1.422	1826	0.502	0.176	0.820	0.011	419	342	52
90	0.07	1.557	2107	0.590	0.217	0.915	0.021	542	447	74
95	0.08	1.668	2350	0.667	0.256	0.993	0.034	654	547	96
99	0.09	1.874	2827	0.820	0.340	1.136	0.077	892	769	148

[a]Per ten leaves

(From Zinke and Stangenberger, 1979)

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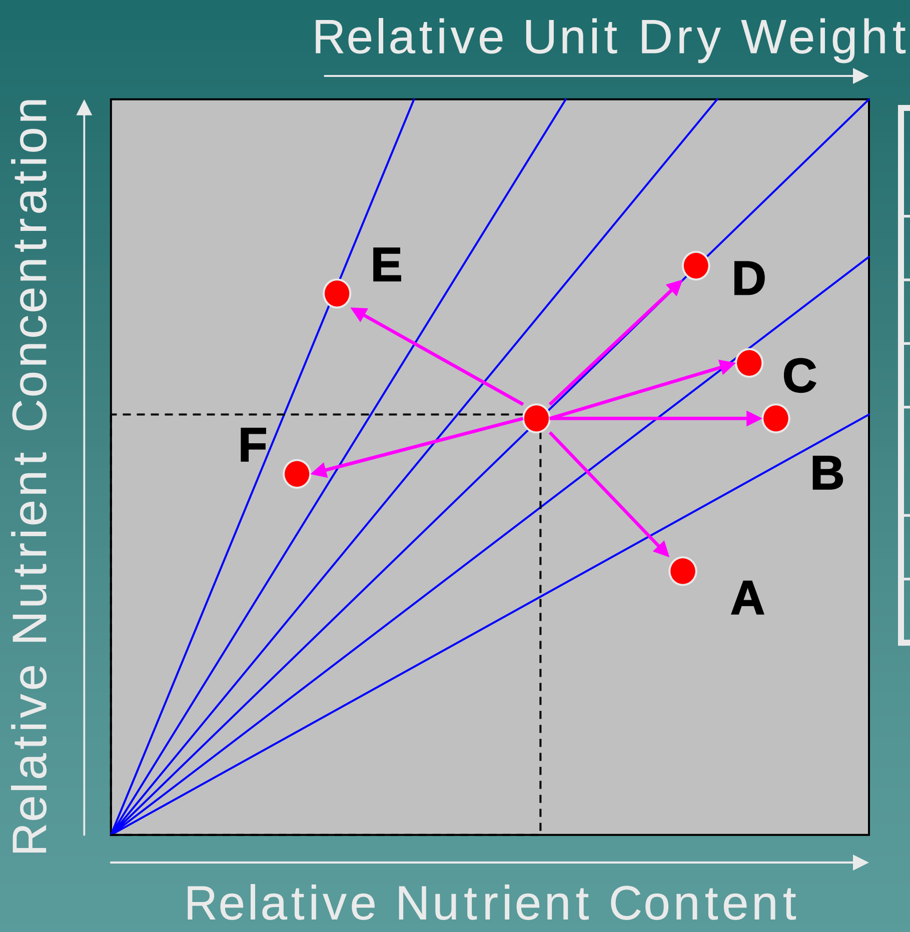
(From Zinke and Stangenberger, 1979)

Ponderosa Pine Response to Elevated CO_2
1-yr Foliage

CO_2 Level	N/P Ratio	N/P % Rank	Ca/K Ratio	Ca/K % Rank	Mn/Fe Ratio	Mn/Fe % Rank
Amb	9.57	42	0.201	9	1.35	57
Amb + 75	12.00	60	0.191	7	1.61	65
Amb + 150	13.11	66	0.280	20	1.70	68
Amb + 300	14.00	71	0.260	17	1.78	69

Anderson, Houpis, Palasou (1986)

