# DRY MATTER AND NUTRIENT RELATIONSHIPS IN STANDS OF PINUS RADIATA*

H. A. I. MADGWICK
Forest Research Institute, New Zealand Forest Service,
Private Bag, Rotorua, New Zealand

(Received for publication 10 July 1985; revision 6 September 1985)

ABSTRACT

Published and previously unpublished data on the weights and nutrient contents of the trees and litterfall in stands of **Pinus radiata** D. Don have been summarised. The 101 observations of tree weight data cover a wide range of silvicultural treatments; the 42 observations of litterfall cover a wider range of stand age and most include nutrient data.

Needle mass can attain 15 t/ha in stands 4 to 8 years old but drops to about 10 t/ha in older stands. Total branch mass is related to stand height in unmanaged stands. Stem mass can be readily estimated from conventional stand measurements. Needle litterfall averaged 3.2 t/ha/yr and total litterfall 4.0 t/ha/yr.

Total nutrient mass in the various ecosystem components increased until canopy closure, after which considerable variability existed among stands.

**Keywords:** biomass; litterfall; nitrogen; phosphorus; potassium; calcium; magnesium.

## INTRODUCTION

*Pinus radiata* is a major component of forest planting in several Southern Hemisphere countries (Scott 1960). Rapid growth has been a major consideration in the introduction of this species and some concern has been expressed that the consequent nutrient demands may affect long-term productivity. Consequently, research commenced in New Zealand over 25 years ago to characterise nutrient cycling by plantations of *P. radiata* and the potential removal of nutrients in harvesting (Will 1959, 1964, 1968; Orman & Will 1960). The rapid growth of *P. radiata* led also to investigations on dry matter production under a variety of silvicultural and nutritional regimes both in New Zealand and Australia (Forrest & Ovington 1970; Madgwick *et al.* 1977; Mead *et al.* 1984).

This paper summarises published and unpublished data on the dry matter and nutrient content of *P. radiata* plantations and the return of organic matter and nutrients to the forest floor in litterfall. Partial data on dry matter were available for 101 stands

* Paper originally presented at the International Energy Agency Workshop on "Nutritional Consequences of Intensive Forest Harvesting on Site Productivity," Rotorua, June 1985.

when treatment means in replicated experiments were counted as single stands, each year's observation in remeasured plots was considered separately, and stands subject to live crown pruning were excluded (Table 1). Tree data dealt almost exclusively with the above-ground portions of the stands which ranged in age between 1 and 29 years. When each year's data were considered separately, 42 observations of litterfall were available from stands ranging in age between 8 and 39 years. Tree nutrient data were available for only 14 stands but most reports of litterfall included both weight and nutrients. The nutrients considered were nitrogen, phosphorus, potassium, calcium, and magnesium which are the most commonly reported, and boron, manganese, copper, and zinc which are less frequently reported.

Many stand descriptions in published papers were incomplete. Stand age was usually reported but many publications failed to give data on one or more of stand height, basal area, or stocking. Papers on litterfall sometimes included only stand age.

It was assumed that stands were closed if they carried at least 1 t dead branches/ha and had no recorded recent history of thinning. The air-dried litterfall weights of Will (1959) were assumed to be 5% heavier than if oven-dried immediately after collection. The "fine litter" of Cromer *et al.* (1984) was assumed to be all needle material although an unknown amount of male cones was also included in this fraction. Where basal area data were not reported but mean diameter and stocking were given, basal area was calculated assuming that the mean diameter referred to the tree of mean basal area.

TABLE 1—Occurrence of data on, and the reported range of age, height, basal area, and stocking for 101 stands for which at least partial stand weight data were available

| | Minimum | Maximum | No. of observations |
|---|---|---|---|
| Age (years) | 1 | 29 | 98 |
| Mean height (m) | 1.3 | 40.7 | 69 |
| Basal area ($m^2$/ha) | 0.01 | 58.30 | 87 |
| Stocking (stems/ha) | 106 | 10 000 | 79 |

## STAND WEIGHT

The oven-dry weight of needles in young stands of *P. radiata* is very variable depending on stocking but may reach a maximum of 15 t/ha between ages 4 and 8 years (Fig. 1). Needle weight averages only about 10 t/ha in later years. When data for closed stands are considered, a maximum needle mass of 14–15 t/ha can occur over a range of stocking from 300 to 10 000 stems/ha (Fig. 2). However, many closed stands with stocking below 3000 stems/ha have less than 10 t needles/ha. Where fertiliser or irrigation has increased stem growth, there has also been an increase in total needle mass (Cromer *et al.* 1984; Mead *et al.* 1984). Repeated thinning may preclude a stand from reaching the normally expected maximum for the age (Siemon *et al.* 1980).

