

MINERAL CYCLING IN FOREST ECOSYSTEMS OF THE PACIFIC NORTHWEST

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ABSTRACT

Accumulation and cycling of nutrient elements has been assessed for a number of Pacific Northwest species including red alder, Pacific silver fir, hemlock, Sitka spruce, and larch. The most comprehensive studies, however, have involved Douglas-fir. This paper reviews the scope and history of this program with special attention given to studies involving nutrient additions by chemical fertilization and the application of wastewaters and dewatered sludge from a municipal sewage treatment facility.

While rates of transfer and many of the processes of cycling vary between these species, there is very little nutrient loss from these ecosystems. Except in the case of alder, nitrogen is tightly conserved and extensively reused in these ecosystems, a process by which the nitrogen demand is minimized for these nitrogen-deficient systems.

Addition of nitrogen in the form of urea and treated secondary effluent has not resulted in accelerated leaching losses. Rather, these additions have resulted in a rapid acceleration of the nutrient cycle and increase in biomass production. Discussed are the mechanisms by which these additions are returned, conserved, and recycled within the ecosystem.

INTRODUCTION

Mineral cycling studies provide a means by which the nutrient dynamics of an ecosystem can be viewed, including such considerations as the pathways and rates of nutrient transfer, rates of nutrient accumulation and loss. More importantly, such studies should also provide us with an understanding as to the processes that regulate these fluxes and way(s) in which such fluxes, acting individually or collectively, regulate behavior of the ecosystem.

In forestry such studies have provided us with a number of insights as to how such systems function under both natural and managed conditions including (1) differences in nutrient requirements and nutrient uptake rates for various forest types, ages, and growing conditions; (2) relationship between nutrient requirement and rates of production; (3) consequences of forest management practices on the nutrition of a forest including fate of applied fertilizers (rate of leaching, quantity taken up) and the impact of harvesting on nutrient loss; and (4) impact of atmospheric inputs such as acid rain on productivity and nutrient stability.

The study of mineral cycling in the forests of the Pacific Northwest represents some of the earliest research of this type. The early forest nutrition research of Gessel provides much of this initial interest. Articles by Cole, Gessel and Held (1961), Gessel and Cole (1965), and Cole, Gessel, and Dice (1967) provided for this region our first descriptions of cycling rates under both natural and managed forest conditions. A research site was established on the Cedar River Watershed for the specific purpose of assessing the pathways, rates, and processes of elemental cycling in forest ecosystems. This site was permanently dedicated for this purpose by the City of Seattle and formally named the Allen Thompson Research Site, after a former director of the Cedar River Watershed. A bulletin was written describing the site and the program activity at that time (Cole and Gessel 1968).

A major step was taken in this program area when the Cedar River Watershed and the Thompson Site became one of the two intensive study areas for the Coniferous Forest Biome of the US-International Biological Program (IBP). The H. J. Andrews Experimental Watershed in Oregon became the second site. Mineral cycling studies were a major part of this overall program which lasted from early 1970 to December 1978. A synthesis of these studies will be available within the coming year (Edmonds, in press). Since the termination of this IBP study a number of new programs concerning mineral cycling in forest ecosystems have emerged. This article will summarize the highlights of this program discussing in particular, those aspects of cycling of significance to tree nutrition and forest fertilization.

PATTERNS OF CYCLING FOR VARIOUS FOREST TYPES OF THIS REGION

The most extensive research on mineral cycling in this region has focused on Douglas-fir, although other species including red alder and silver fir and, to a lesser extent, hemlock, Sitka spruce, poplar, larch, and ponderosa pine have also been studied. The following section briefly reviews the more comprehensive of these studies, comparing when appropriate the general patterns of cycling found in western forest ecosystems.

DOUGLAS-FIR

As mentioned above, the species most extensively studied in this region is Douglas-fir. Although some of the earlier research was conducted at Pack Forest and other Pacific Northwest sites (Cole et al. 1961, Heilman and Gessel 1963), the more recent studies have been carried out on the Cedar River Watershed at the Thompson Research Site and the H. J. Andrews experimental forest in Oregon. Because of the attention that has been placed on this species, we now know many facts of its cycling characteristics. In this discussion, specific attention will be directed at the rate of nutrient transfer including leaching rates and the changing patterns of cycling with stand development.

It was observed early on in this program that nutrients, especially N and P, are not readily lost by leaching from these ecosystems (Gessel and Cole 1965; Cole, Gessel, and Dice 1967). The dissertations by McColl (1969) and Johnson (1975) addressed this question and proposed a general mechanism by which ions are transported by means of a leaching process through forest soils (McColl and Cole 1972). In order for cations, such as ammonium cation, K, and Ca to be leached from the soil, they have to be accompanied by an equivalent number of anion charges (Figure 1). In the forest soils of this region the major anion is typically bicarbonate ion, a hydrolysis and ionization product of carbon dioxide (Cole, Crane, and Grier 1975). The amount of bicarbonate ion present is regulated by both pH and carbon dioxide partial-pressure. Thus, any condition that increases the pH or the rate of soil respiration will in turn increase the potential for cation leaching. With the modest respiration rates and acid conditions of our forest soils, there is consequently little opportunity for nutrient leaching to occur. Typical leaching rates that have

been observed for this second-growth Douglas-fir forest at the Thompson Research Site are tabulated in Table 1.

For N, this rate of leaching past the 100 cm depth is somewhat less than the rate of N addition in rainfall (Table 2). While the other elements indicate a slight net loss, the magnitude of loss is insignificant when compared to the total nutrient pool within the soil component. For example, net loss of 1.7 kg/ha/yr of Ca represents only 0.0005% of the total Ca pool and 0.2% of available Ca located on the soil exchange sites. For K and P, this net loss is even less significant when compared to the supplies present within the soil.

It is clear from this data that nutrients are tightly conserved within this ecosystem and only minimal losses occur. Although it will not be a subject of this discussion, research at this site also indicated that management practices such as clearcutting and burning had only a minimal effect in changing the leaching rates discussed above (Gessel and Cole 1965; Cole, Crane, and Grier 1975).

Cycling of elements between ecosystem components clearly changes as the forest matures. Studies by Turner (1975) in a wide range of stand ages between 9 and 95 yr clearly documented such changes for Douglas-fir at the Thompson Site. Grier et al. (1974) provide a comparison in cycling between the second-growth forests at Thompson Site and the 450-yr-old forest at H. J. Andrews in Oregon. From this research it is clear that closure of the forest canopy has a significant impact on the nutrient cycle. Before stand closure, the understory vegetation assumed a prominent position in the structure of these ecosystems. For example, at 9 yr there was approximately an equal distribution of N between the forest and understory. This relationship rapidly changed, however, as the

Figure 1. Role of the bicarbonate ion, pH, and CO₂ in the leaching process (Cole et al. 1975).