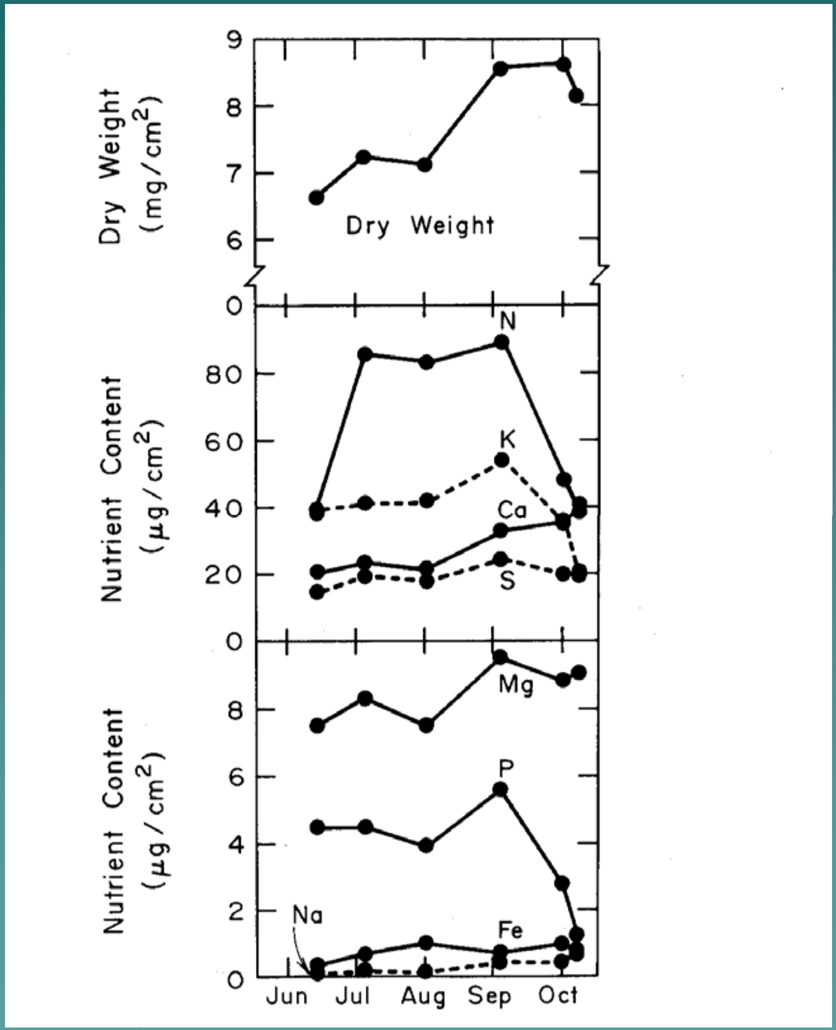
Interpretation of Nutrient Status



Shift	Dry Wt.	Conc.	Cont.	Interpretation
A	+	-	+	Dilution
B	+	0	+	Sufficiency
C	+	+	+	Deficiency
D	0	+	+	Luxury Consumption
E	-	+ +	+ / -	Excess
F	-	-	-	Excess

Haase and Rose (1995)

Seasonal Changes in Foliage Nutrient Content: Scarlet Oak in New York

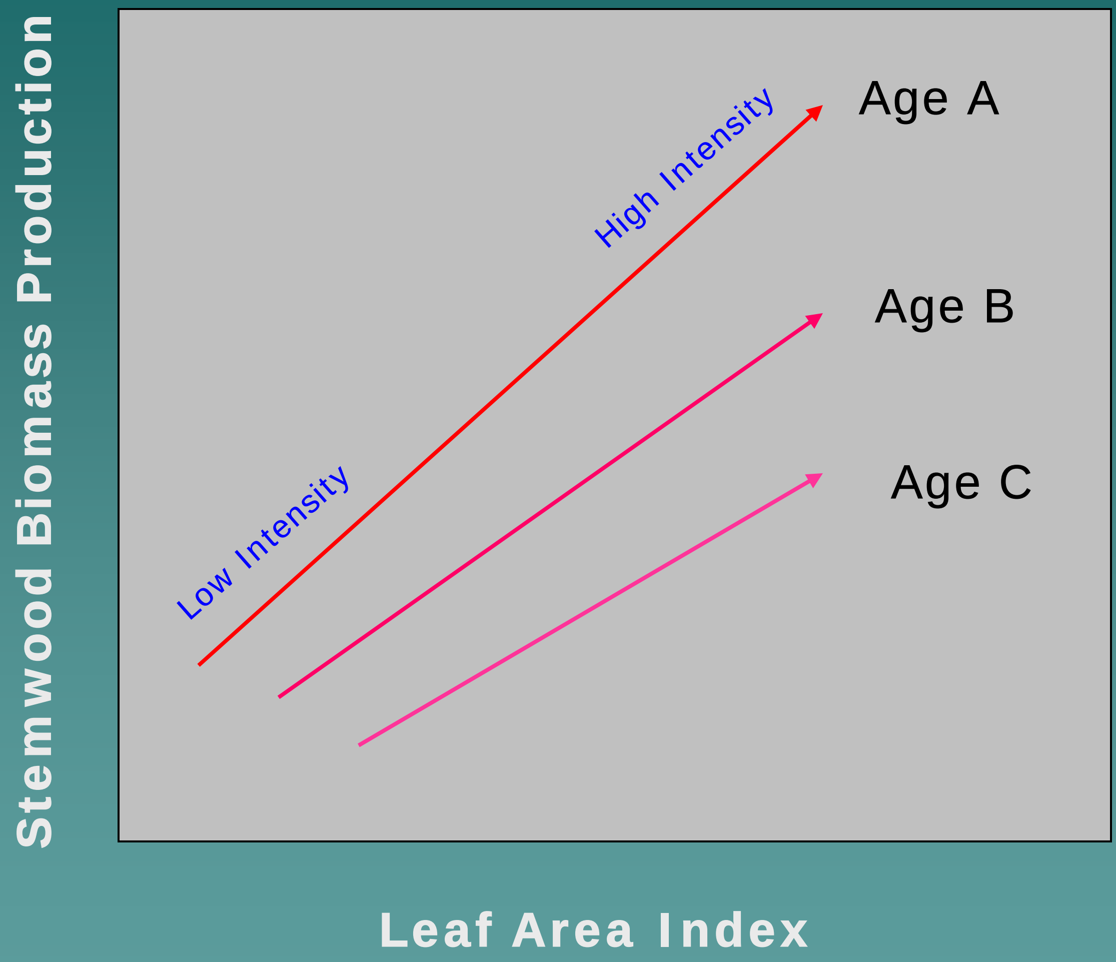


Nutrient Use Efficiency (NUE):
Net Primary Production (NPP) per Unit Nutrient Uptake