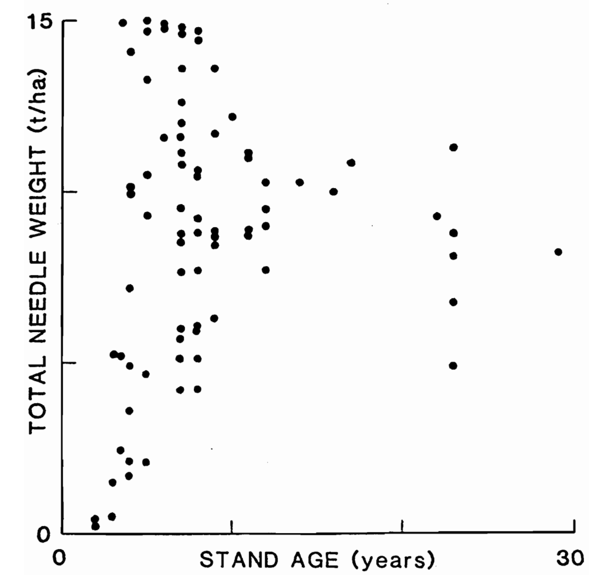


FIG. 1—Relationship between total needle weight and stand age in plantations of **Pinus radiata**.

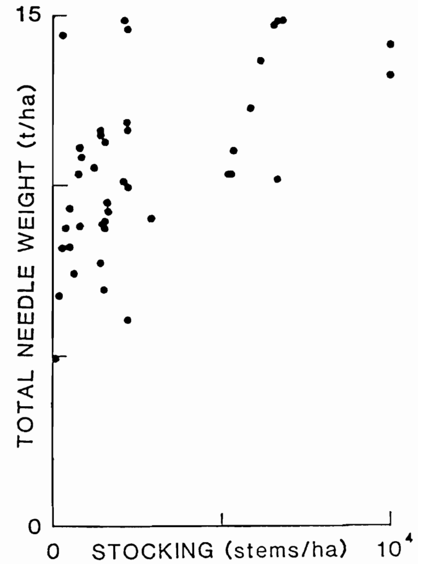


FIG. 2—Relationship between total needle weight and stocking in plantations of **Pinus radiata**.

The weight of 1-year-old needles also reaches a maximum at ages between 4 and 8 years when values up to 10.6 t/ha have been recorded (Fig. 3). After age 10 values range between 2 and 5 t/ha with variation partly accounted for by past thinning treatment (Siemon *et al.* 1980). There is a tendency for needle longevity to increase with stand age. For instance, Madgwick *et al.* (1977) found few 3-year-old needles in 6- and 8-year-old plantations whereas their 22-year-old stand in the same area carried some 5-year-old needles. The mean weight of 1-year-old needles in 18 stands at least 10 years old was 3.92 ± 0.78 t/ha while the 36 observations of needle fall for stands at least 10 years old averaged 3.19 ± 0.73 t/ha/yr.

In a 4-year-old stand growing in the centre of the North Island of New Zealand new needles became measurable in September (early spring) and attained a maximum weight about 4 months later (Fig. 4) (Madgwick 1983). Total needle mass ranged between 6.8 and 10.6 t/ha with a summer maximum. The annual range in total needle mass will depend on the pattern of needle production and will decrease with increased needle longevity.

The total dry weight of branches on stands of *P. radiata* increases rapidly for the first 10 years (Fig. 5). The rate of increase will depend on initial stocking. Plotting total branch weight against stand mean height indicates that there is an upper limit to stand branch weight which rises steeply up to a top height of about 12 m (Fig. 6). With further increase in height the rate of increase in branch weight slows owing to a lower production of branches per unit of height growth and to death, decay, and shedding of lower branches.

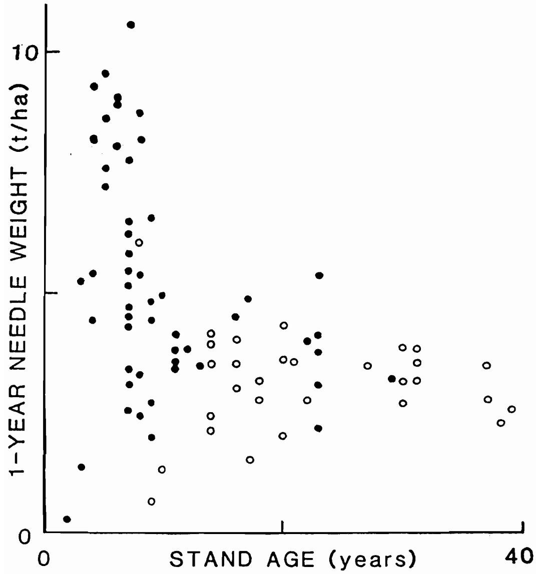


FIG. 3—Relationship between the weight of 1-year-old needles (●) and needle litterfall (O) and stand age in plantations of **Pinus radiata**.

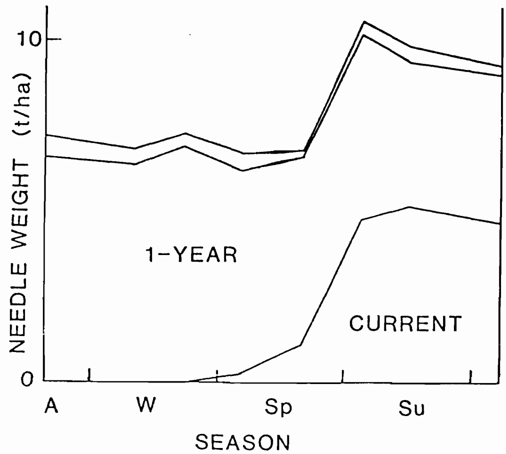


FIG. 4—Seasonal changes in needle weight (by age-class) in a young plantation of **Pinus radiata**. The unlabelled component comprises older needles. Source: Madgwick (1983).

