PRINCIPLES OF FOREST SOIL FERTILITY

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ABSTRACT

Soil fertility can be construed strictly as the soil nutrient level or it can be viewed more broadly in relation to this productivity of a particular soil. In this paper nutrient supply rather than productivity will be stressed. Plant nutrient supply is a major factor in fertility assessment and for the most part this supply is derived from the soil solution. Soil solution concentration is linked to many soil chemical and biological processes. These processes and their rates determine an essentially unique soil solution composition.

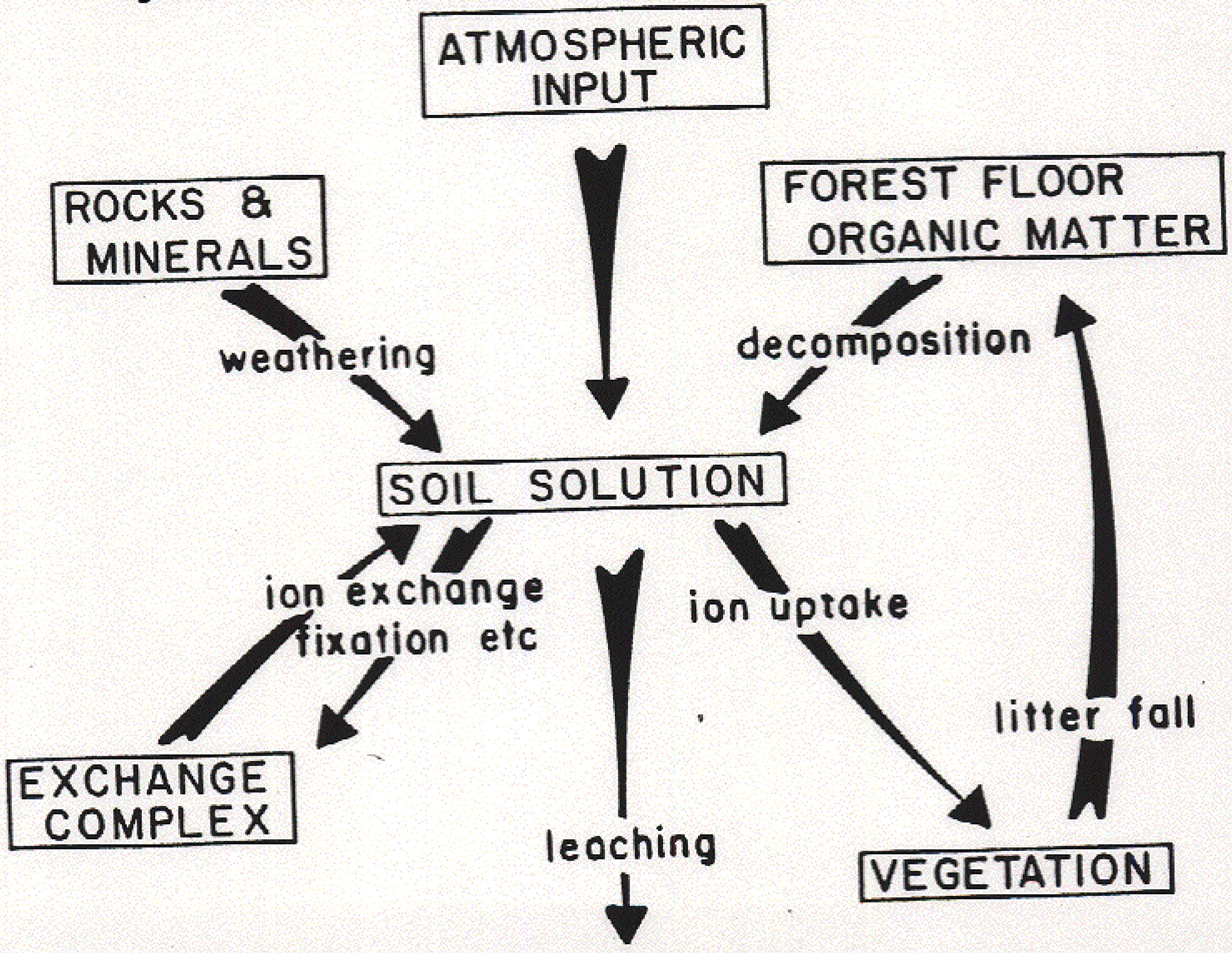
Soil solution dynamics can be conceptualized in a model having inputs from the atmosphere, organic matter, rocks and minsrals, root exudates, and the ion exchange complex. Ion export from the soil solution can occur by leaching, plant uptake, immobilization by microbes, precipitation, volatilization, dsnitrification, ion exchange, and fixation.

The processes ars intensively studied and well known, however the in situ rate and relative contribution of each process are little known. These processes have seasonal trends and are also modified by periodic major disturbances such as fire and overstory removal. Each essential plant nutrient is distributed in the soil-plant system in a unique manner. Certain elements are associated with the biological components and their abundances change as the soil develops. Other elements are mainly associated with the inorganic fraction and more weathered soils may be wanting in these elements. Knowledge of elemental distributions and assumptions about rate processes can be utilized to related fertility to parent material, climate, and soil age.

INTRODUCTION

Soil fertility construed as the ability to supply nutrients can be conceptualized in a simple model presented in Figure 1. This model consists of nutrient sources or inputs from the atmosphere, the soil exchange complex, rocks and minerals in the soil, and organic matter decomposition. Export from the soil-plant system is via leaching and volatilization (not depicted). Loss from the soil occurs by plant uptake. Central to this model, and discussion of soil fertility, is the soil solution and its composition. Nutrients supplied to trees come from soil solution and growth increases as nutrient levels increase, so that regulation of soil solution composition is the key to determining soil fertility.

Figure 1. Schematic representation of nutrient distribution in forest soils.