Nutrient Use Efficiency ($kg\ ha^{-1}\ yr^{-1}$)		
Nutrient	**Deciduous Forest**	**Coniferous Forest**
N	143	194
P	1859	1519
K	216	354
Ca	130	217
Mg	915	1559

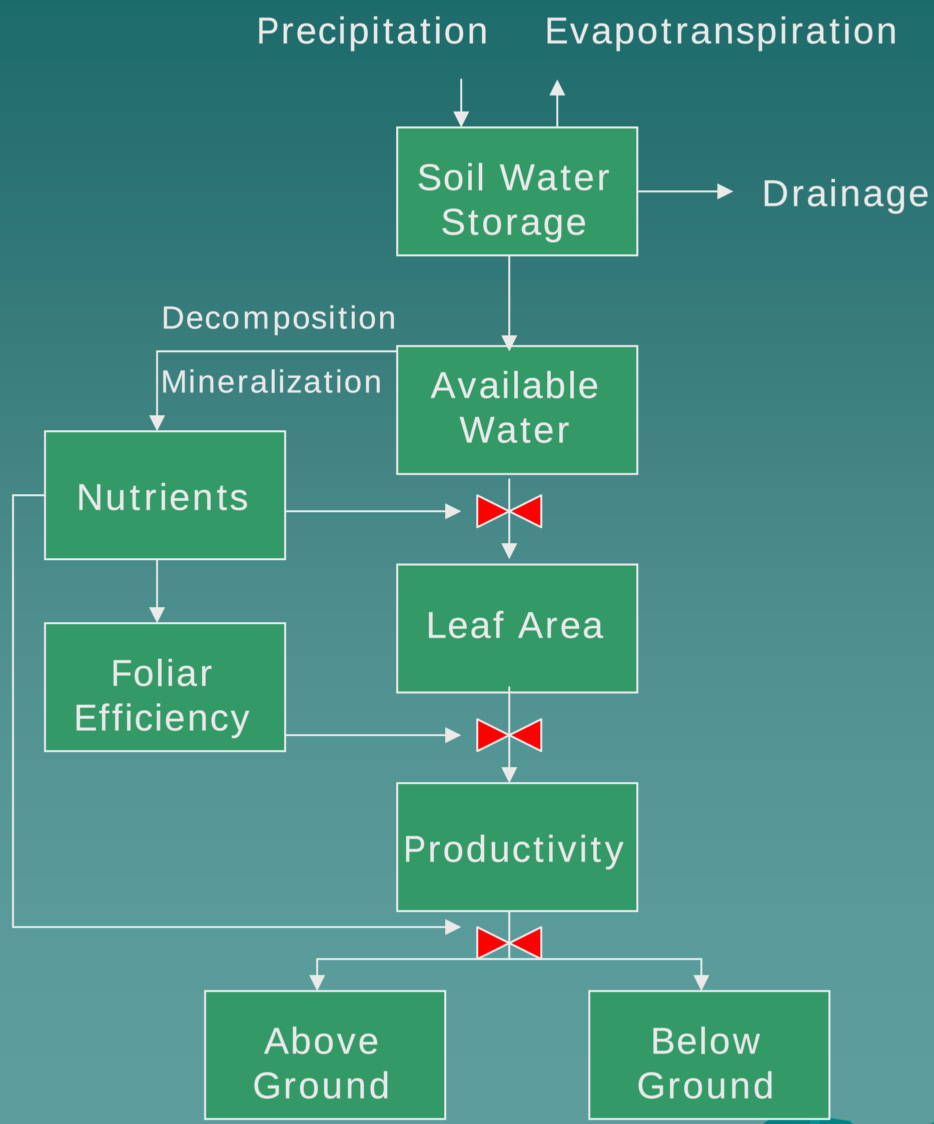
From Cole and Rapp (1981)

Growth Efficiency



Adapted from Jokela and Martin (2000)

Foliage, Production and the Availability of Water and Nutrients



Grier (1990)
Long et al. (2004)

