# THE UPTAKE, CYCLING AND REMOVAL OF MINERAL NUTRIENTS BY CROPS OF *PINUS RADIATA*

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## INTRODUCTION

This paper brings together the results obtained, so far, from a series of studies of the quantities of mineral nutrients moving into, within, and out of a *Pinus radiata* forest growing on a pumice soil in the North Island. Most of the data have already been published but it seems worthwhile to bring together all the information at present available and to review the present extent of our knowledge.

Large-scale planting of exotic conifers in the central region of the North Island began only in the late 1920s but growth rates are high (Will 1966b) and over large areas the first crop of *P. radiata* has been harvested. Some second crops are old enough for logs to be extracted during thinning. Unlike some other areas which grow *P. radiata*, e.g., South Australia (Keaves 1966), and Nelson, New Zealand (Stone and Will 1965), there is no evidence of a reduced growth rate in the second crop. However, on the same soils agriculture is successful only with the use of relatively heavy initial and maintenance applications of fertilisers. Although agriculture makes higher demands on the soil than forestry, its high fertiliser requirements suggest that successive tree crops could deplete the soil of one or more nutrients to the point where tree growth was retarded.

Various aspects of the cycling of nutrients within trees, between trees and the soil, and possible nutrient gains and losses have been studied to provide a basis for assessing which nutrients could become seriously depleted.

## EXPERIMENTAL

A large part of the work reported in this paper was done in or near Compartment 69, Kaingaroa Forest, part of which has been set aside as an experimental site. Tree growth in the first crop of radiata pine was typical of that over a large part of the forest. The soil, Kaingaroa silty sand, is similar to that over many thousands of acres including those at the site of a root study (Will 1966b) in a more northerly part of Kaingaroa Forest and the site, in Whakarewarewa Forest, where measurements were made of dry weights and nutrient uptake in second crop trees (Will 1964). At each site the main tree rooting zone is in Taupo Ash (Vucetich *et al.* 1960; Healy *et al.* 1964).

Details of field and laboratory experimental methods have been reported in previous publications (Orman and Will 1960; Will 1957, 1959, 1964, 1966b).

## RESULTS AND DISCUSSION

Insufficient data are yet available to summarise all aspects of nutrient cycling and re-use, particularly as some nutrients are recycled faster than others. However, data on the quantities of nutrients returned to the soil surface in slash, litter and rain have been obtained. When these results are added to the amounts of nutrients removed from the forest in logs the total nutrient uptake by a tree crop, including recycled nutrients, may be estimated.

### *Return to soil in litter and rainwater*

In the early 1950s studies of litter-fall and release of nutrients from the litter layer were begun in Whakarewarewa Forest. In results, so far unpublished, I found that, at least for potassium and sodium, much larger quantities were being leached from the litter layer than were being added to it in litter-fall. These findings led me to collect and analyse rainwater, as well as litter, under the tree canopy. I reported (Will 1959) average figures for additions to the soil under *P. radiata* in two pumice soil forests as follows:

| | N. | P. | K. | Ca. | Na. | |
|---|---|---|---|---|---|---|
| Litter | 31.0 | 3.0 | 12.5 | 18.5 | 3.0 | lb./ac./yr. (1) |
| Rainwater | * | 1.0 | 19.5 | 3.5 | 26.0 | lb./ac./yr. (2) |
| Total | †31.0 | 4.0 | 32.0 | 22.0 | 29.0 | |

* Not determined. † Not less than.

Most of the nutrients which are returned to the soil dissolved in rain, are presumably immediately available for re-use by the trees but this is not true of nutrients in the litter-fall. My study of decomposing litter (Will 1967) has shown that most of the potassium in litter is leached out within the first three months; about half the phosphorus is removed in the same time, but the release of calcium and nitrogen is much slower. More than half of the calcium remains after two years and there is no release of nitrogen in the first two to three years. There is also evidence to suggest that any nitrogen in rainwater may be immobilised in litter for some time before becoming available to trees.