As depicted in Figure 1, the model components are interrelated by transfers through the soil solution which depend on the relative rates of decomposition, weathering, ion uptake, ion exchange, fixation, and leaching. These processes and their relative rates determine the soil solution composition and plant nutrient supply. Both seasonal and spacial variations in solution composition are expected. In the following section the model components and the processes responsible for nutrient transfers between these components will be discussed.

In order to limit the discussion, some aspects of nutrient cycling such as throughfall crown wash, stem flow, and internal recycling are not considered. That is not to say they are not important to a complete description of nutrient dynamics in forest systems, but rather they do not lend additional insights to the processes determining soil nutrient supplies.

MODEL COMPONENTS

ATMOSPHERIC INPUTS

Dissolved, particulate, and gaseous inputs from the atmosphere are derived from both natural and anthropic sources. The concentration and quantities derived from these sources vary considerably depending upon the element in question and the location. Near industrial sources and in maritime areas significant quantities of some elements can be anticipated; however, for most elements this is a minor source. In the eastern United States and northern Europe where air masses move over continental areas of industrialization, inputs are much greater than in the Pacific Northwest where relatively clean air masses from the Pacific Ocean move onshore (Voigt 1979). Table 1 presents data on atmospheric inputs.

LITTERFALL

Litterfall is a pathway for return of nutrients absorbed by the vegetation and any nutrients trapped in particulate material by the foliage. Species return various quantities of litterfall and, with this, various quantities of nutrients (Tarrant et al. 1951, Youngberg 1979). These annual additions of foliage and branches become incorporated into the forest floor and eventually a portion becomes part of the soil organic matter. Litterfall is an important input since it obviously contains all the nutrients necessary to plant growth. Table 2 presents some litterfall and nutrient data for the Pacific Northwest.

Soil Organic Matter and Forest Floor

Decomposition and leaching modify litter into forest floor and provide organic matter which, along with roots and soil fauna and flora, become part of the soil organic matter. During decomposition, nutrients are released to the soil solution and soluble organics are transported into the mineral soil. The resultant forest floor is a morphological feature that distinguishes temperate zone forest soils from agronomic soils.

The forest floor is not a static quantity and it varies with season, stand age (Cole and Johnson 1979, Armson 1977), climate (Olsen 1963), and past history of the site; i.e., fire frequency, logging, and slash burning.

As decomposition of the organic material is a biological process it is strongly dependent on temperature, and decomposition rate should approximately double as the temperature increases 10°C. The type of organic substrate will also influence decomposition. Amino acids, sugar, and proteins are readily consumed, while the more complex molecules such as lignin are quite refractory (Alexander 1977).

ROCKS AND MINERALS— SOIL PARENT MATERIALS

Rocks and minerals are the source of many cationic nutrients, which are balancing ions in the mineral structure. Anionic nutrients such as S, B, and P are constituents of some minerals. Figure 2 shows the relationship between various igneous rocks and their mineral constituents. The chemical for-

Table 1. Nutrients added by precipitation inputs.

Location	Precipitation mm/yr	N	P	K	Ca	Mg	S	Source
		Nutrient quantities kg/ha/yr						
Oregon	2150–2510	0.90–1.08	0.27	0.11–0.27	2.33–7.65	0.72–1.32	--	Fredriksen, 1972
Washington	~1000	1.1	trace	0.8	2.8	--	--	Cole et al. 1967
Wisconsin	--	13.1	0.3–0.4	1.0–4.0	2.0–7.0	0.5–1.1	--	Boyle and Ek, 1972
Mississippi	1270	13.3	0.3	4.0	5.0	1.0	--	Switzer and Nelson, 1972
Germany	624	20	0.1	4.6	19	--	--	Neumann, 1966
Washington	5360	5.6	1.2	3.8	11	6.8	14	Larsen, 1979
Coastal	3100	2.0	1.0	3.9	10	5.2	7.5	
Washington Puget Sound Basin	1200	8.1	0.4	--	--	--	8.9	Stednick, 1979

Table 2. Litterfall and nutrient inputs from litterfall in the Pacific Northwest.