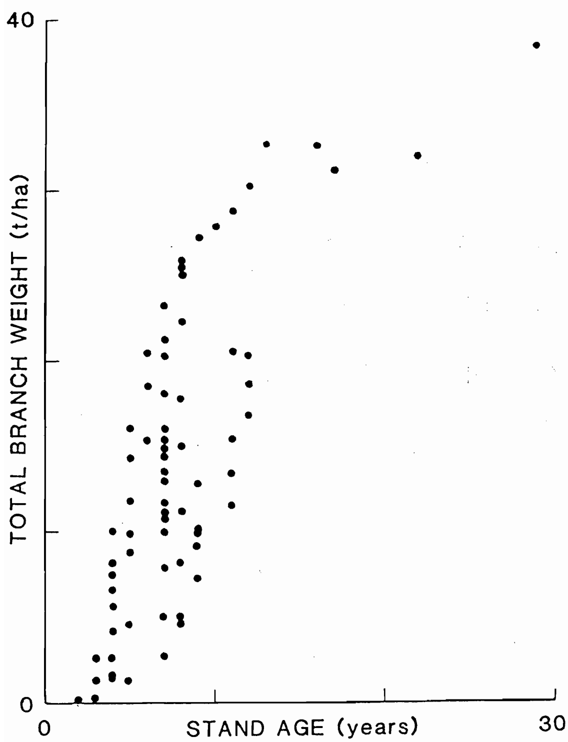


FIG. 5—Relationship between total branch weight and stand age in plantations of **Pinus radiata**.

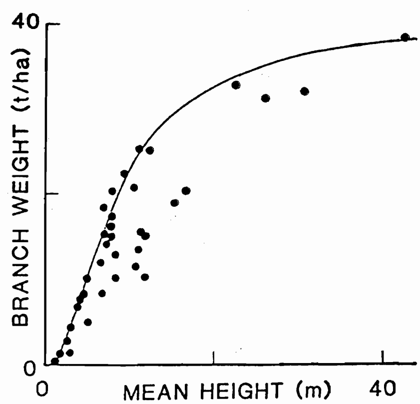


FIG. 6 — Relationship between total branch weight and stand height in plantations of **Pinus radiata**. The line indicates an upper asymptotic relationship between weight and height drawn by eye.

The dry weight of live branches on an area basis in closed stands tends to decrease with increased stocking (Fig. 7). Variation is large for lower stocked stands. While this variation partly reflects the larger number of stands of lower stocking for which data are available, it probably also reflects variation in both genetic make-up and site quality among the sample stands.

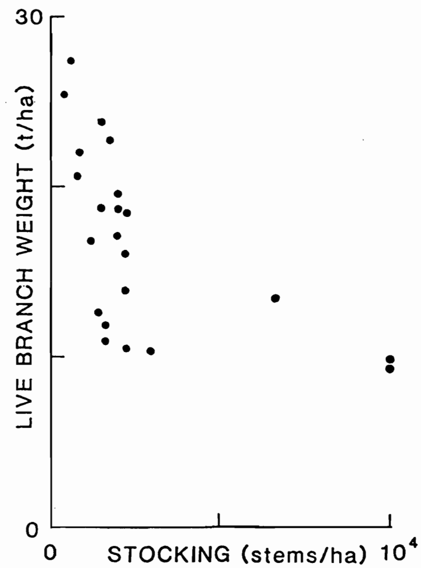


FIG. 7—Relationship between live branch weight and stocking in plantations of **Pinus radiata**.

The dry weight of stems increases rapidly with stand age in relation to increases in both height and basal area. Total stem weight (W t/ha) may be estimated from stand mean height (H m), basal area (B $m^2$/ha), and stocking (S stems/ha). Based on 61 observations the equation:

$$W = H \cdot (0.354 + 0.141 \cdot B + 0.000041 \cdot H \cdot S)$$

explained over 99% of the variation in stand stem weight (Fig. 8). Bark comprised about one-third of stem weight at age 2 years but only one-tenth of stem weight at age 10 (Fig. 9).

Male cones on a 22-year-old stand were found to weigh 0.53 t/ha (Madgwick *et al.* 1977). Female cone weights have not been reported for stands below age 6. For stands at least 13 years old weight of female cones varied from 1 to 9 t/ha.

Data on root (including stump) weights for *P. radiata* are very limited. Ovington *et al.* (1967) reported a root : stem ratio of 0.4 in an 8-year-old stand while Will (1966) found a ratio of 0.14 in an 18-year-old stand. Jackson & Chittenden (1981) found that the weight of roots greater than 5 mm diameter on individual trees (R kg) could be estimated from diameter at breast height (D cm) with the formula:

$$\ln(R) = 2.73 \ln(D) - 5.009$$

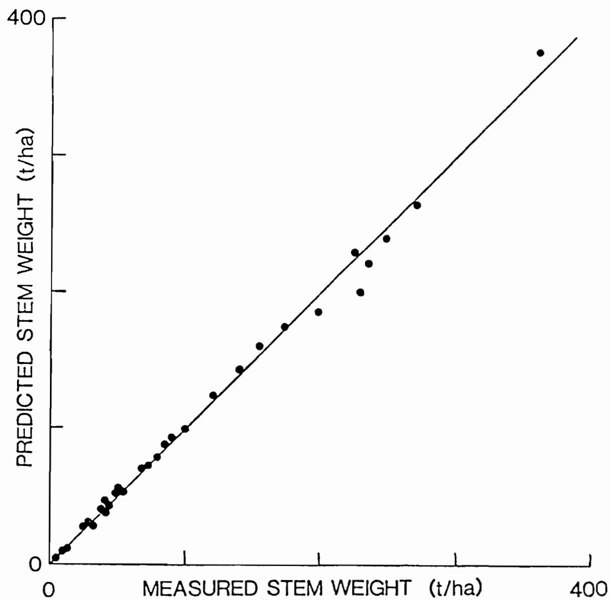


FIG. 8—Relationship between predicted and measured total stem weight in plantations of **Pinus radiata**. Not all data for weights less than 50 t/ha have been plotted.

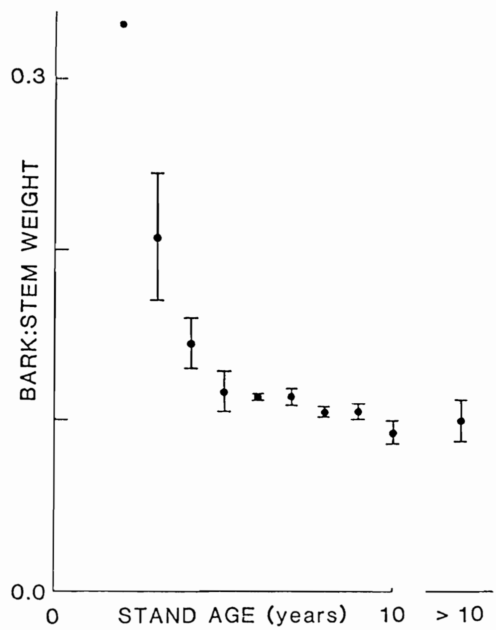


FIG. 9—Relationship between the ratio of bark to total stem weight and stand age in plantations of **Pinus radiata**. Vertical bars represent plus and minus one standard deviation of individual estimates.

A similar regression of stem weight (S kg) on D based on 246 trees is:

$$\ln (S) = 2.50 \ln (D) - 3.233$$

Comparison of these two regressions indicates that root : stem ratios would be expected to increase with D from about 0.29 for D = 10 to 0.39 for D = 40. These ratios do not agree with the measured ratios reported above, suggesting the need for further research.

Annual needle litterfall for all stands illustrated in Fig. 3 averaged 3.19 ± 0.94 t/ha/yr (n = 38) but almost no data have been reported from young stands with high rates of needle production (Fig. 3, Table 2). Total litterfall averaged 4.01 ± 1.46 t/ha/yr (n = 42). The greater variability of total litterfall is related to the erratic nature of branch fall (Baker 1983). Variations in litterfall from year to year in the same stand can be large. Versfeld (1981) reported a ratio of maximum to minimum needle fall between years of 1.14 while the 15- to 16-year-old stand of Will (1959) had a ratio of 1.49. Cromer *et al.* (1984) found that moisture stress caused a major increase in needle fall.

TABLE 2—Numbers of observations, means, and standard deviations of characteristics of needle fall and total litterfall in stands of **Pinus radiata** ranging in age from 8 to 39 years

| Character | Needles | | | Total | | |
|---|---|---|---|---|---|---|
| | n | mean | s.d. | n | mean | s.d. |
| Dry weight (t/ha/yr) | 38 | 3.19 | 0.94 | 42 | 4.01 | 1.46 |
| Nitrogen (kg/ha/yr) | 22 | 21.8 | 11.8 | 30 | 27.5 | 13.0 |
| Phosphorus (kg/ha/yr) | 24 | 2.35 | 1.45 | 30 | 2.93 | 1.64 |
| Potassium (kg/ha/yr) | 20 | 7.99 | 5.31 | 21 | 10.50 | 6.02 |
| Calcium (kg/ha/yr) | 20 | 17.0 | 7.6 | 21 | 19.9 | 8.9 |
| Magnesium (kg/ha/yr) | 20 | 5.77 | 2.50 | 21 | 6.05 | 2.52 |
| Nitrogen (%) | 22 | 0.62 | 0.15 | 30 | 0.69 | 0.20 |
| Phosphorus (%) | 24 | 0.071 | 0.028 | 30 | 0.070 | 0.022 |
| Potassium (%) | 20 | 0.24 | 0.101 | 21 | 0.24 | 0.08 |
| Calcium (%) | 20 | 0.52 | 0.14 | 21 | 0.48 | 0.12 |
| Magnesium (%) | 20 | 0.17 | 0.05 | 21 | 0.15 | 0.06 |

## NUTRIENT CONTENTS

Foliar analysis for diagnostic purposes indicates that wide variations occur from area to area in nutrient concentrations (Table 3). An equally wide range of stands has not been examined for total nutrient contents so the data presented must be treated with caution. The ranges of published values for different components of the tree are given in Table 4. Concentrations of most elements in the foliage and cones tend to be unrelated to stand age (Madgwick *et al.* 1977). Concentrations in live woody com-