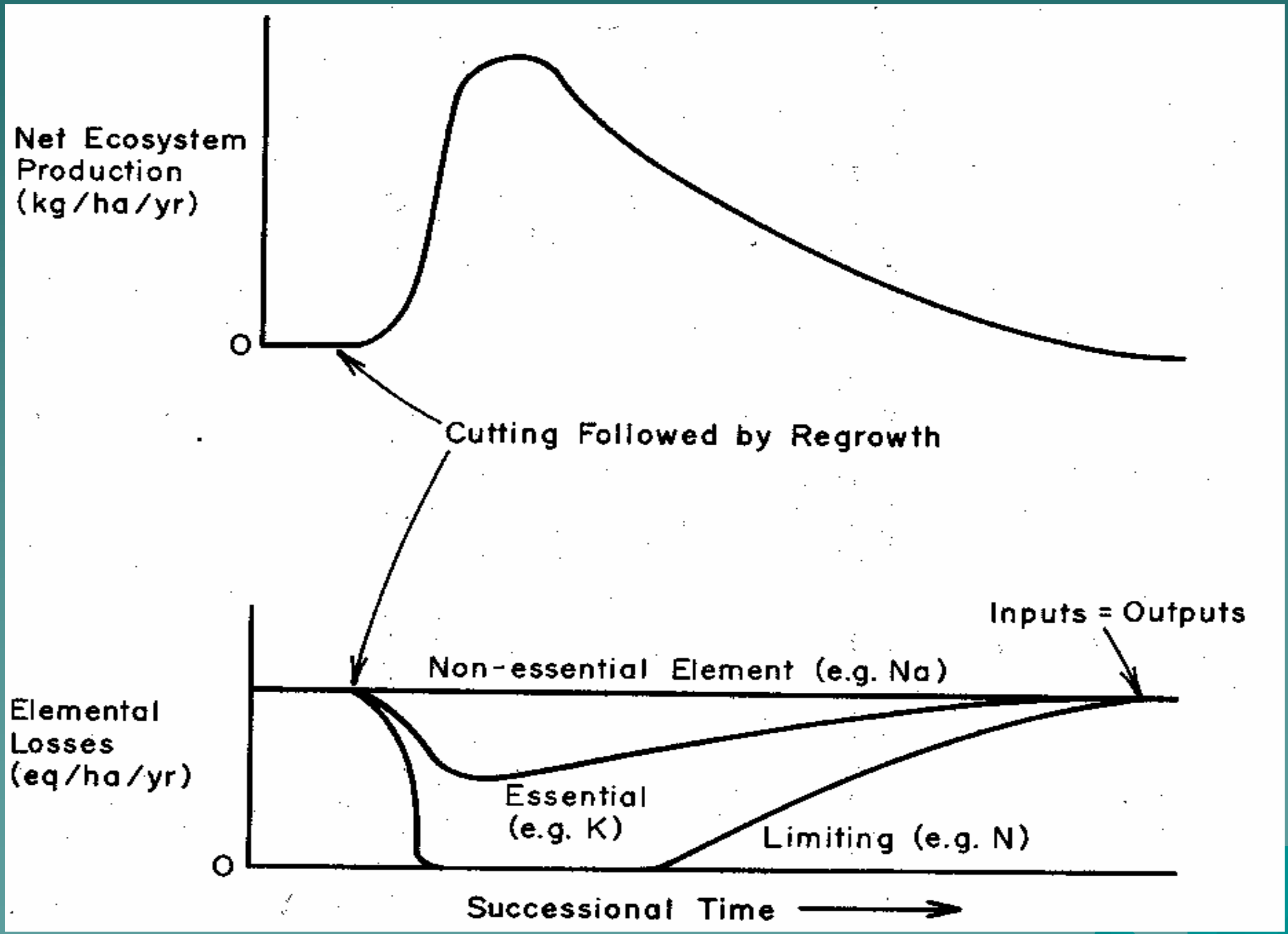
Summary

- Nutrients are elements and compounds used in plant metabolism, growth or function
- Macro and micro nutrients differ in relative abundance, but are essential
- Availability and uptake varies
- They are allocated in different concentrations and contents among plant parts
- They are seasonally variable
- They are linked to productivity through many functions – an important one being leaf area development