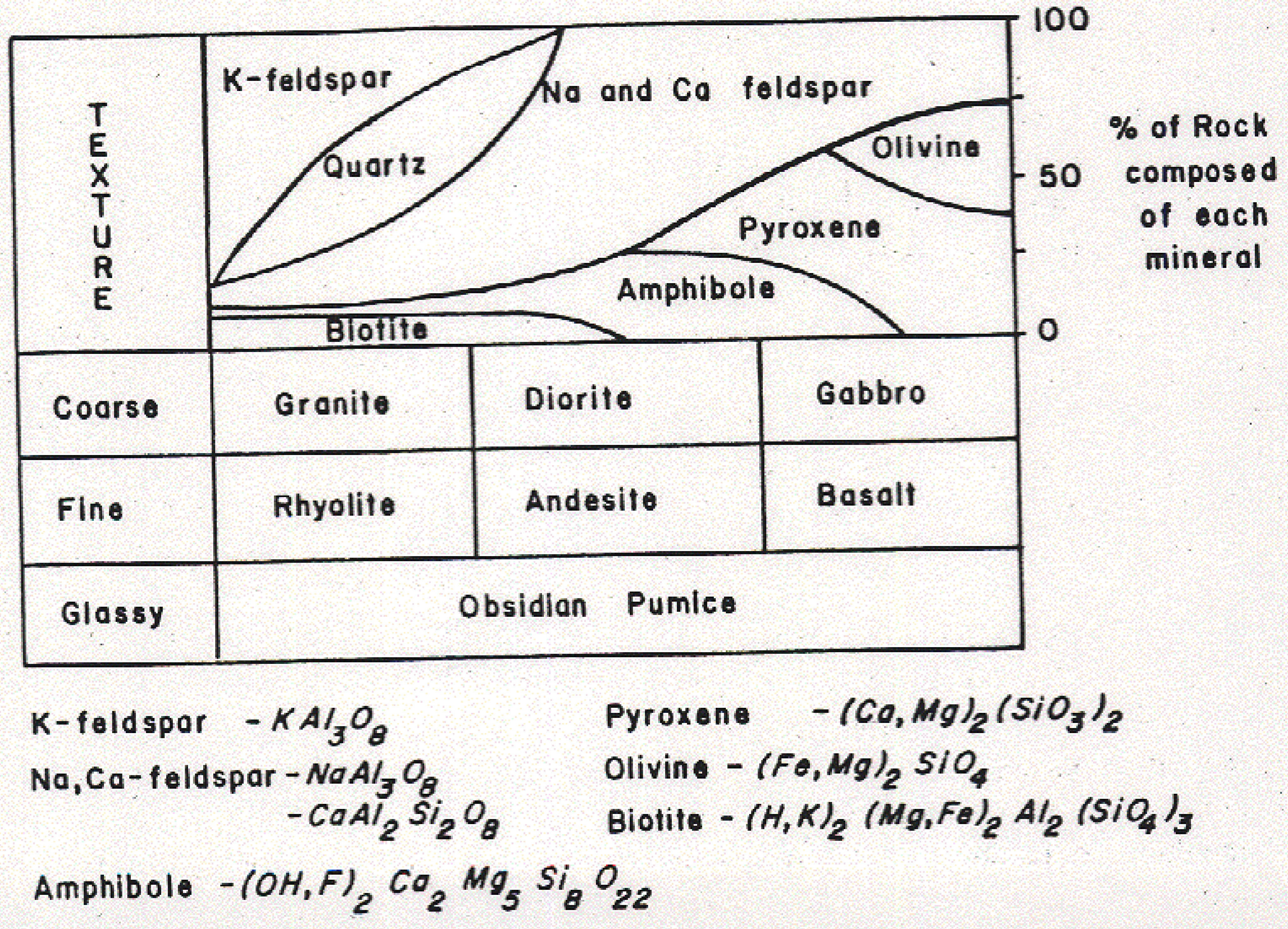
Species	Litterfall	N	P	K	Ca	Mg	S	Source
		kg/ha						
Red alder	1315	31	1.7	13	10.8	0.1	--	Tarrent et al.[a] 1951
Red alder	5635	98	0.17	39	63	13	--	Gessel and Turner, 1974
Red alder Western redcedar	2147	13.4	1.9	7.74	47.8	0.9	--	Tarrent et al., 1951
Douglas-fir 350-yr-old	1985	17	3.0	3.0	18.6	0.9	--	Tarrent et al., 1951
Western hemlock	1050	8.1	1.12	2.0	6.3	0.7	--	Tarrent et al., 1951
Sitka spruce	902	10.4	6.9	2.1	4.4	0.8	--	Tarrent et al., 1951
Douglas-fir 100-yr-old	922	7.9	0.8	1.9	9.0	0.22	--	Tarrent et al., 1951
Douglas-fir	--	19.2	0.15	12.0	47.4	5.4	--	Gessel and Turner,

[a]Values presented by Tarrent et al., 1951, are for foliage and not litter, but indicates the potential nutrient content of litter.

mula for these minerals are also included. This points out that some rock types have an abundance of some nutrients and a paucity of others. The same argument can be pursued for micronutrient supplies in various parent materials (Krauskopf 1972). Primary minerals are formed under high temperatures and pressures and, as such, are unstable in the surface environment. Rocks weather at different rates which can be related to their chemical structure and bonding system, releasing nutrients and other ions to soil solution. If an equilibrium system in the soil is assumed, mineral stability in a given soil environment can be predicted (Kittrick 1977, Bohn et al. 1979).

Weathering rates of rocks and minerals are difficult to establish, and nutrient cycling studies estimate that these sources supply 8–24 kg/ha/yr of Ca, 4–15 kg/ha/yr of K, and about 8 kg/ha/yr of Mg (Woodwell and Whittaker 1967, Likens et al. 1970, Cole et al. 1967). Differences in the stability of different rock types and differences in their chemical composition will

Figure 2. Classification and composition of primary rocks.



tion of sources and sinks will determine a unique soil solution composition. Plants compete for the nutrients in the soil solution with microbes and the other nonbiological processes. Growth will be related to nutrient supply if other factors are held constant.

To examine the functioning of the model, N and basic cations including K will be considered as specific examples. The approach taken will be a qualitative one. For the purpose of this introductory paper little would be gained by computer simulation and semiquantitative results.