TABLE 3—Mean foliage nutrient concentrations by grouped forests in the North Island, New Zealand

| Group | N | P | K | Ca | Mg | B | Mn | Zn | Cu |
|---|---|---|---|---|---|---|---|---|---|
| | ——— (% dry weight) ——— | | | | | ——— (ppm) ——— | | | |
| Kaingaroa | 1.41 | 0.20 | 1.20 | 0.16 | 0.12 | 16 | 260 | 46 | 6.6 |
| Clay forests | 1.58 | 0.13 | 1.03 | 0.20 | 0.16 | 25 | 288 | 43 | 5.4 |
| Santoft | 1.20 | 0.14 | 1.00 | 0.16 | 0.15 | 17 | 77 | 34 | 3.9 |
| Other sand forests | 1.30 | 0.17 | 0.94 | 0.18 | 0.19 | 21 | 165 | 40 | 4.6 |
| East Coast forests | 1.60 | 0.16 | 1.32 | 0.16 | 0.14 | 21 | 121 | 47 | 5.0 |
| Gwavas and Ngaumu | 1.50 | 0.17 | 1.37 | 0.19 | 0.18 | 19 | 182 | 53 | 6.3 |
| **Key** | | | | | | | | | |
| Low if less than | 1.2 | 0.12 | 0.30 | 0.10 | 0.07 | 8 | 10 | 10 | 2 |
| Satisfactory over | 1.5 | 0.14 | 0.50 | 0.10 | 0.10 | 12 | 20? | 20 | 4 |

Sources: NZFS (1982); Will (1985)

TABLE 4—The range of nutrient concentrations (% d.w.) in ***Pinus radiata*** biomass components

| Nutrient | | Needles | Branches | | Cones | Stems | |
|---|---|---|---|---|---|---|---|
| | | | Live | Dead | | Wood | Bark |
| Nitrogen | min. | 1.18 | 0.23 | 0.13 | 0.47 | 0.028 | 0.17 |
| | max. | 1.47 | 0.41 | 0.28 | 0.69 | 0.082 | 0.35 |
| Phosphorus | min. | 0.09 | 0.03 | 0.01 | 0.07 | 0.005 | 0.02 |
| | max. | 0.18 | 0.05 | 0.04 | 0.11 | 0.013 | 0.05 |
| Potassium | min. | 0.66 | 0.25 | 0.08 | 0.16 | 0.062 | 0.17 |
| | max. | 0.99 | 0.43 | 0.24 | 0.20 | 0.100 | 0.66 |
| Calcium | min. | 0.12 | 0.13 | 0.18 | 0.02 | 0.033 | 0.13 |
| | max. | 0.40 | 0.35 | 0.41 | 0.03 | 0.052 | 0.24 |
| Magnesium | min. | 0.12 | 0.06 | 0.06 | 0.04 | 0.018 | 0.07 |
| | max. | 0.18 | 0.10 | 0.09 | 0.09 | 0.022 | 0.09 |

Source: Stewart *et al.* (1981)

ponents (stem wood, stem bark, and live branches) tend to decrease with increasing stand weight, as illustrated for stem wood nitrogen in Fig. 10 (Madgwick *et al.* 1977).

Total nutrient content in stands unaffected by live crown pruning tends to increase until crown closure (Table 5). In older stands, variation in nutrient concentration between stands becomes more important than stand age even though most of the existing data are from stands located in the relatively fertile Kaingaroa State Forest in the centre of the North Island in New Zealand.

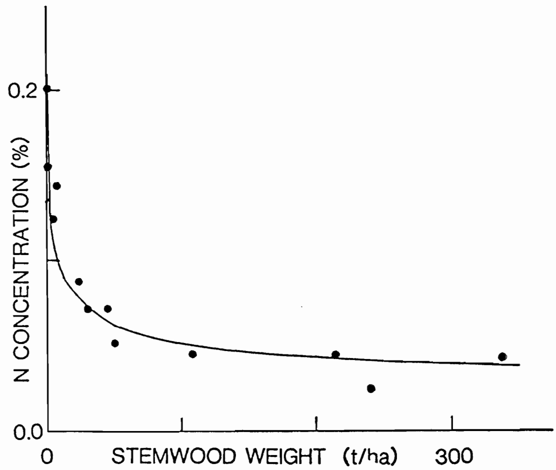


FIG. 10—Relationship between nitrogen concentration in stem wood and total stem wood weight in plantations of **Pinus radiata**.

TABLE 5—The nutirent content (kg/ha) of stands of **Pinus radiata** unaffected by live crown pruning (n.d. = not determined)