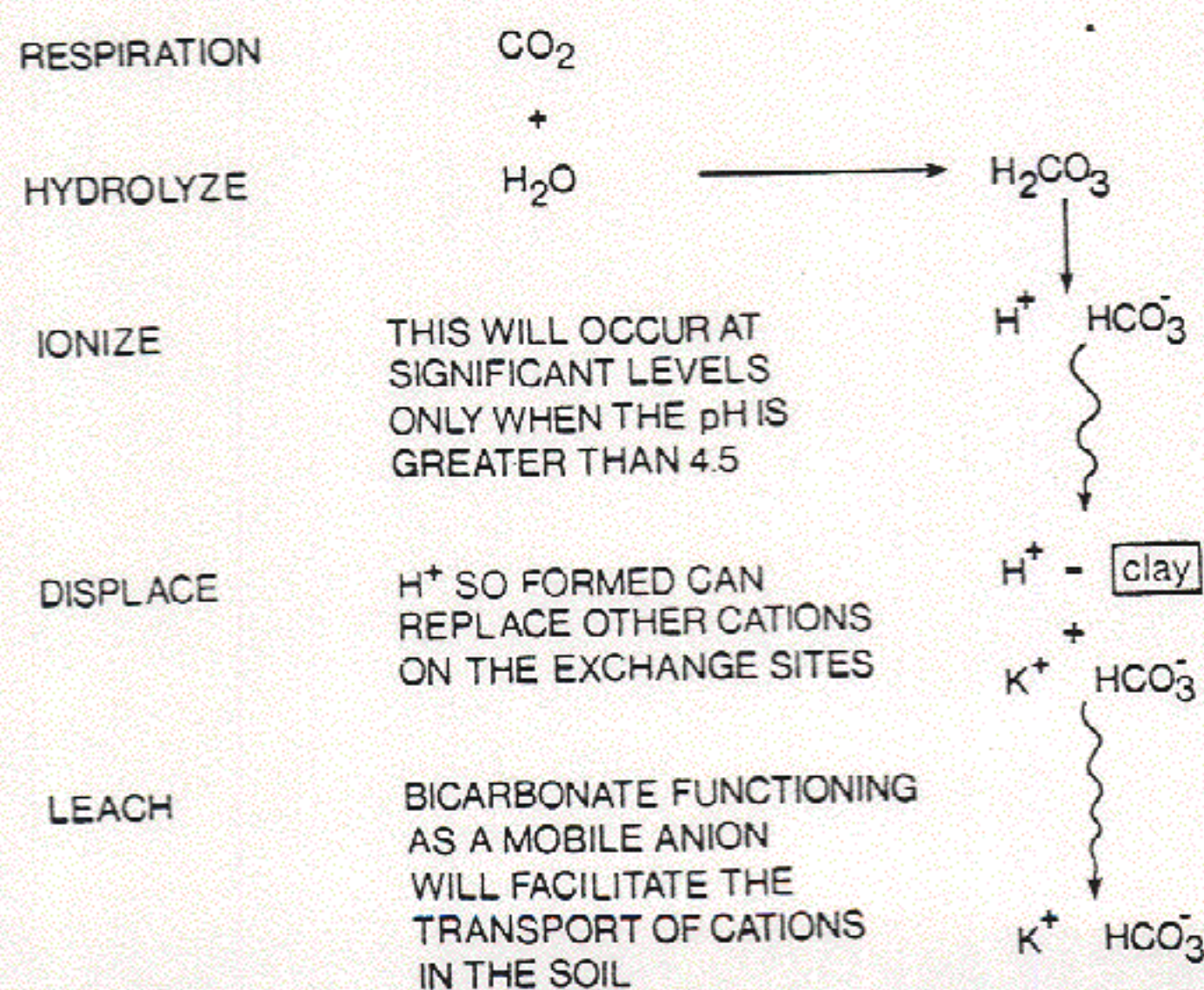


Table 1. Leaching of N, P, K, and Ca (kg/ha/yr) through the forest floor and soil at the Thompson Research Site, Cedar River Watershed.

	N	P	K	Ca
Leaching past forest floor	4.8	0.95	10.5	17.4
Leaching past 100 cm depth	0.6	0.02	1.0	4.5

Table 2. Net balance of nutrients entering and leaving the Douglas-fir ecosystem at the Thompson Research Site (kg/ha/yr).

Nutrient	Atmospheric input	Leaching loss	Net balance
N	1.1	0.6	+0.5
P	T	0.02	-0.02
K	0.8	1.0	-0.20
Ca	2.8	7.5	-1.7

crown began to close at age 22 yr. By age 30 yr, N accumulation in the understory vegetation declined rapidly (Figure 2).

With closure of the forest canopy at about age 30 yr, there was little increase in elemental accumulation in the forest foliage. As expected, uptake remained relatively stable after this period. Data from Grier et al. (1974) for a 450-yr-old stand suggest that N uptake declined as the forest reached a state of overmaturity (Table 3). Similar relationships between stand development, ground cover vegetation, and nutrient uptake declined as the forest reached a state of overmaturity (Table 3). Similar relationships between stand development, ground cover vegetation, and nutrient uptake was found for spruce, *Picea abies*, in Russia (Kazimirov and Morozova 1973). The reason for this change in uptake with stand development is undoubtedly coupled with many other aspects of the system. As a stand matures there are changes in biomass production, mineralization of the soil organic matter, and length of needle retention. Whether N translocation changes with age, thus also affecting uptake rates, has not been demonstrated.

RED ALDER

Cycling of nutrients in red alder ecosystems is very different than that noted for Douglas-fir. At the Thompson Research

Site it was possible to directly compare the cycling of these two forest types. The Douglas-fir forest was the result of a plantation established in 1931. At the boundary of this plantation a red alder stand naturally regenerated providing an excellent comparison for research purposes between these two species.

A number of interesting ecological comparisons have been reported from this research (Turner et al. 1978, Cole et al. 1978). Data derived from these studies allow us to estimate average annual rate of N accumulation in red alder stands. During the approximate 38-yr period of alder growth on this site an average annual N accumulation of 85.3 kg/ha has occurred. This annual increment of N is distributed within all ecosystem components, with 57.4 kg in the soil, 18.4 kg in the forest floor, and 9.5 kg in overstory and understory vegetation (Table 4). This rate of N accumulation is not inconsistent with other values reported in the literature. Tarrant and Miller (1963) calculated an average annual accumulation of 41 kg/ha over a 30-yr period of alder occupancy relative to Douglas-fir occupancy of similar sites.