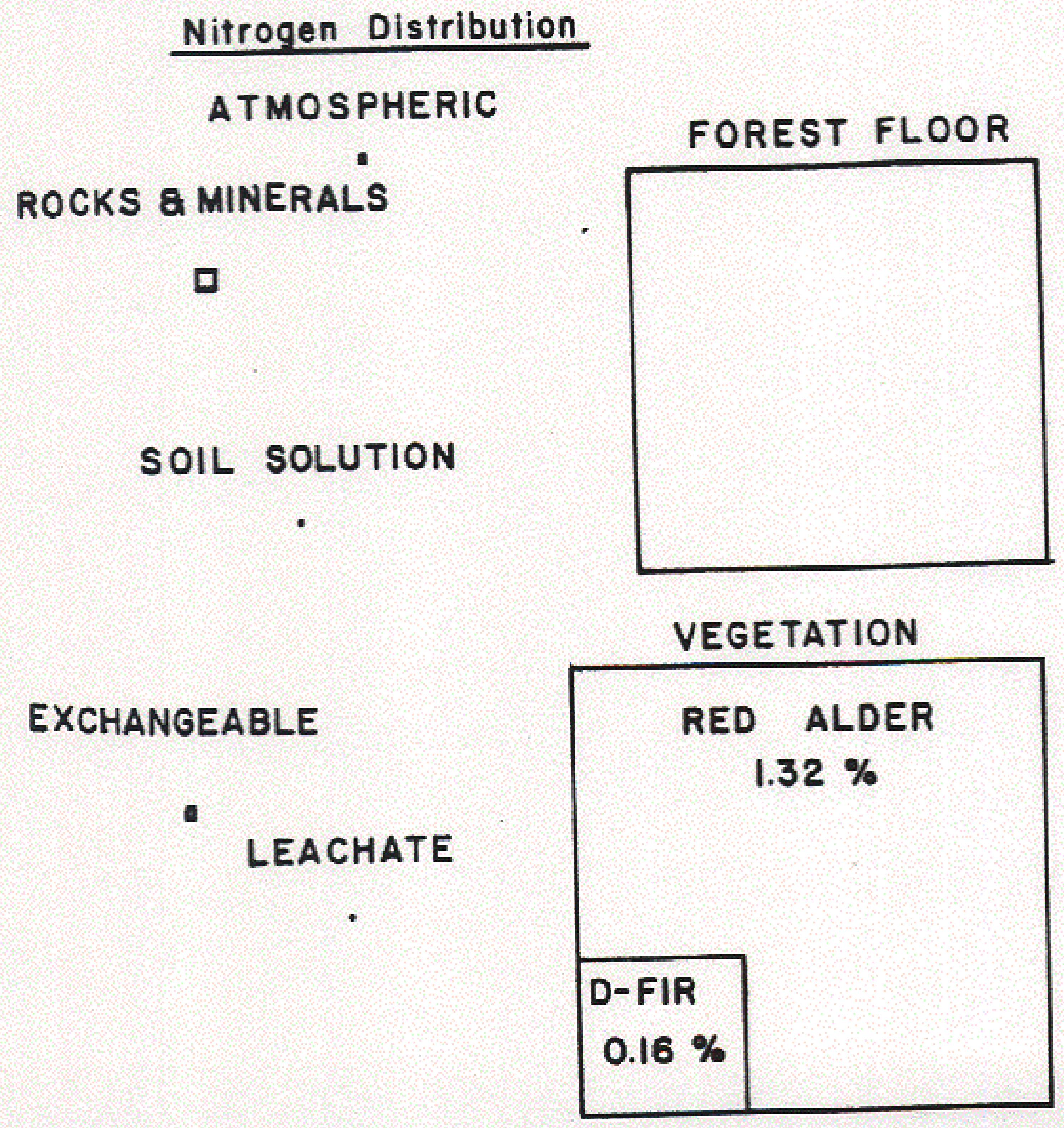
NITROGEN

Nitrogen deficiency is a nearly universal growth limitation and its cycling is a complex part of a forest's function. Figure 3 shows the concentration of N in the various model components. It is obvious that rocks and minerals are poor sources of N, and that both exchangeable N and atmospheric inputs are also small quantities. Organic matter and the forest floor are the large sources of N; however, before plants can obtain this N, it must be converted from complex organic forms to either ammonium or nitrate ions.

Inherent in schematic N distribution presented by Figure 3 is a previous N accretion, since the rocks and minerals or soil parent material cannot supply this element.

The majority of N on site must be added by the biological process of N fixation. Alders are well known for this symbiotic fixation, and this is reflected in the average N content of their

Figure 3. Schematic representation of nitrogen distribution among components in a forest.



aboveground biomass (Tarrant et al. 1969, van Cleve et al. 1971). Litterfall from this species adds N to the forest floor and which must be metabolized to yield ammonium or nitrate ions. When decomposition of carbonaceous material gives rise to a net release of usable N, the process is called mineralization or N mineralization. Figure 3 shows that only very small concentrations of N are in soil solution at any one time.

Nitrogen in the aboveground biomass must cycle through the soil solution from the large reserves via mineralization or decomposition. Control in the system is easily assigned to this decomposition rate. Mineralization rates have been extensively studied. Temperature and moisture regimes of the forest floor and mineral soil strongly influence decomposition rates. High elevation or high latitudes will limit decomposition in spite of large nutrient pools. Litterfall is the substrate for decomposition, with a C content of ~44% and a N level near 1% in foliage and 0.05% in woody litterfall the C/N ratio is not suited for decomposition to proceed rapidly. Because of the differences between foliage and woody tissues decomposition would be expected to proceed more rapidly in young stands where the bulk of litterfall is senescent foliage.

Shumway and Atkinson (1977) have shown that N fertilizer response is inversely related to the mineralization rates in some Douglas-fir stands, and Powers (1976) has shown a positive relationship between mineralizable N and site index. Stands that can mineralize significant quantities of N grow better and do not respond as well to fertilization as those with limited mineralization capacity.

Fertilization with N avoids the limitation imposed on the system by decomposition and adds a soluble N source which can either be adsorbed by the vegetation, taken up by microbes and immobilized, and leached or adsorbed on the exchange sites. Adsorption on exchange sites was demonstrated by Baker (1970) in the western hemlock stands. His data show that ammonium derived from urea occupies sites made available by the increased pH dependent exchange capacity of the litter layer. Further details about urea hydrolysis and pH effects are available in this volume.

Bulk soil pH changes induced by urea additions may have important influences on plant nutrition, but N source may also influence soil pH in the immediate vicinity of the root. The so-called rhizosphere pH is usually found to increase with nitrate sources and decrease with ammonium sources (Simley 1974, Riley and Barber 1971). Figure 4 shows the effect of N source on rhizosphere pH in Alderwood soil. These pH effects will undoubtedly influence the availability of other nutrients. Riley and Barber (1971) showed an effect on K availability. Using Douglas-fir seedlings Rollwagen and Zasoski (1979) showed that this pH effect occurs rapidly and differences are apparent one week after fertilization (Figure 5). In summary, examining N by use of a simple component model suggests that once N has accreted in the system by biological N fixation, controls on N fertility can be assigned to the decomposition rate. This decomposition rate varies with a host of chemical and environmental site factors, but nonetheless the rate limiting step is the transfer from the litter and soil organic matter to soil solution.