| Age (years) | 2 | 4 | 6 | 8 | 15 | 17 | 22 | 29 |
|---|---|---|---|---|---|---|---|---|
| Stocking (stems/ha) | 2496 | 2347 | 2224 | 1507 | 1068 | 855 | 544 | 360 |
| Source | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 3 |
| **Nitrogen** | | | | | | | | |
| 1-year needles | 4.6 | 75.7 | 102.0 | 81.9 | n.d. | 74.7 | 43.0 | 46.4 |
| Total needles | 5.4 | 92.1 | 134.0 | 86.9 | 122.7 | 155.7 | 91.3 | 116.6 |
| Live branches | 0.7 | 20.6 | 39.0 | 60.0 | 65.4 | 52.1 | 47.6 | 57.8 |
| Dead branches | 0.0 | <0.1 | 0.6 | 2.6 | 11.1 | 13.4 | 4.5 | 20.9 |
| Cones | 0.0 | 0.0 | 0.0 | <0.1 | 41.6 | 2.1 | 0.8 | 22.2 |
| Stem bark | 0.5 | 8.0 | 15.1 | 22.8 | 36.7 | 60.2 | 49.3 | 67.9 |
| Stem wood | 0.4 | 10.3 | 19.2 | 35.6 | 89.1 | 101.0 | 58.4 | 149.0 |
| Total | 6.9 | 131.0 | 207.9 | 207.8 | 366.6 | 384.5 | 251.8 | 434.4 |
| **Phosphorus** | | | | | | | | |
| 1-year needles | 0.44 | 8.01 | 11.41 | 9.29 | n.d. | 8.80 | 4.82 | 6.9 |
| Total needles | 0.52 | 10.01 | 15.17 | 9.95 | 9.26 | 17.56 | 10.41 | 16.4 |
| Live branches | 0.11 | 3.97 | 19.00 | 11.78 | 7.84 | 10.49 | 6.32 | 10.9 |
| Dead branches | 0.00 | 0.00 | 0.06 | 0.28 | 1.04 | 1.60 | 0.34 | 2.2 |
| Cones | 0.00 | 0.00 | 0.00 | 0.00 | 6.72 | 0.25 | 0.17 | 5.5 |
| Stem bark | 0.06 | 0.84 | 2.19 | 3.17 | 4.06 | 10.61 | 6.98 | 7.4 |
| Stem wood | 0.07 | 1.68 | 3.74 | 8.59 | 14.13 | 30.23 | 6.53 | 24.0 |
| Total | 0.76 | 16.49 | 40.16 | 33.77 | 43.05 | 70.74 | 30.75 | 66.3 |

TABLE 5—(Continued)

| Age (years) | 2 | 4 | 6 | 8 | 15 | 17 | 22 | 29 |
|---|---|---|---|---|---|---|---|---|
| Stocking (stems/ha) | 2496 | 2347 | 2224 | 1507 | 1068 | 855 | 544 | 360 |
| Source | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 3 |
| **Potassium** | | | | | | | | |
| 1-year needles | 2.6 | 38.6 | 57.6 | 47.3 | n.d. | 41.8 | 19.4 | 33.6 |
| Total needles | 3.1 | 50.0 | 78.9 | 51.1 | 68.1 | 93.1 | 44.6 | 81.4 |
| Live branches | 0.9 | 30.4 | 53.9 | 79.4 | 68.8 | 72.4 | 43.7 | 82.7 |
| Dead branches | 0.0 | 0.0 | 0.2 | 1.7 | 5.9 | 13.1 | 3.7 | 8.9 |
| Cones | 0.0 | 0.0 | 0.0 | 0.0 | 12.1 | 0.4 | 0.3 | 6.0 |
| Stem bark | 0.5 | 7.3 | 17.0 | 33.3 | 41.9 | 98.4 | 64.7 | 90.6 |
| Stem wood | 0.5 | 15.2 | 34.6 | 60.0 | 100.0 | 139.8 | 109.1 | 194.8 |
| Total | 4.9 | 103.0 | 184.6 | 225.3 | 296.8 | 417.1 | 266.2 | 464.3 |
| **Calcium** | | | | | | | | |
| 1-year needles | 0.8 | 20.6 | 23.7 | 15.0 | n.d. | 11.4 | 5.3 | 8.0 |
| Total needles | 1.2 | 32.2 | 45.2 | 17.2 | 41.1 | 34.6 | 17.2 | 32.4 |
| Live branches | 0.2 | 11.2 | 28.3 | 40.0 | 55.8 | 49.5 | 27.6 | 52.4 |
| Dead branches | 0.0 | 0.0 | 0.8 | 3.3 | 26.8 | 26.1 | 6.3 | 26.9 |
| Cones | 0.0 | 0.0 | 0.0 | 0.0 | 1.6 | 0.1 | 0.0 | 1.1 |
| Stem bark | 0.1 | 3.6 | 7.9 | 14.5 | 33.6 | 60.7 | 36.7 | 48.8 |
| Stem wood | 0.1 | 3.3 | 10.2 | 24.5 | 56.5 | 113.4 | 89.5 | 171.7 |
| Total | 1.5 | 50.3 | 92.4 | 99.4 | 215.4 | 284.2 | 177.4 | 333.3 |
| **Magnesium** | | | | | | | | |
| 1-year needles | 0.40 | 8.31 | 9.52 | 7.31 | n.d. | 5.98 | 3.72 | 4.5 |
| Total needles | 0.50 | 11.34 | 14.64 | 7.97 | 19.03 | 11.76 | 7.91 | 10.4 |
| Live branches | 0.13 | 6.46 | 9.94 | 15.04 | 15.52 | 13.93 | 12.15 | 16.0 |
| Dead branches | 0.00 | 0.00 | 0.22 | 0.98 | 6.05 | 6.20 | 1.96 | 6.1 |
| Cones | 0.00 | 0.00 | 0.00 | 0.00 | 5.52 | 0.16 | 0.12 | 3.4 |
| Stem bark | 0.08 | 1.59 | 2.76 | 5.49 | 12.88 | 17.01 | 13.68 | 14.5 |
| Stem wood | 0.07 | 2.37 | 5.45 | 11.18 | 23.91 | 41.34 | 34.69 | 51.8 |
| Total | 0.78 | 21.75 | 33.03 | 40.67 | 82.91 | 90.41 | 70.52 | 102.2 |
| **Manganese** | | | | | | | | |
| 1-year needles | 0.02 | 0.88 | 2.20 | 3.00 | n.d. | 1.06 | 0.39 | 1.11 |
| Total needles | 0.03 | 1.20 | 3.70 | 3.48 | 2.20 | 2.91 | 1.16 | 4.10 |
| Live branches | <0.01 | 0.50 | 1.32 | 3.36 | 0.69 | 1.56 | 1.07 | 3.27 |
| Dead branches | 0.00 | 0.00 | 0.02 | 0.25 | 0.41 | 1.04 | 0.25 | 1.45 |
| Cones | 0.00 | 0.00 | 0.00 | 0.00 | 0.11 | 0.01 | 0.00 | 0.24 |
| Stem bark | <0.01 | 0.10 | 0.24 | 0.65 | 0.38 | 1.10 | 0.79 | 1.66 |
| Stem wood | <0.01 | 0.25 | 0.91 | 2.59 | 2.17 | 5.48 | 3.44 | 18.17 |
| Total | 0.04 | 2.05 | 6.20 | 10.32 | 5.96 | 12.09 | 6.72 | 28.88 |
| **Zinc** | | | | | | | | |
| 1-year needles | 0.02 | 0.24 | 0.30 | 0.28 | n.d. | 0.25 | 0.14 | 0.18 |
| Total needles | 0.03 | 0.34 | 0.46 | 0.31 | 0.11 | 0.47 | 0.29 | 0.49 |
| Live branches | 0.01 | 0.20 | 0.33 | 0.46 | 0.16 | 0.44 | 0.36 | 0.63 |
| Dead branches | 0.00 | 0.00 | 0.01 | 0.03 | 0.03 | 0.14 | 0.05 | 0.26 |
| Cones | 0.00 | 0.00 | 0.00 | 0.00 | 0.12 | 0.01 | <0.01 | 0.09 |
| Stem bark | <0.01 | 0.05 | 0.11 | 0.20 | 0.14 | 0.76 | 0.71 | 2.98 |
| Stem wood | <0.01 | 0.08 | 0.23 | 0.48 | 0.36 | 1.81 | 1.50 | 2.20 |
| Total | 0.04 | 0.68 | 1.15 | 1.49 | 0.92 | 3.64 | 2.91 | 4.66 |