Major differences in pathways of elemental transfer in these

Figure 2. Accumulation of N, K, and Ca in the understory vegetation of various aged stands of Douglas-fir (Cole et al. 1975).

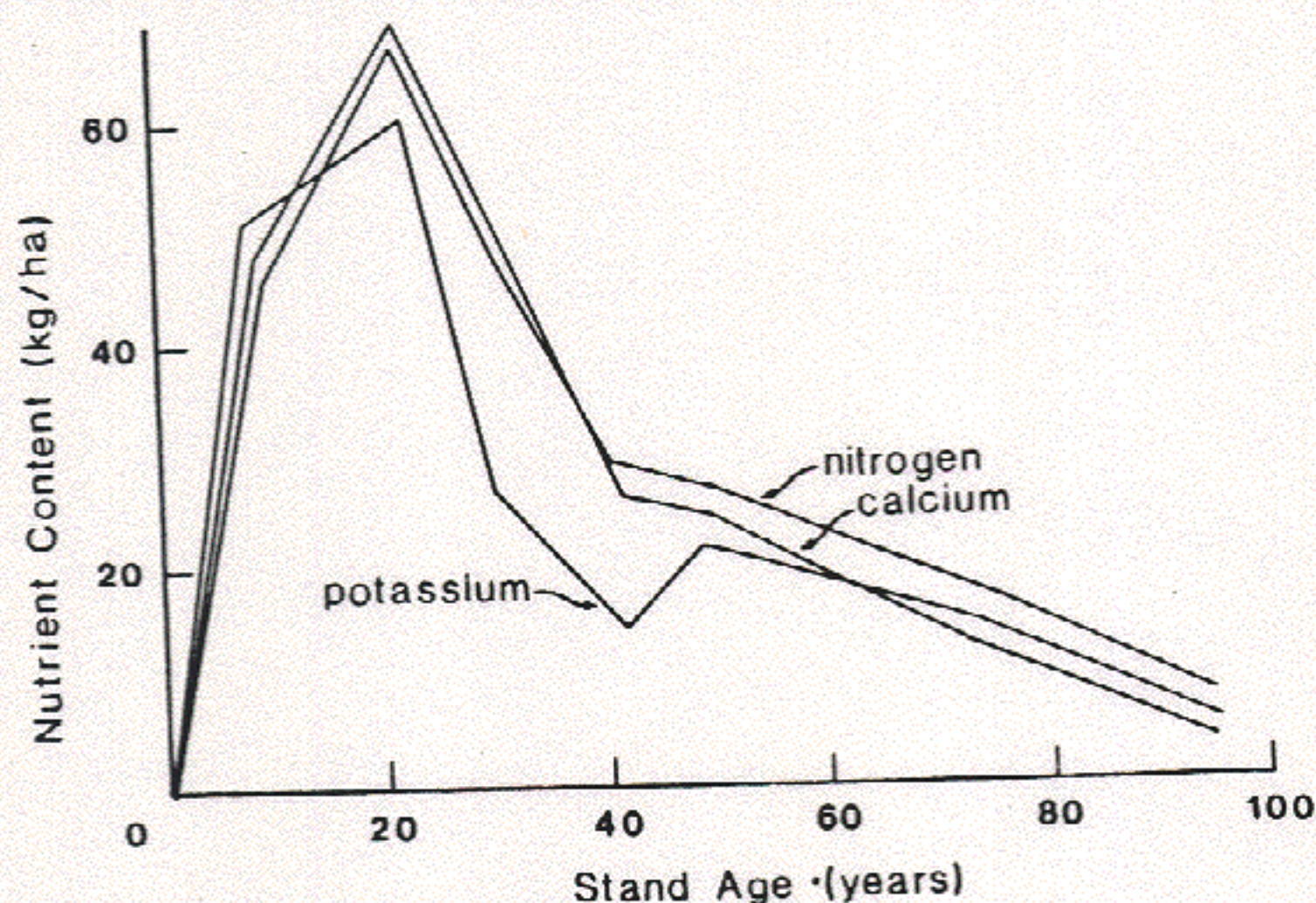


Table 3. Effect of stand age on uptake of nitrogen by Douglas-fir (*Pseudotsuga menziesii*) (after Turner 1975; Grier et al. 1974).

Stand age	Annual uptake (kg/ha/yr)
9	3.7
22	33.7
30	32.1
42	32.8
73	32.5
95	37.3
450	23.7

Table 4. Total and average annual nitrogen accumulation by 38-yr-old red alder (kg/ha).

	Estimated N accumulation Douglas-fir	red alder	Increase in red alder over Douglas-fir	Average annual accumulation
Overstory	320	590	270	7.1
Understory	10	100	90	2.4
Forest floor	180	880	700	18.4
Soil	3270	5450	2180	57.4
Total	3280	7020	3240	85.4

ecosystems are also apparent (Table 5). Annual return of K and Ca as well as N by throughfall and litterfall is six to eight times greater in the case of alder than in Douglas-fir. Annual uptake of N, K, and Ca is three to five times greater. Comparing uptake with return clearly shows that the Douglas-fir system still has a net annual increase, while alder has nearly reached a steady state between uptake and return. This fact implies that alder has reached maturity and is nearly at the end of its rotation age while Douglas-fir is still growing. These results are consistent with the respective ages of the two stands and from what we know to be their life expectancy.

Loss of nutrients by leaching appears to be slightly greater under the alder ecosystem (Table 5). Lysimeter collections of soil solution beneath the rooting zone have demonstrated that some increase in the leaching of N was found, because a greater amount of soil N is converted to the nitrate form in the presence of alder.

The added N derived through fixation in the alder stand has resulted in an increase in cycling rates and rates of leaching loss. However, these losses are low especially when compared to the high rates of input.

PACIFIC SILVER FIR

Pacific silver fir is typically found in the subalpine zone of this region. Consequently, climatic conditions for decomposition are not as favorable as those in the lower elevations where alder and Douglas-fir are found. This depressed rate of decomposition has not had a significant impact on the mineral cycle of this ecosystem. Rate of leaching through the soil (Grier, un-

pub. data) is not significantly different from that noted for the Douglas-fir ecosystem discussed previously (Table 6).