POTASSIUM AND BASIC CATIONS

In contrast to N which is distributed in relation to organic matter, K, Ca, and Mg distribution are related to the inorganic soil fraction.

Potassium distribution is shown in Figure 6. In this case the parent material determines the supply of K rather than the biological accumulation as with N. Parent material can have a large influence on K supply. Figure 6 shows that K is well supplied by rocks containing biotite and K-feldspar, while K supply in basic rocks such as amphiboles and pyroxenes is much lower. Acidic rocks such as granite and rhyolite provide large K supplies, while basic rocks such as amphiboles and pyroxenes do not have K as a major constituent. In fact, the ultrabasic rocks such as olivine and peridotite have such a large supply of Mg that Ca deficiencies can be found on soils formed on these minerals (Proctor and Woodwell 1975).

Figure 4. Influence of Varying rates of ammonium and nitrate-nitrogen on rhizosphere pH of Douglas-fir seedlings grown in Alderwood soil.

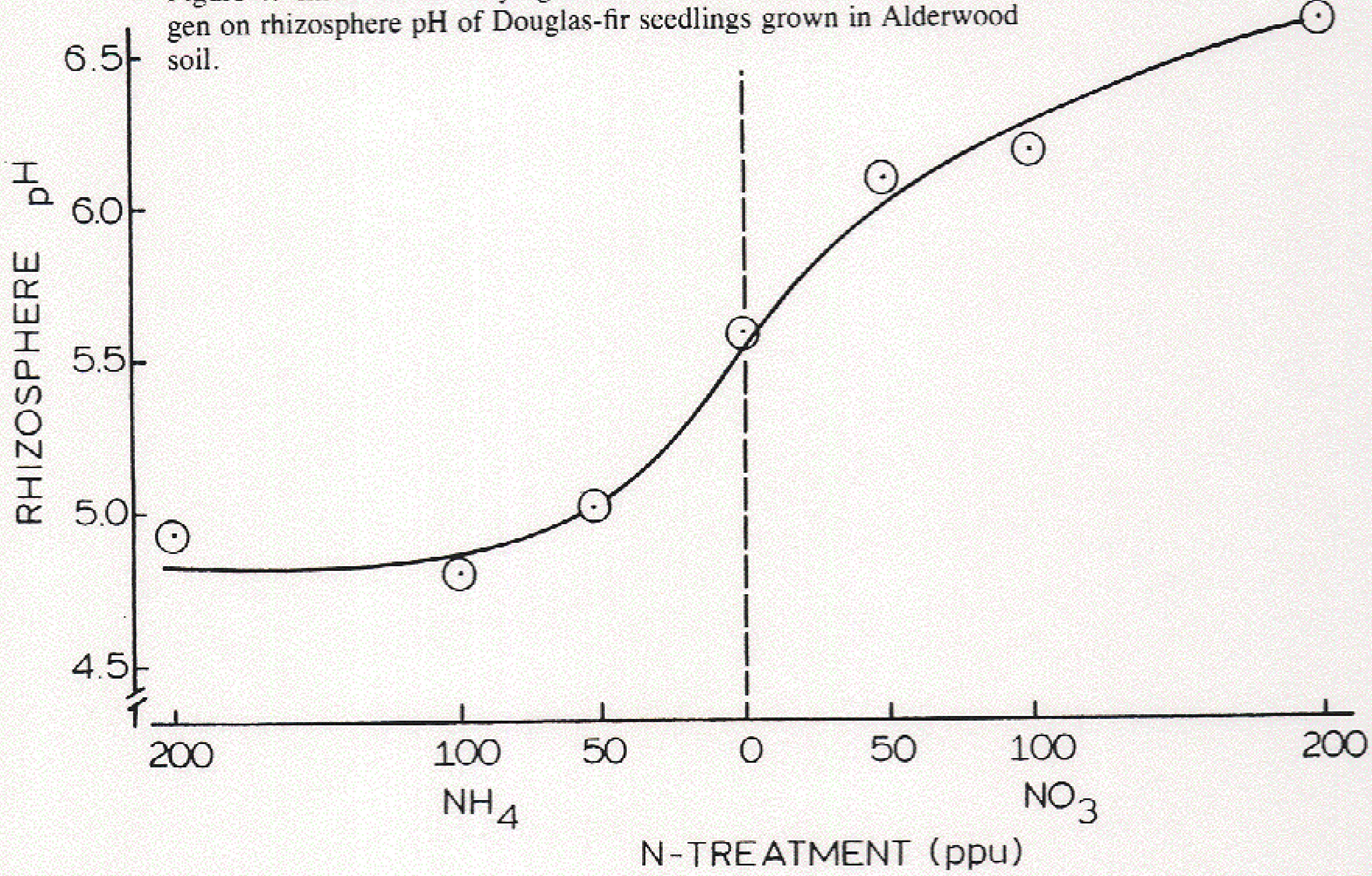


Figure 5. Effects over time of ammonium ion and nitrate-nitrogen on rhizosphere pH of Douglas-fir seedlings grown in Alderwood soil.