*Removal in logs and return in slash*

Orman and Will (1960) found that a 26-year-old Site Quality IIa stand of *P. radiata* (first crop with no silvicultural treatment) consists of about 200,000 lb. of dry matter per acre above ground which contain 200 lb. of nitrogen, 25 lb. of phosphorus, 200 lb. of potassium and 115 lb. of calcium. Applying the results of another study (Will 1966b), an estimate of the weight and content of roots is 25,000 lb. dry matter containing 30 lb. nitrogen, 12 lb. phosphorus, 25 lb. potassium and 25 lb. calcium. The total nutrient content of a 26-year-old crop is therefore:

| N. | P. | K. | Ca. |
|---|---|---|---|
| 230 | 37 | 225 | 140 lb./ac. |

At clear felling the following amounts would be removed and the remainder left in the ground or on it as slash:

| | N. | P. | K. | Ca. |
|---|---|---|---|---|
| Removed in logs | 114 | 16 | 140 | 94 lb./ac. |
| Left in roots and slash | 116 | 21 | 85 | 46 lb./ac. |

The removal from the site in logs would thus be equivalent to an average loss of about:

| N. | P. | K. | Ca. |
|---|---|---|---|
| 4.4 | 0.6 | 5.4 | 3.6 lb./ac./yr. |

These figures apply only to an untreated Site Quality IIa crop. In a properly tended crop, the estimated removal over 35 years is equal to (Will 1964):

| N. | P. | K. | Ca. |
|---|---|---|---|
| 205 | 29 | 253 | 168 lb./ac. |

equivalent to an average of:

| N. | P. | K. | Ca. |
|---|---|---|---|
| 5.9 | 0.8 | 7.2 | 4.8 lb./ ac./yr. (3) |

In drawing up a balance sheet for nutrient uptake and return in a stand receiving silvicultural treatment, I estimated (Will 1964) that slash from a first thinning to waste would contain about:

| N. | P. | K. | Ca. |
|---|---|---|---|
| 260 | 23 | 190 | 90 lb./ac. |

whereas slash from clear felling at age 35 years would return to the soil:

| N. | P. | K. | Ca. |
|---|---|---|---|
| 120 | 13 | 85 | 32 lb./ac. |

Field observations suggest that it is reasonable to assume that slash from a second thinning and pruning would add an amount similar to that from clear felling. Thus, total return in slash during the life of the crop would be:

| N. | P. | K. | Ca. |
|---|---|---|---|
| 500 | 49 | 360 | 154 lb./ac. (4) |

This estimate of total return in slash during the life of a 35-year crop must be taken as only approximate, as different silvicultural treatments (e.g. a productive first thinning) would alter the quantities returned to the soil.

To this total from slash should be added return to the soil from rotting roots. No estimate is available of the decomposition of fine roots during the life of a crop but a study of root systems in an 18-year-old stand has shown that root grafting results in most of the roots of trees removed in thinnings remaining alive (Will 1966b). A conservative estimate of the nutrients in root systems at time of clear felling is:

| N. | P. | K. | Ca. |
|---|---|---|---|
| 40 | 16 | 33 | 33 lb./ac. (5) |

Adding (4) and (5) gives a total return to the soil in roots and slash of:

| N. | P. | K. | Ca. |
|---|---|---|---|
| 540 | 65 | 393 | 187 lb./ac. |

If, for the sake of comparison with litter-fall and rain-wash, these figures are expressed as an average return to the soil, they are equivalent to:

| N. | P. | K. | Ca. |
|---|---|---|---|
| 15 | 1.9 | 11 | 5.3 lb./ac./yr. (6) |

Comparison of the figures in (1), (2), (3) and (6) shows that the quantities of nutrients removed in logs are less than the quantities left on the site in roots and slash. When litter-fall and rain-wash are added to the roots and slash, over 85% of all nutrients taken up by a tree crop are returned to the soil.

*Relocation of nutrients within trees*

The average life of pine needles before they fall as litter is about three years, but some remain on trees for up to five years. During this time there are both progressive and seasonal changes in mineral content.

In the foliage of trees growing on pumice soils, calcium and phosphorus increase with age while nitrogen decreases; potassium remains relatively constant (Will 1957). Subsequent work, which is still in progress, has shown that seasonal changes may be appreciable. For example, the nutrient content of foliage on an individual tree has been found to vary as much as: nitrogen 0.97–1.40%; phosphorus 0.08–0.12%; potassium 0.46–0.77%.

It seems that a major factor in these fluctuations is the high demand for nutrients during the spring flush of growth. I have shown (Will 1966a) that when magnesium uptake from the soil was restricted by a spring drought and pruning had recently reduced the amount of foliage on a tree, the translocation of magnesium from the remaining foliage to new growth led to severe symptoms of deficiency in the older needles.