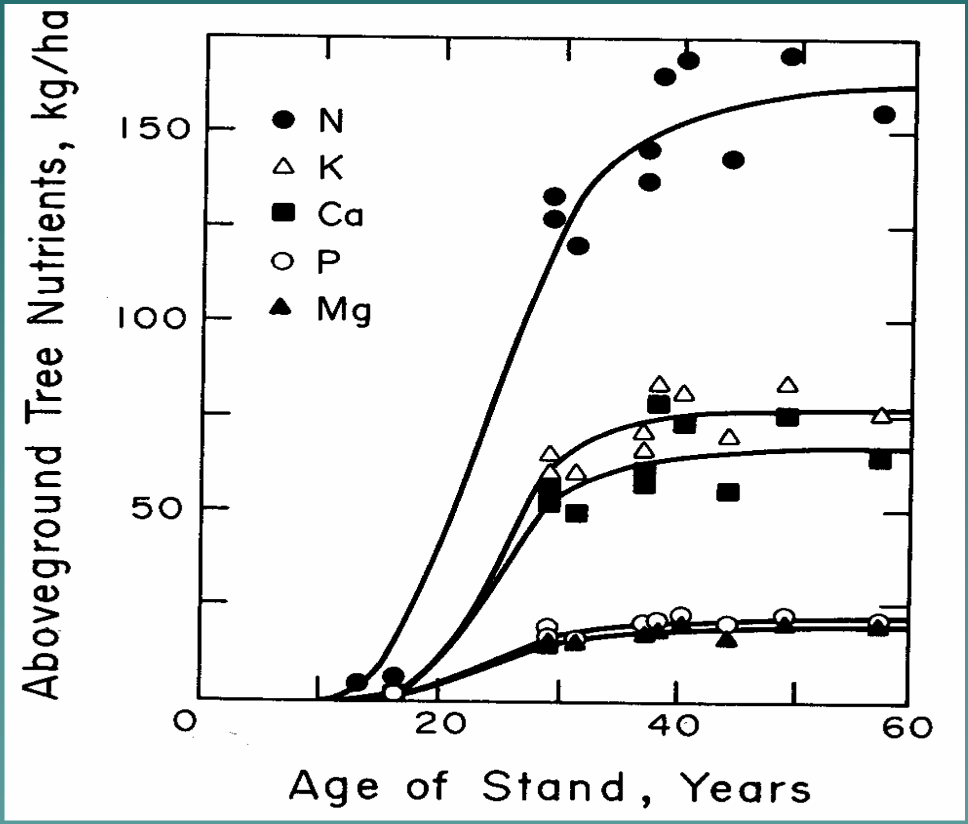
Nutrient Cycling through Forests:

- Nutrient Inputs
  - Atmospheric deposition; wet and dry
  - Nitrogen fixation
  - Rock weathering
  - Hydrologic inputs; transport to site
- Accumulation and Storage
  - Accumulation during forest development
  - Storage in forest ecosystems
- Ecosystem Losses
  - Streams and ground water
  - Losses to atmosphere
  - Losses in fire
  - Losses in forest harvest
- Inputs – Losses = Change in Storage

Storage in Forest Ecosystems: Trends in Net Ecosystem Production and Nutrient Losses During Succession



Nutrient Accumulation During Forest Development: Post-fire Jack Pine, New Brunswick, Canada



From MacLean and Wein, 1977

Macronutrient Storage and Annual Circulation: A Mixed-deciduous Forest in Great Britain

	N	P	K	Ca	Mg
Storage (kg/ha)					
Foliage	85.7	4.6	38.9	41.9	9.5
Wood and branches	192.4	12.1	174.2	437.4	16.5
Roots	223.0	11.9	112.8	235.3	30.8
Understory	8.1	5.4	42.9	66.9	9.7
Total	509.2	34.0	368.8	782.5	66.5
Annual requirement (kg/ha/yr)					
Foliage	85.7	4.6	38.9	41.9	9.5
Wood increment in					
Branches	2.1	0.1	1.5	3.9	0.3
Boles	4.1	0.2	3.4	8.9	0.7
Roots	13.2	0.6	6.6	14.3	1.7
Total increment	19.4	0.9	11.5	27.1	2.7
Leaching					
Throughfall	8.8	0.7	30.3	22.8	11.9
Stemflow	0.4	0.03	4.8	5.2	3.4
Total leaching	9.2	0.73	35.1	28.0	15.3
Total requirement	114.3	6.23	85.5	97.0	27.5
Annual uptake (kg/ha/yr)					
Woody increment	19.4	0.9	11.5	27.1	2.7
Returns					
Leaching	9.2	0.73	35.1	28.0	15.3
Litterfall	63.5	2.6	19.0	83.3	9.7
Total return	72.7	3.33	54.1	111.3	25.0
Total uptake	92.1	4.23	65.6	138.4	27.7
Reabsorption (kg/ha/yr)	22.2	2.00	19.9	0	0
Comparison of annual turnovers and flux (%)					
Bole wood increment/bole wood pool	3.1	2.4	3.0	3.0	8.2
Foliage and root growth/total requirement	87	83	53	58	41
Litterfall/total return	87	79	35	75	39
Uptake/aboveground pool	18.1	12.4	17.8	17.7	41.7
Return/uptake	79	79	82	80	90
Reabsorption/requirement	19	32	23	0	0

[a] From Cole and Rapp (1981, p. 404).

Comparative Losses of Nutrients as a result of Timber Harvest in Different Ecosystems

Locale/process	N	P	K	Ca
British Columbia				
(Western hemlock–Douglas fir)				
Losses (kg/ha)				
Harvested products	234	34	168	260
Streamflow (2 yr)[a]	10	0	8	0
Total	244	34	172	260
Precipitation input (kg/ha/yr)	4	0	1	7
Replacement time (yr)[b]	61		176	37
Minnesota (aspen)				
Losses (kg/ha)				
Harvested products	454	43	355	1034
Streamflow (5 yr)[a]	0	0	0	62
Total	454	43	355	1096
Precipitation input (kg/ha/yr)	7	3	10	5
Replacement time (yr)[b]	65	14	36	219
Florida (slash pine)				
Losses (kg/ha)				
Harvested products	179	15	73	128
Streamflow[a]	4		1	0
Total	183	15	74	128
Precipitation input (kg/ha/yr)	5	0	3	5
Replacement time (yr)[b]	37	75	25	26
Costa Rica				
(tropical rain forest)				
Losses (kg/ha)				
Harvested products[c]	111	4		96
Streamflow (11 mo.)[a]	329	11		392
Total	440	15		488
Precipitation input (kg/ha/yr)	7	2	4	9
Replacement time (yr)	63	8		54