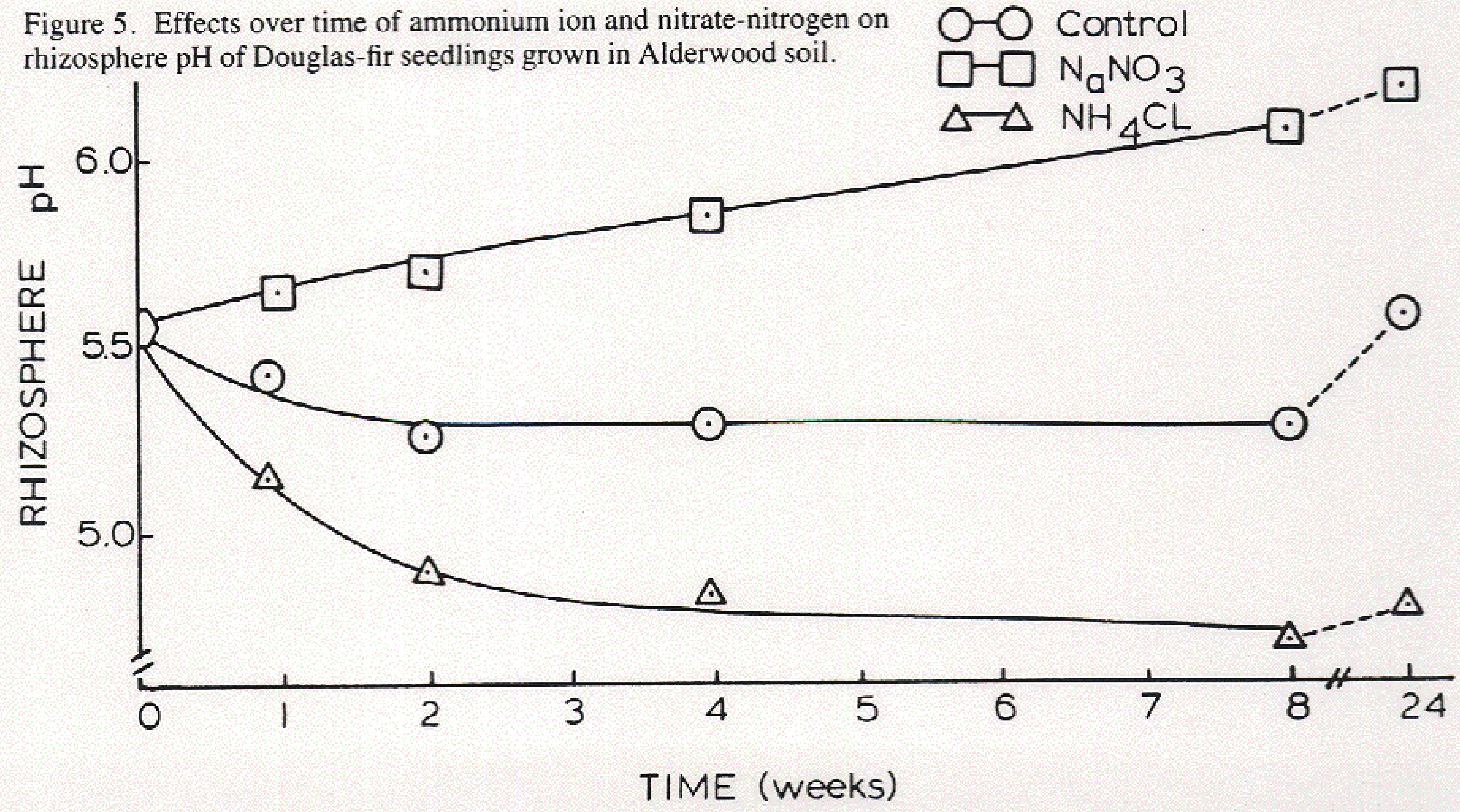
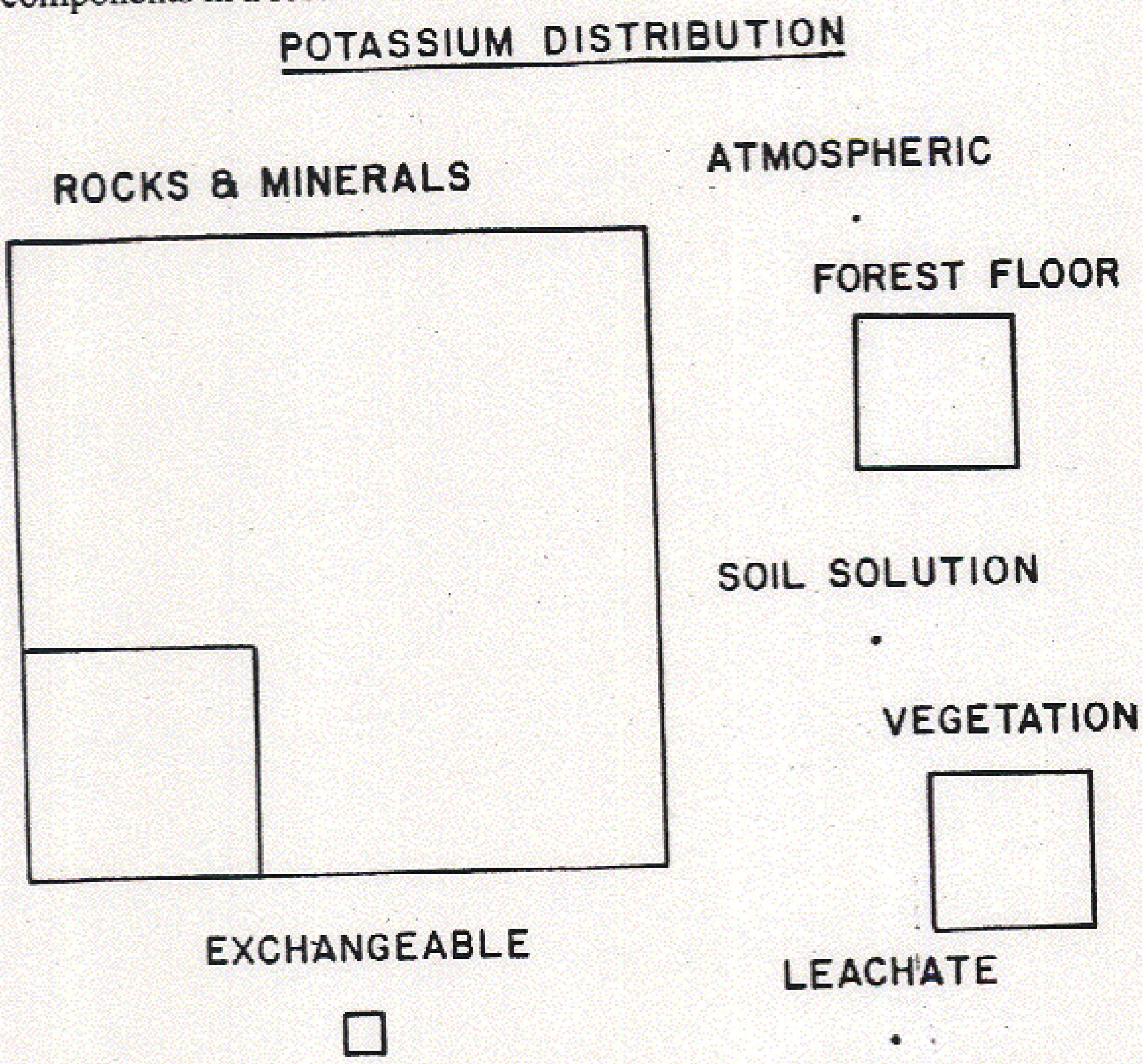