In both cases there is very little nutrient loss due to deep leaching. However, the mechanism regulating leaching is different. Rather than bicarbonate acting as the carrier ion regulating cation losses, the carrier ion is largely derived from ionization of organic acids (Johnson et al. 1977). A comparison between Douglas-fir and Pacific silver fir regarding anion composition of leachates passing through these ecosystems is illustrated in Figure 3.

This decrease in forest floor decomposition has also caused a shift in root distribution and the zone in the soil where nutrients are taken up. A relatively thick forest floor layer accumulates as a Pacific silver fir stand develops toward maturity. Consequently with time, N is systematically redistributed within the soil, accumulating within the forest floor layer. A correspond-

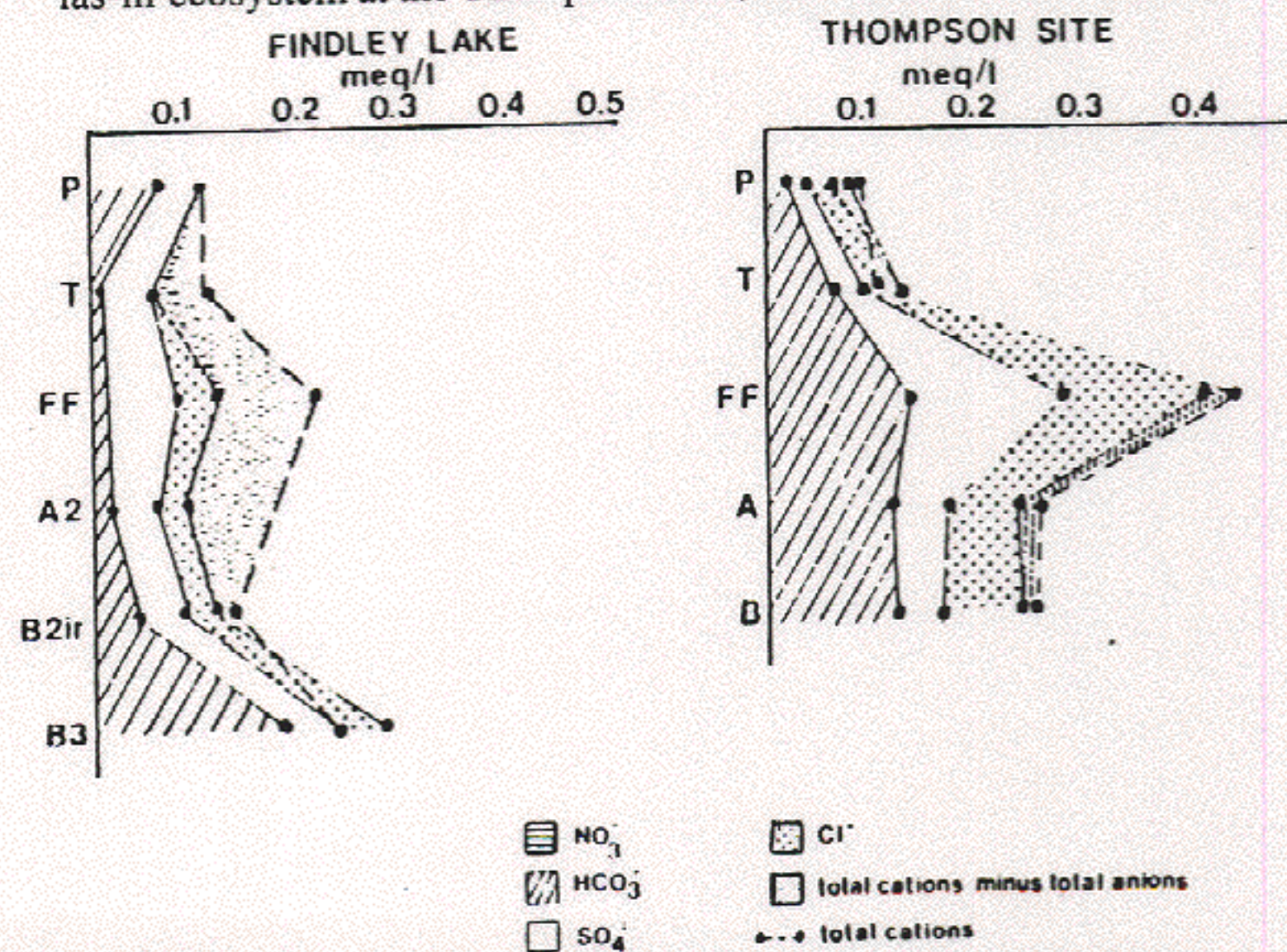
Table 6. Rate of nutrient transfer (kg/ha/yr) in a 22- and 180-yr-old Pacific silver fir ecosystem (unpublished data from Grier).

	Nitrogen	Phosphorus	Potassium
180-yr-old stand			
Throughfall	9.9	1.5	7.7
Litterfall	12.0	1.5	5.4
Forest floor leaching	4.0	1.2	6.8
Leaching 70 cm	1.7	0.2	6.0
22-yr-old stand			
Throughfall	9.9	1.2	10.3
Litterfall	12.1	1.6	5.5
Forest floor leaching	4.1	0.4	6.9
Leaching 70 cm	1.6	0.2	5.8

Table 5. Annual nutrient transfers in red alder and Douglas-fir ecosystems (kg/ha).

	Douglas-fir	Red alder
Nitrogen		
Precipitation	1.1	1.7
Throughfall	1.5	8.8
Litterfall	13.6	111.1
Uptake	39.0	130.0
Leaching loss	0.6	2.2
Potassium		
Precipitation	0.8	2.2
Throughfall	10.7	12.4
Litterfall	2.7	67.0
Uptake	29.0	98.0
Leaching loss	0.02	No data
Calcium		
Precipitation	2.8	2.2
Throughfall	3.5	10.0
Litterfall	11.1	83.0
Uptake	24.0	116.0
Leaching loss	4.5	5.6

Figure 3. Weighted average anion and total cation concentrations in solutions from Pacific silver fir ecosystem at Findley Lake and Douglas-fir ecosystem at the Thompson Site (from Johnson et al. 1977).



ing shift in fine-root biomass into the forest floor layer from the 22 to 180-yr-old forest was noted by Grier (submitted for publication). The mycorrhizae fungi associated with these fine roots are shifted in their distribution pattern and became more prevalent in the forest floor layer in the 180-yr-old forest (Figure 4).