Nutrient Losses Associated with Harvest: Hubbard Brook

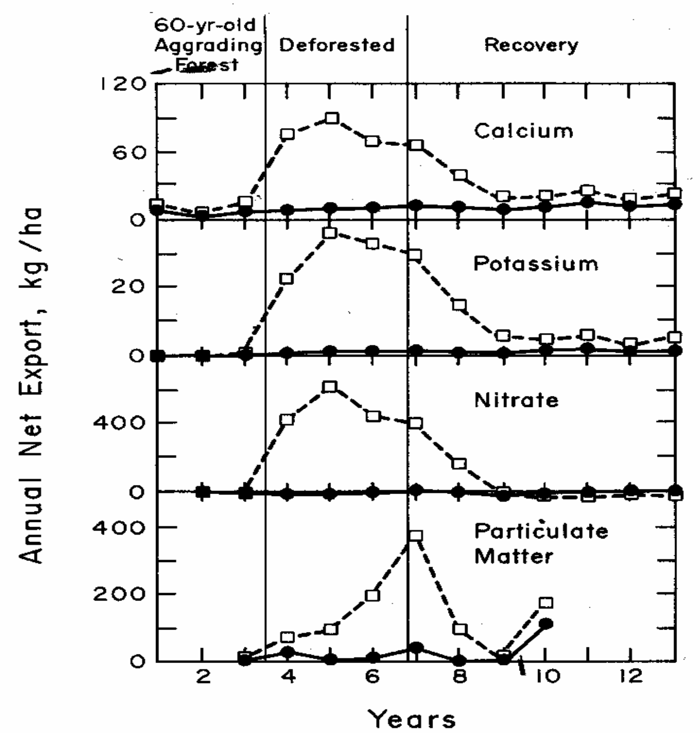