Besides the changes in nutrient content in the needles, there are marked changes in the nutrient content of wood and bark. Concentrations in the living bark vary because it is a conducting tissue and a current study shows that nutrient levels change with season as much as: nitrogen 0.45–0.58%; phosphorus 0.034–0.12%; potassium 0.34–1.84%.

As bark becomes a dead tissue lesser amounts of nitrogen, phosphorus, potassium and calcium are present (Orman and Will 1960). Nitrogen, phosphorus and potassium also decrease as a percentage of dry weight in wood as it ages and becomes further removed from the cambium. However, the calcium content increases steadily up to the time of heartwood formation. There is also evidence that all nutrients are present in higher concentrations in the dry wood zone between sapwood and heartwood than in these tissues themselves. This zone of higher levels has also been found in Corsican and Scots pine (Wright and Will 1958).

*Changes in nutrient requirements with age of tree crop*

The nutrient requirements of a tree crop are at a peak during the period of development of the canopy. Once it has closed and foliage quantity has become constant, nutrient demands are reduced because tree growth consists mainly of the accumulation of wood — a tissue with a lower content of nutrients. Later, when heartwood formation begins, it is heartwood which makes up most of the increase in dry weight. Nutrient demands other than for calcium continue to decrease.

These reduced requirements in the later stages of growth are accompanied by the full operation of the cycles returning nutrients in rainwater, litter, and slash from pruning and thinning. The overall effect is a dramatic reduction in the demand for nutrients placed upon the soil reserves.

I have estimated (Will 1964) that the net demand on soil reserves during the first 10 years of growth would be:

| N. | P. | K. | Ca. |
|---|---|---|---|
| 440 | 37 | 275 | 180 lb./ac. |

but during the next 25 years the reduced demand would be supplied by returning nutrients except for:

| N. | P. | K. | Ca. |
|---|---|---|---|
| 0 | 11 | 75 | 80 lb./ac. |

The second and subsequent crops, growing as they do in the presence of decomposing litter and slash from the previous crop, place a lower initial demand on soil reserves, and so the quantities required during the first 10 years would be only:

| N. | P. | K. | Ca. |
|---|---|---|---|
| 220 | 18 | 178 | 88 lb./ac. |

*Additions to a forest site*

In experiments where rainwater was collected under trees and collections were made just outside the stands (Will 1959), analyses showed that the following quantities reached the ground outside the stand:

| P. | K. | Ca. |
|---|---|---|
| 0.25 | 5.0 | 3.0 lb./ac./yr. |

If these figures represent an import of nutrients from outside the forest, they would go a considerable way towards replacing losses due to removal in forest produce (see 3). However, as these collection points in the open were within 100 ft. of trees more than 100 ft. high, contamination from the trees in the form of solid material as well as in rain blown from the trees by high winds is very likely. Another study was begun early in 1967 in which collections were made well clear of overtopping trees; these, so far, show lower nutrient contents than those found in the earlier study.

Considerable attention has recently been given to the fixation of atmospheric nitrogen in coniferous forests. Richards and Voigt (1963), in reviewing published work, state that nitrogen often accumulates at rates of 50 lb./ac./yr. in the absence of known nitrogen-fixing organisms and that the site of this nitrogen fixation is probably in the soil in the vicinity of roots. But they were not able to identify the active agent.

The Kaingaroa pumice soils which are young and consist of largely unweathered material are known to be weathering relatively rapidly. However, nothing is really known of the rate of release of nutrients by the weathering of primary minerals in pumice soils under a stand of trees.

*Leaching losses*

These free-draining pumice soils lie on porous ignimbrite rock, so any nutrients leached down beyond the rooting zone are lost. To estimate such losses a lysimeter was constructed in 1962. Measurements made over the next three years showed the following losses:

| | Rainfall | N. | P. | K. | Na. | Cl. | Ca. | Mg. | |
|---|---|---|---|---|---|---|---|---|---|
| 1962 | 84 in. | 4.8 | .03 | 23 | 38 | 2.8 | 46 | 2.7 | lb./ac./yr. |
| 1963 | 45 in. | 3.8 | .04 | 5 | 18 | 0.9 | 16 | 1.0 | lb./ac./yr. |
| 1964 | 60 in. | 4.3 | .20 | 11 | 9 | 0.4 | 24 | 2.3 | lb./ac./yr. |

The exceptionally high rainfall in 1962 and the settling down of the replaced soil in the lysimeter obviously had their effects in the first year. The calcium figures are probably unreliable because of contamination from the concrete base of the lysimeter. Even in the third year the figures do not represent losses under normal conditions as the trees planted after building the lysimeter had not formed a closed canopy or started to drop litter. For phosphorus and potassium the 1964 figures suggest that, without a complete canopy and a litter layer, leaching losses equal additions in rain.