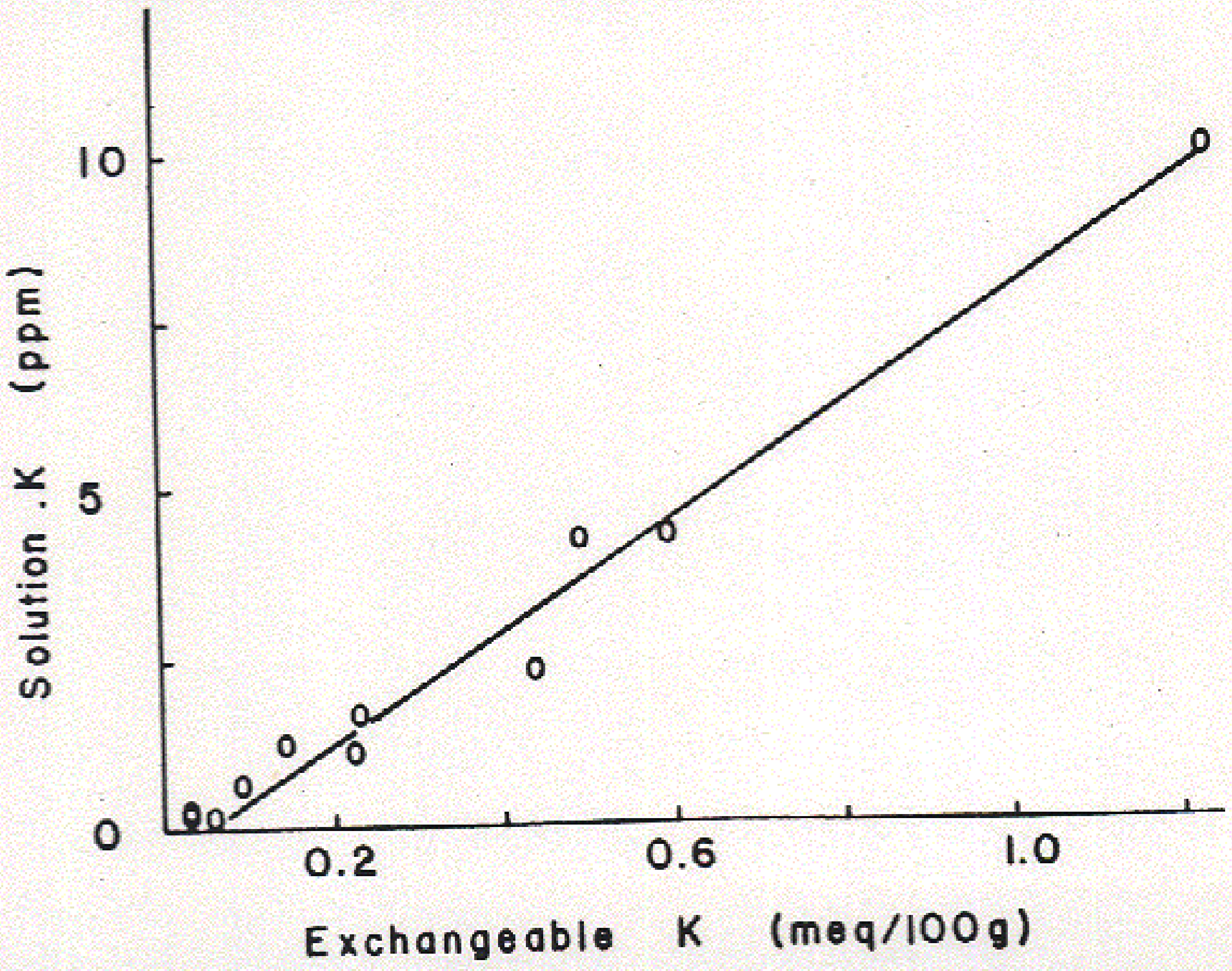
Figure 6. Schematic representation of potassium distribution among components in a forest.



Weathering of serpentine releases large quantities of Mg and only traces of K, Ca, and Na (Clayton 1979). Parent material must be weathered to supply basic cations to solution and the other model compartments, although highly weathered soils may not have large supplies of basis because of extensive leaching. There is a general relationship between soil pH and supply of basic cations. As pH decreases, more exchange sites are occupied by H and/or Al, thus exchangeable base levels will be expected to decrease (Brady 1974).