Due to low mineralization rates in this subalpine zone, Pacific silver fir has evolved a means of maintaining biomass production under minimal rates of N uptake. This is primarily achieved by retaining foliage for nearly 12 yr. Therefore only a small fraction of the canopy has to be replaced each year. Such an increase in foliage retention results in a decrease in the amount of N uptake required for each unit of biomass produced. For example, Douglas-fir at the Thompson site takes up 0.057 kg of N for each kg of biomass produced. In contrast, Pacific silver fir takes up only 0.0044 kg of N for the same unit of production, some 30% less.

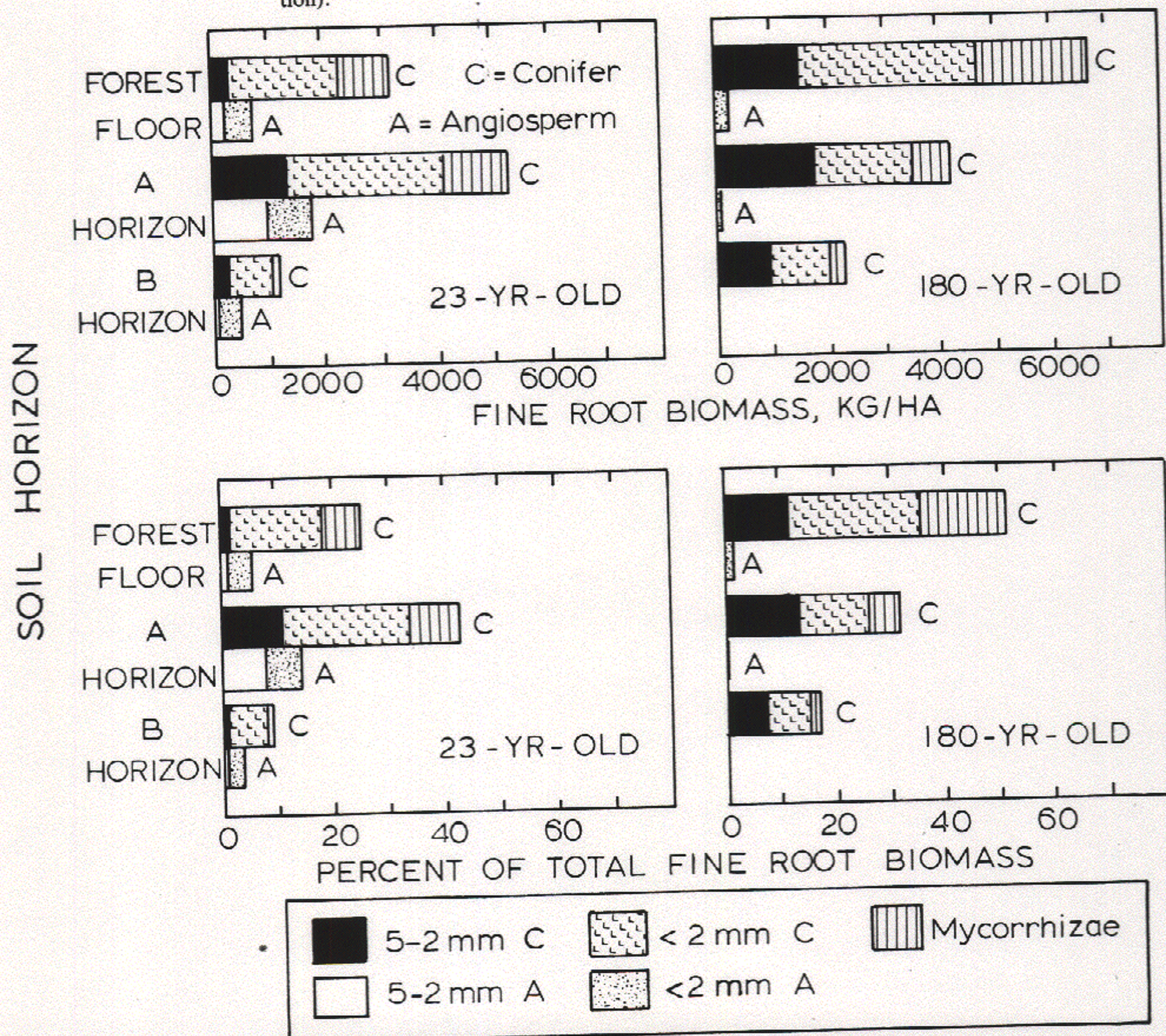
THE EFFECT OF NUTRIENT ADDITIONS ON THE MINERAL CYCLE

UREA FERTILIZATION

Application of urea to a forest ecosystem will predictably change some aspects of the nutrient cycle. If a greater growth response is noted, a part of the addition was taken up by the forest. Heilman and Gessel (1963) first measured this increase in uptake for Douglas-fir in their studies nearly 20 yr ago. In most cases only 10% to 20% of the added N can be found in aboveground biomass. Thus the question remained as to the fate of the remaining fertilizer that had been applied.

At the Thompson site research by Cole and Gessel (1965) clearly showed that added N did not leach out of the soil but

Figure 4. Distribution of fine roots and mycorrhizae in a 23- and 180-yr-old *Abies amabilis* ecosystem (Grier et al., submitted for publication).