After a break of two years, collections and analyses were begun again in 1967. The canopy had then closed and a litter layer had started to form. Measurements over the next few years should give an estimate of leaching losses under normal conditions in *P. radiata* plantations.

*Present soil reserves of available nutrients*

The cycling of nutrients by a stand of trees and gains and losses in the ecosystem are in themselves of considerable interest but their practical significance becomes most apparent when they are considered along with nutrients in the soil that are likely to be available for uptake by a crop of trees.

I have determined the total and available calcium, potassium and phosphorus in the top three feet of a pumice soil (Will 1964). Since then I have made a more comprehensive study of the nitrogen, phosphorus, potassium, calcium and magnesium in the six major layers that make up the soil profile to a depth of nine feet in the central region of Kaingaroa Forest (Will and Knight 1968).

The 'available' quantity of individual nutrients was assayed by growing four successive crops of 1-year radiata pine seedlings with the other nutrients supplied in fertilisers. Every seedling in each crop was removed entire and analysed. This work was supplemented by a number of soil analyses designed to measure the fractions of nutrients available, and potentially available, for uptake over a short period. These experiments showed that the following quantities of nutrients are available to a tree crop:

| N. | P. | K. | Ca. | Mg. | |
|---|---|---|---|---|---|
| 520 | 50 | 3,800 | 2,800 | 670 | lb./ac. |

When these figures are compared with both the quantities removed in logs and the maximum quantities contained in a crop it is obvious that supplies of potassium and calcium are adequate for many crops.

Although the quantities of nitrogen and phosphorus at present available will be sufficient for only one or two crops, there are 10 times greater quantities of each nutrient in the soil in unavailable form in organic matter. In pumice soils allophane-organic matter complexes are known to be very stable and in buried soils have resisted breakdown for many hundreds of years. However, in the present topsoil under radiata pine forest there is fungal activity commonly known as 'bleaching' which can largely destroy the organic matter present and release the nutrients (Vucetich *et al.* 1960). A mycorrhizal fungus which mobilises the nutrients for use by trees is possibly responsible, but even if the nutrients were released into the soil they should not be lost to the trees as this fungal activity occurs in the zone where the majority of feeding roots are found. It is also possible that fixation of atmospheric nitrogen adds to the supply and some phosphorus may become available from the weathering of primary minerals in the soil.

As the greater part of the magnesium present in the rooting zone occurs in a fossil soil at a depth of about eight feet, adequate supplies of this nutrient will depend on tree roots exploiting this layer. Field observations show that roots are present at this depth and it seems probable that the cycling of nutrients will eventually increase the amount of magnesium in the present topsoil.

## SUMMARY

Evidence is presented that the cycling of nutrients in *Pinus radiata* plantations on a pumice soil will retard serious depletion of nutrients at least until the end of the second crop.

Of the quantities of nitrogen, phosphorus, potassium and calcium taken up from a pumice soil by *P. radiata* forest, at least 85% is returned to the soil as litter and wash from the tree crowns in rain, and as slash from thinnings, prunings and clear felling. This slash returns more nitrogen, phosphorus and potassium to the soil than is removed in logs.

There are seasonal fluctuations in the nutrient content of foliage and living bark as well as progressive changes in foliage, bark and wood as the tissues age. Levels of all nutrients in bark fall as it becomes older: the same is true of wood except for calcium. This results in reduced demands on soil reserves of nutrients during the latter part of the life of each crop when the greatest part of dry matter accumulation is in the form of heartwood.

Nutrient additions from outside the forest in rainfall are likely to be offset by losses through leaching.

Soil nutrient reserves of potassium and calcium seem adequate for a number of tree crops but supplies of nitrogen and phosphorus will largely depend on their release from soil organic matter which forms stable complexes with allophane in these soils. Fungal activity associated with tree roots does seem capable of destroying these complexes and releasing nutrients.

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