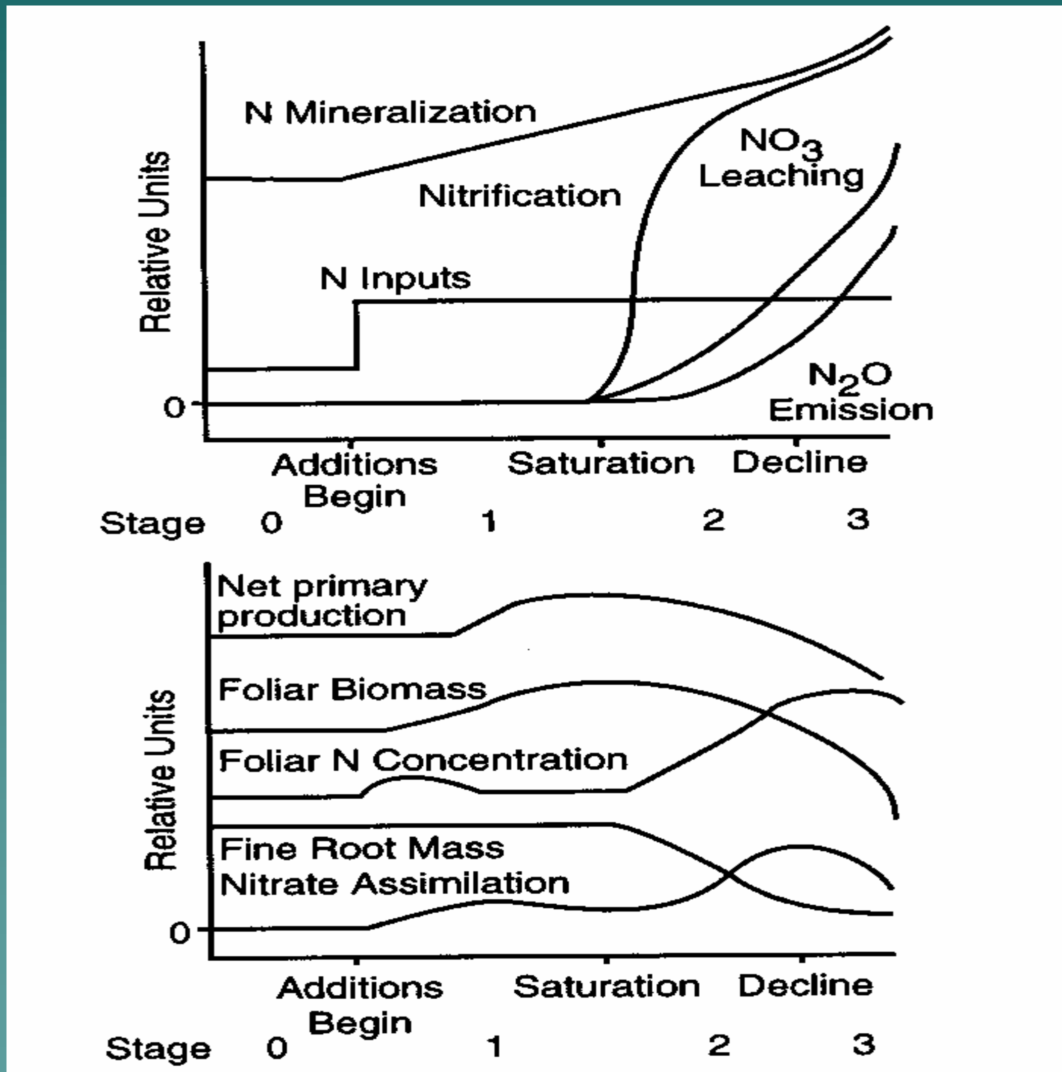
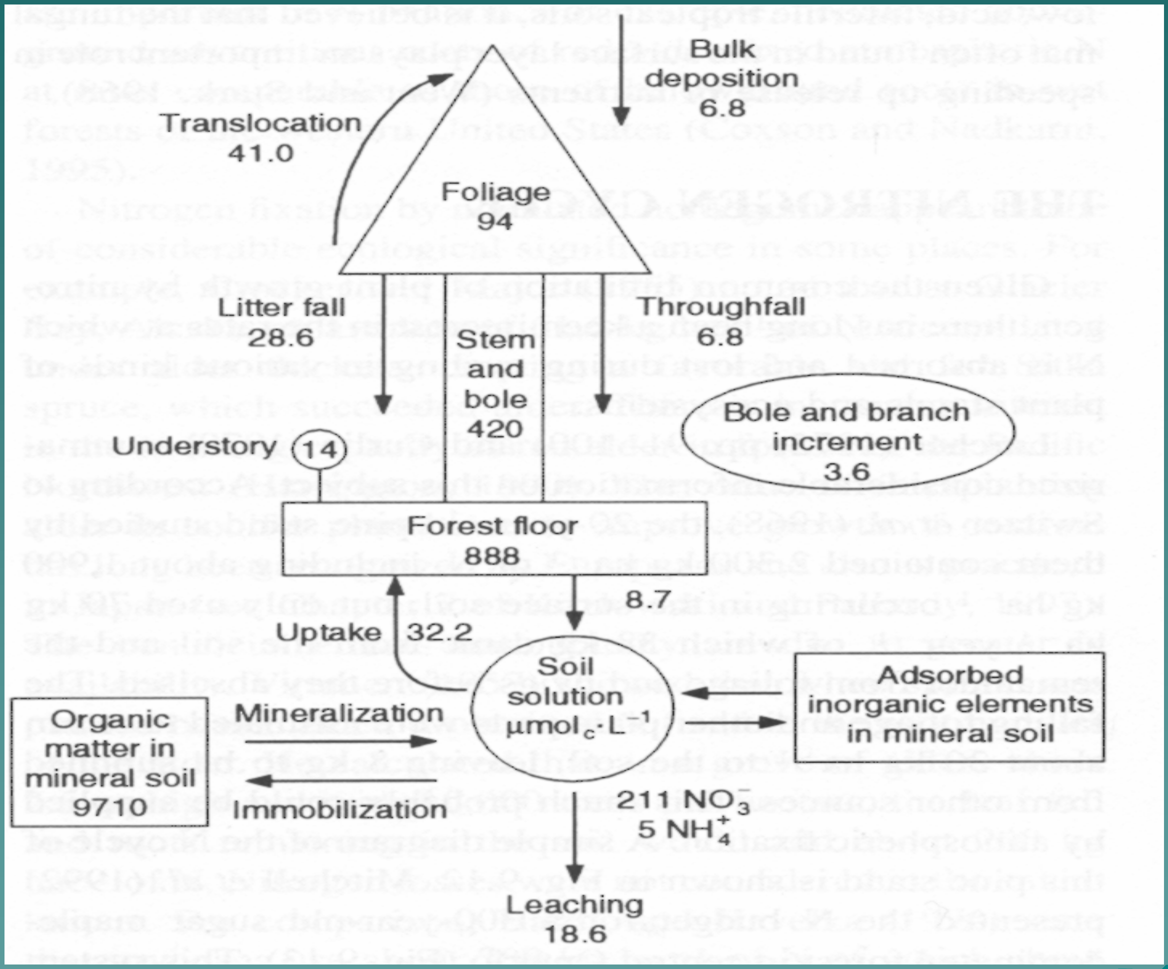