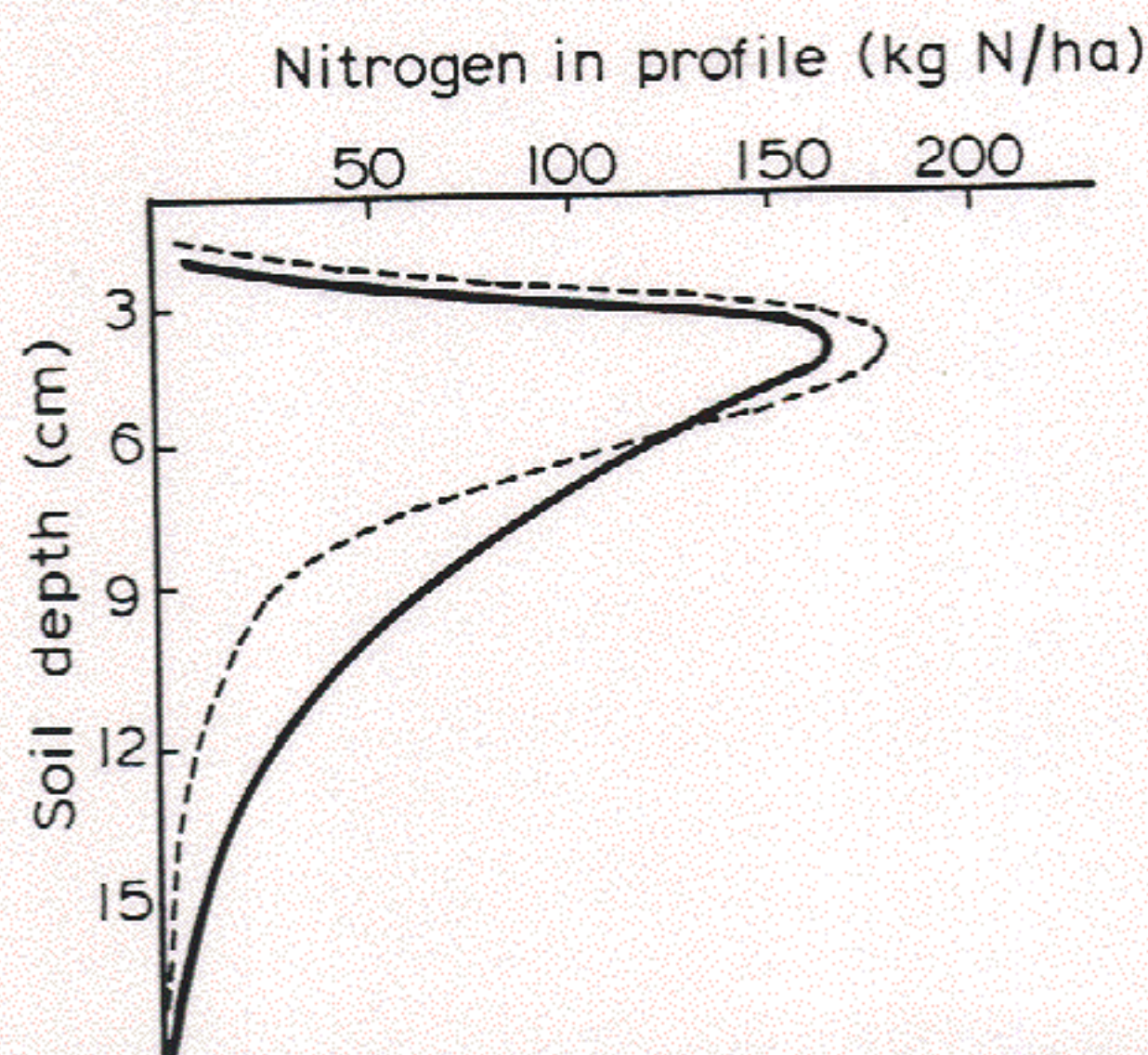


remained within the rooting zone. In his dissertation research Crane (1972) established that N remained within the top 30 cm of the soil surface (Figure 5). Increasing rates to 400 kg/ha and irrigating did not significantly change the leaching of applied urea. This lack of deep leaching in the soil can be explained as follows. Urea is a highly soluble nonionic polar organic compound, and it is therefore readily leached if applied during rainy period.

However, urea rapidly hydrolyzes to ammonia carbonate and bicarbonate through an enzymatic reaction involving urease. Urease is commonly present in forest soils. Since carbonic acid is a weakly dissociated acid and there are two ammonia molecules produced for each carbon dioxide, the net result is a sharp rise in solution pH. In most cases bicarbonate anion remains the dominant carbonate form (pH remains below 8.3), so that an ammonium bicarbonate solution results. As the ammonium bicarbonate solution moves through the soil profile ammonium displaces native cations such as K, Ca, Mg, and H from the exchange sites by mass action (Figure 6). Thus, urea fertilization increases the solution concentrations of cation nutrients in addition to ammonium.

In deeper horizons displaced H combines bicarbonate anion to form carbonic acid, so that bicarbonate concentrations as well as ammonium concentrations decrease as solutions pass deeper into the soil. The result is that ammonium ion is largely retained in the upper 15 cm of the soil. Should the initial hydrolysis of urea be delayed or blocked, far greater leaching losses of N would occur. In most cases the hydrolysis is rapid enough so that little N loss occurs. Should ammonium ion produced from hydrolysis be further oxidized to nitrate anion through nitrification, leaching could again be expected. Fortunately this does not appear to happen.

Figure 5. Nitrogen distribution in the soil profile following urea fertilization. Solid line shows results after heavy irrigation, dashed line is after light irrigation (from Crane 1972).



APPLICATION OF MUNICIPAL WASTEWATER

With the increasing concern over disposal of wastewaters from municipal and industrial sewage treatment facilities into aquatic systems there has been interest in recent years to determine the feasibility of using these wastewaters in the irrigation of forest and agricultural lands. A study was initiated 5 yr ago at Pack Forest to determine if forests in the Northwest could be used in this way. Two critical questions were addressed. (1) Would the forest ecosystems remove sufficient quantities of nutrients from the wastewaters to meet drinking water stands of US-EPA? (2) Would the forest produce a significant increase in growth due to these irrigations?

Wastewaters (derived from the METRO treatment plant at Renton) contain approximately 16 ppm ammonium ion and 2 ppm nitrate anion. By applying 5 cm of wastewater to the plots each week, approximately 8 kg/ha of mineral N was being applied weekly or 400 kg/ha yearly for this entire 5-yr period. These irrigations were made to seedlings of Douglas-fir and

Figure 6. Effect of urea fertilization on leaching processes in the soil profile (Cole et al. 1975).