In the short term, basic cation supply can be related to exchangeable levels which in turn can be related to solution levels. Figure 7 shows the amount of K released from the A, B, and C horizons of three different forested soil solutions by treatment with 0.01 *M* calcium chloride. In forest soils, exchangeable K may not be a good K source; however, other sources are available. Weathering has been shown to supply from 4.0 to 15 kg K/ha/yr (Pritchett 1979). This represents a substantial portion of a stand's demand for K which varies for several forest ecosystems between 5 and 75 kg/ha/yr (Pritchett 1979).

Figure 7. Solution potassium displaced by 0.01 M calcium chloride in relation to exchange potassium in several forest soils.



Since the exchange fraction of mineral soil may be low in K, the organic fraction may be an important supply of K. Figure 8 shows the amount of K lost or gained by a forest soil (Everett Series) when faced with 0.01 *M* calcium chloride containing various K levels. These Quantity-Intensity plots (Beckett 1964) show that only the 02 horizon and the highly organic A1 horizon released K to solution, while the mineral horizons adsorbed added K. Organic matter is an important source of K in these soils.

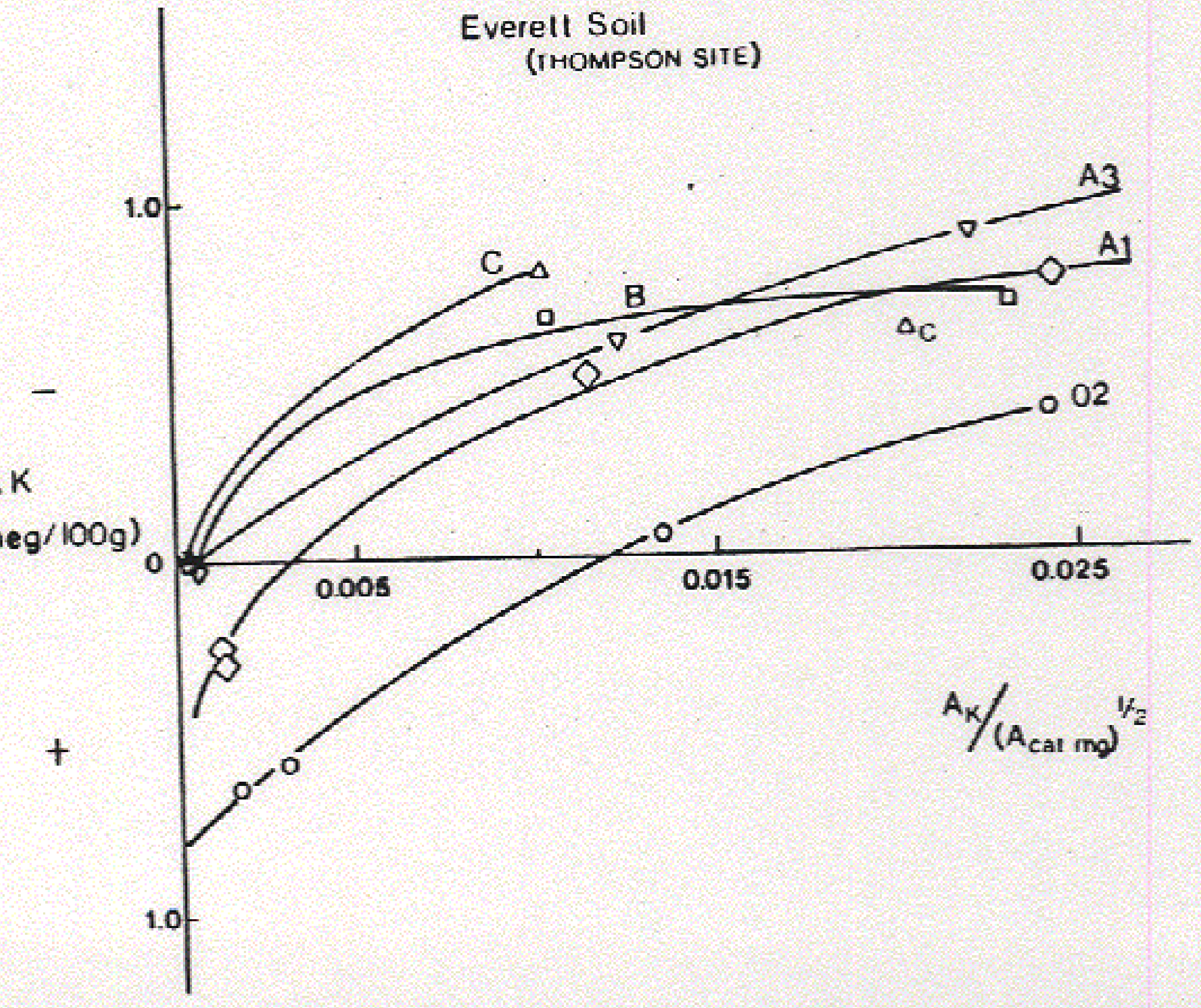
Examination of K and other basic cations in the context of this model suggests that base supply is regulated first by the amount available in the parent material, which is modified by the extent of weathering and the exchangeable cation levels. Potassium associated with the forest floor and organic matter is important to forest stands. Controls on K in basic cation supply forests are much less dependent on biological mediation than are the controls on N.

SUMMARY

Soil fertility is a broad subject and encompasses much more than nutrient supplies; however, even a consideration of nutrient supplies must be given a sketchy treatment in a paper of this length.

To conceptualize the wide array of possibilities which influ-

Figure 8. Quantity-intensity relationships for the various horizons of the Everett soil (Thompson site).



ence nutrient supply, a model having input sources and sinks was constructed. Using this framework, factors influencing nutrient supplies were discussed and the specifics of N and K supplies were outlined. Necessarily many details were omitted; however, differences between N and K are readily observed using a simple model and the essential factors regulating nutrient supplies are evident.

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