Fig. 6.11. Export patterns of dissolved substances (Ca, K, and nitrate) and particulate matter in streamwater from (□- -□) the experimentally clearcut watershed (W2) and (●—●) the forested reference watershed (W6). (From Bormann and Likens, 1979a.)

Ecosystem Response to Long-term Small-quantity Nitrogen Additions

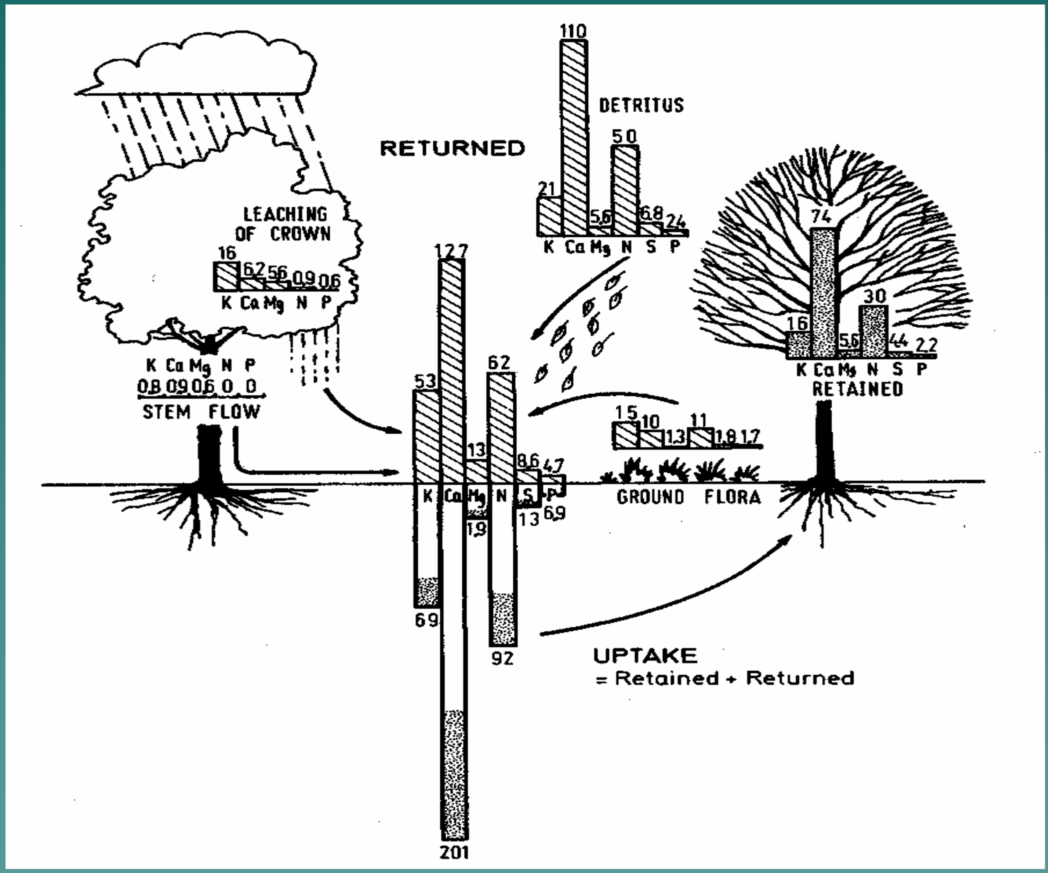


Nitrogen Pools and Flux:
A 300-year-old Maple Forest



N Pool sizes in kg ha^{-1} and fluxes in kg ha^{-1} yr^{-1}.
(From Mitchell et al. 1992)

Mineral Cycling in a Mixed Forest of Oak, Hornbeam, and Beech



All units are kg ha^{-1} yr^{-1}. Stippled area is quantity retained in phytomass. Hatch area is that quantity returned to the soil by washing and leaching of the canopy, stem flow, and litter.

From Duvigneaud and Denaeyer-De Smet (1970).

Nutrient and Biomass Content for Major Forest Types

Content in kg ha^{-1}

Forest type	Biomass		N		P	
	Median	Range	Median	Range	Median	Range
Boreal	129,000	37,000–336,000	447	174–1,915	50	33–67
Temperate coniferous	291,000	274,000–604,000	664	375–1,327	47	—
Temperate broadleaf	338,000	147,000–504,000	1,085	406–1,608	73	36–99
Tropical	378,000	276,000–1,189,000	4,260	3,280–5,290	241	26–1,212
	K		Ca		Mg	
	Median	Range	Median	Range	Median	Range
Boreal	291	133–449	488	243–732	108	74–142
Temperate coniferous	263	—	717	—	—	—
Temperate broadleaf	463	286–531	1,142	644–1,334	115	93–123
Tropical	2,157	1,606–10,395	4,005	1,891–13,472	437	374–1,452
	S		Fe		Mn	
	Median	Range	Median	Range	Median	Range
Boreal	58	24–91	46	16–76	28	27–28
Temperate coniferous	—	—	—	—	—	—
Temperate broadleaf	76	70–82	27	—	125	—
Tropical	—	—	—	—	—	—

From Marion (1979)

Nitrogen Use Efficiency:
Net Primary Production (NPP) per Unit Nitrogen Uptake

Forest Region	Biomass Production per kg Nitrogen Uptake (kg ha-1 yr-1)
Boreal Coniferous	295
Boreal Deciduous	92
Temperate Coniferous	179
Temperate Deciduous	103
Mediterranean	92
Tropical	120

From Cole (1984)