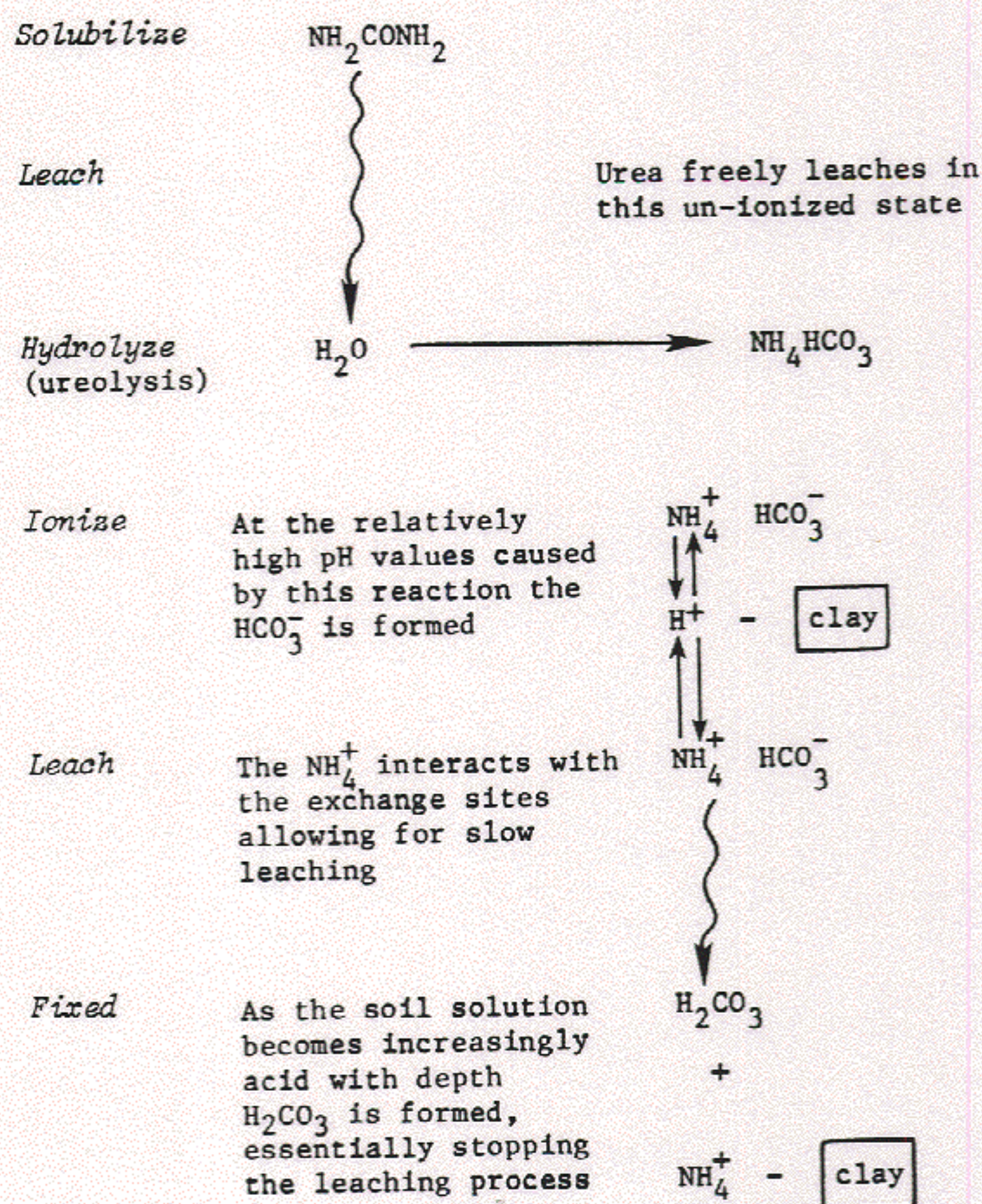


Figure 1. Effect of urea fertilization on leaching processes in the soil profile (Cole et al., 1975).

poplar. Five years of such irrigations clearly demonstrated that these seedlings could indeed utilize such additions since less than 20% of the added N leached beyond the rooting zone (Table 7). Furthermore much of this loss occurred in the first year before the trees were well established. As evident from Figure 7, N uptake values for these species after 4 yr of wastewater irrigation were manyfold higher than those of the control, irrigated with equal quantities of riverwater. Results after five growing seasons have not been measured at this time.

Uptake rate observed for these plots far exceeds uptake rates previously reported for forest ecosystems of any age or silvicultural treatment. Interestingly, total uptake values of 215 kg/ha/yr for the Douglas-fir plot and 350 kg/ha/yr for the poplar plot are similar to those one would expect in an intensively managed agricultural ecosystem (Frissel 1978).

This data clearly demonstrates the capacity of forest ecosystems to respond to greatly elevated levels of nutrient additions.

The increase in N uptake resulted in a dramatic increase in biomass production (Figure 8). Over 30 metric tons/ha of biomass are produced annually from the poplar plot after only 4 yr following establishment. Production on the Douglas-fir plot is over 20 metric tons/ha. In both cases production is still increasing rapidly.

Table 7. Net flux of nitrogen on wastewater treated plots from 1974-1978 (kg/ha).

Plot	Applied	Leached	% Retained
Poplar	1629	249	85
Douglas-fir	1438	271	81
Grass	1679	248	85
Barren	1801	830	54

Figure 7. Nitrogen uptake from plots irrigated with wastewater and river water (1977-1978, ages 3 and 4 yr).