Sources: 1 – Madgwick, H. A. I.; Jackson, D. S.; Knight, P. J. (unpubl. data)
2 – Stewart et al. (1981)
3 – Webber & Madgwick (1983)

There are several clear gaps in our knowledge. Almost all existing data have been collected on relatively fertile sites. We do not know how the needle-carrying capacity of stands is related to climatic and nutrient variables. Data on the nutrient concentrations of woody components are almost totally lacking. We do not know how nutrient concentrations in conventional diagnostic foliar samples relate to the average concentration in whole crowns. Data on the weights of roots and their nutrient contents on a stand basis are also lacking. Some of these deficiencies are being remedied in current research programmes in New Zealand and in Australia. Until such time as our knowledge of the various factors affecting dry matter production and nutrient cycling is more complete, estimates of dry matter production and nutrient removal from plantations of *P. radiata* grown under any given silvicultural regime will be subject to considerable error.

## REFERENCES

BAKER, T. G. 1983: Dry matter, nitrogen, and phosphorus content of litterfall and branchfall in **Pinus radiata** and **Eucalyptus** forests. **New Zealand Journal of Forestry Science 13:** 205–21.

CROMER, R. N.; TOMPKINS, D.; BARR, N. J.; WILLIAMS, E. R.; STEWART, H. T. L. 1984: Litter-fall in a **Pinus radiata** forest: the effect of irrigation and fertilizer treatments. **Journal of Applied Ecology 21:** 313–26.

FORREST, W. G.; OVINGTON, J. D. 1970: Organic matter changes in an age series of **Pinus radiata** plantations. **Journal of Applied Ecology 7(1):** 177–86.

JACKSON, D. S.; CHITTENDEN, J. 1981: Estimation of dry matter in **Pinus radiata** root systems. 1. Individual trees. **New Zealand Journal of Forestry Science 11:** 164–82.

MADGWICK, H. A. I. 1983: Seasonal changes in the biomass of a young **Pinus radiata** stand. **New Zealand Journal of Forestry Science 13:** 25–36.

MADGWICK, H. A. I.; JACKSON, D. S.; KNIGHT, P. J. 1977: Above-ground dry matter, energy, and nutrient contents of trees in an age series of **Pinus radiata** plantations. **New Zealand Journal of Forestry Science 7:** 445–68.

MEAD, D. J.; DRAPER, D.; MADGWICK, H. A. I. 1984: Dry matter production of a young stand of **Pinus radiata**: some effects of nitrogen fertiliser and thinning. **New Zealand Journal of Forestry Science 14:** 97–108.

NZFS 1982: Report of Forest Research Institute for 1 January to 31 December 1981. New Zealand Forest Service, Wellington. 120 p.

ORMAN, H. R.; WILL, G. M. 1960: The nutrient content of **Pinus radiata** trees. **New Zealand Journal of Science 3:** 510–22.

OVINGTON, J. D.; FORREST, W. G.; ARMSTRONG, J. E. 1967: Tree biomass estimation. Pp. 3-31 **in** Young, H. E. (Ed.) Symposium on "Primary Productivity and Mineral Cycling in Natural Ecosystems." University of Maine Press, Orono, Maine.

SCOTT, C. W. 1960: **Pinus radiata**. FAO Forestry and Forest Products Studies No. 14, FAO, Rome.

SIEMON, G. R.; MULLER, W. J.; WOOD, G. B.; FORREST, W. G. 1980: Effect of thinning on the distribution and biomass of foliage in the crown of radiata pine. **New Zealand Journal of Forestry Science 10:** 461–75.

STEWART, H. T. L.; FLINN, D. W.; JAMES, J. M. 1981: Biomass and nutrient distribution in radiata pine. **Proceedings, Australian Forest Nutrition Workshop, "Productivity in Perpetuity", Canberra:** 173–85.

VERSFELD, D. B. 1981: Litter fall and decomposition in stands of mature **Pinus radiata**. **South African Forestry Journal 116:** 40–50.

WEBBER, B.; MADGWICK, H. A. I. 1983: Biomass and nutrient content of a 29-year-old **Pinus radiata** stand. **New Zealand Journal of Forestry Science 13:** 222–8.

WILL, G. M. 1959: Nutrient return in litter and rainfall under some exotic conifer stands in New Zealand. **New Zealand Journal of Agricultural Research 2:** 719–34.

——— 1964: Dry matter production and nutrient uptake by **Pinus radiata** in New Zealand. **Commonwealth Forestry Review 43:** 55–7.

——— 1966: Root growth and dry-matter production in a high-producing stand of **Pinus radiata. New Zealand Forest Service, Forest Research Institute, Research Note No. 44.**

——— 1968: The uptake, cycling and removal of nutrients by crops of **Pinus radiata. Proceedings of the New Zealand Ecological Society 15:** 20–4.

——— 1985: Nutrient deficiencies and fertiliser use in New Zealand exotic forests. **New Zealand Forest Service, FRI Bulletin No. 97.**

## OTHER SOURCES OF DATA

BEETS, P. N. 1982: Modelling dry matter content of a managed stand of **Pinus radiata** in New Zealand. Ph.D. Thesis, University of Georgia, Athens, Georgia.

CALVO DE ANTA, R. M.; GONZALEZ, A. P.; DIAZ FIERROS, F. 1979: Nuevos datos sobre la influencia de la vegetacion en la formacion del suelo en Galicia (III). Aportes por hojarasca, perididas por drenaje y escorrentia. Balance del agua los elementos a traves del suelo. **Anales de Edafologia y Agrobiologia 38:** 1984-2000.

GADGIL, R. 1976: Nitrogen distribution in stands of **Pinus radiata** with and without lupin in the understorey. **New Zealand Journal of Forestry Science 6:** 33–9.

——— 1979: The nutritional role of **Lupinus arboreus** in coastal sand dune forestry. IV. Nitrogen distribution in the ecosystem for the first five years after planting. **New Zealand Journal of Forestry Science 9:** 324–36.

GIULIMONDI, G.; DURANTI, G. 1975: Produzione di sostanza secca e contenuti in elementi nutrivi di un impianto di quattro anni di **Pinus radiata. Pubblicazione del Centro di Sperimentazione Agricola e Forestale 13:** 17–28.

GROTTKER, T. W. 1984: On the potential of **Pinus radiata** for biomass production for energy in Eyrewell Forest, Canterbury Plains, New Zealand. M.F.S. Thesis, University of Canterbury.

HENG, S. 1980: The addition, decomposition and accumulation of organic matter in some native **Nothofagus** spp. forests and **Pinus radiata** plantations in the South Island of New Zealand. Ph.D. Thesis, University of Canterbury.

LAMB, D.; FLORENCE, R. G. 1975: Influence of soil type on the nitrogen and phosphorus content of radiata pine litter. **New Zealand Journal of Forestry Science 5:** 143–51.

LEVETT, M. P.; ADAMS, J. A.; WALKER, T. W. 1985: Nutrient returns in litterfall in two indigenous and two radiata pine forests, Westland, New Zealand. **New Zealand Journal of Botany 23:** 55–64.

MADGWICK, H. A. I. 1981: Above-ground dry-matter content of a young close-spaced **Pinus radiata** stand. **New Zealand Journal of Forestry Science 11:** 203–9.

PAWSEY, C. K. 1959: The seasonal fall of litter under Monterey pine in the south east of South Australia. **Newsletter, Institute of Foresters of Australia 2(4):** 16–7.

STEPHENS, C. G.; BOND, R. D. 1957: Nitrogen economy of plantations of **Pinus radiata**. **Australian Forestry 21:** 117–9.

WARING, H. D. 1969: The role of nitrogen in the maintenance of productivity in conifer plantations. **Commonwealth Forestry Review 48:** 226–37.

——— 1974: Early fertilization for maximum production. **In** FAO-IUFRO International Symposium on Forest Fertilisation, Paris.

WILLIAMS, D. F. 1976: Forest fuels in unthinned radiata pine stands. **Australian Forester 39:** 238–44.