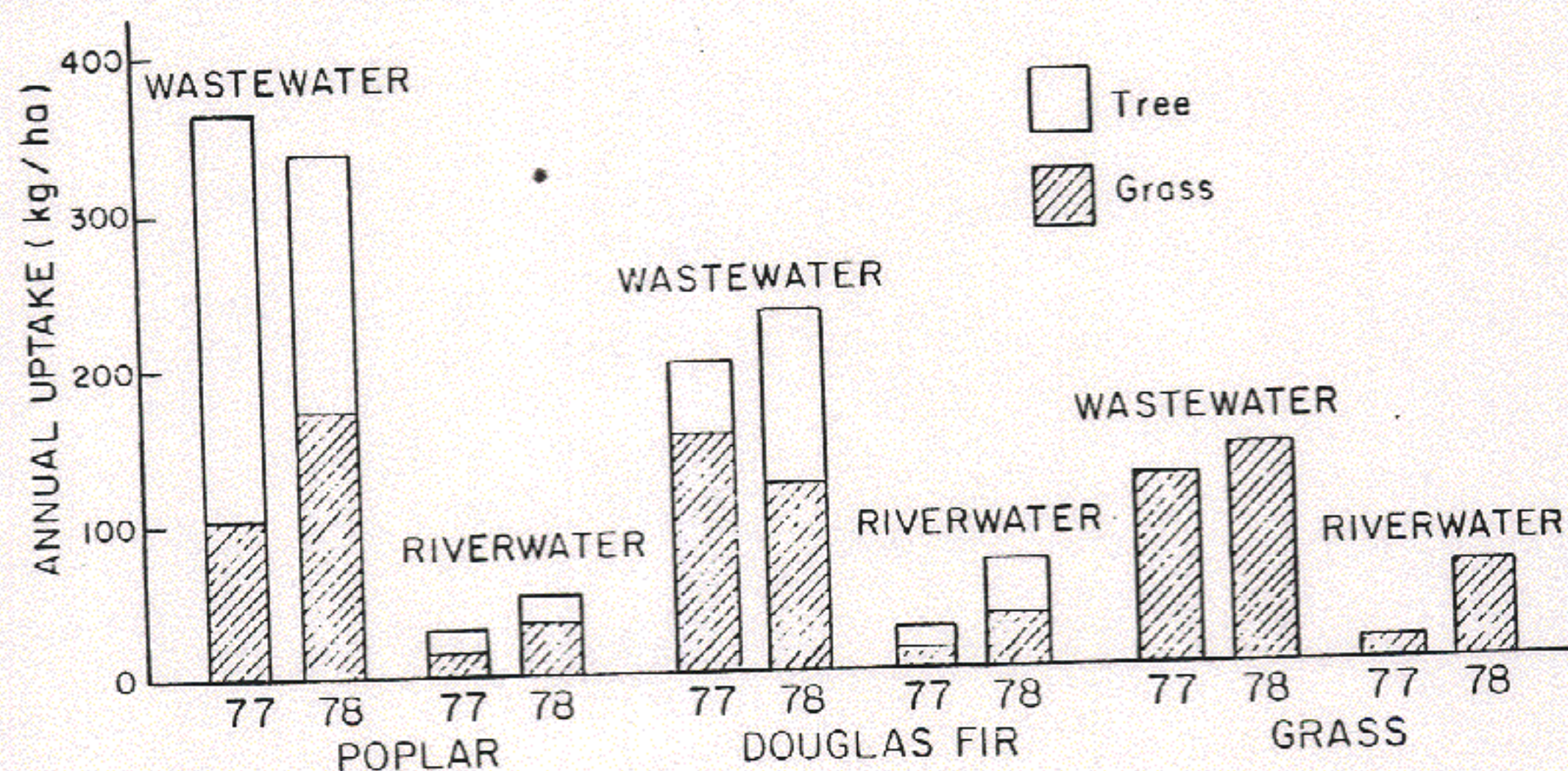
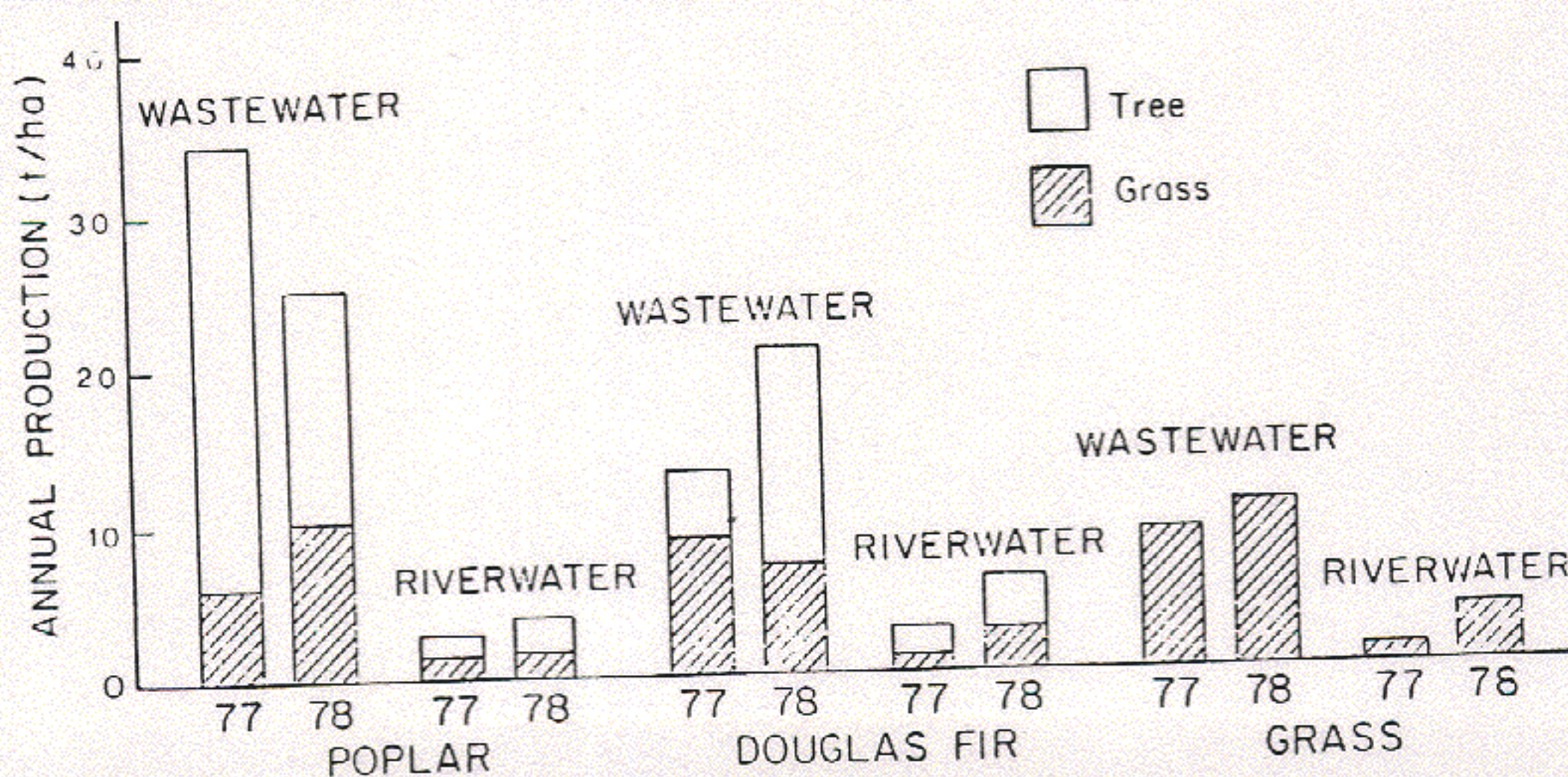


Figure 8. Aboveground biomass production from plots irrigated with wastewater and river water (1977-1978, ages 3 and 4 yr).



CONCLUSIONS

In comparison to most other forest regions of the world, we know a great deal about the mineral cycle of the forests of the Pacific Northwest. This is especially true of Douglas-fir on which mineral cycling studies have now been focused for nearly 20 yr.

From these studies much has been learned about how these ecosystems behave. Perhaps some of the most significant findings to forestry and forest fertilization are:

1. These forest ecosystems are basically very stable. Nutrients, especially N, will not easily leach out of these systems. Addition of fertilizers, and even large quantities of wastewater, does not appear to increase these low leaching rates.
2. There is a very close relationship between ecosystem components. Changing one part of the nutrient cycle will change the dynamics and nutrient distribution within the entire system. This happens naturally as a forest matures. It can also happen when a forest is managed.
3. Uptake of N is closely related to production of biomass.
4. Uptake rates can be achieved in forestry that are many times higher than those observed in nature and as high as those found in intensive agriculture.

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