PURUKI EXPERIMENTAL CATCHMENT: SITE, CLIMATE, FOREST MANAGEMENT, AND RESEARCH

P. N. BEETS and R. K. BROWNLIE
Ministry of Forestry, Forest Research Institute,
Private Bag, Rotorua, New Zealand

(Received for publication 30 September 1987)

ABSTRACT

Multidisciplinary research has been undertaken at the Purukohukohu experimental basin, particularly in the Puruki catchment over the past 15 years. This period covers the conversion of Puruki from pasture to **Pinus radiata** D. Don, the development of the trees to canopy closure, and the effects of differential intensities of thinning on growth to the middle of the rotation. Results of investigations into tree growth, nutrient cycling, and catchment hydrology are presented in papers collected in this issue of the Journal. This paper backgrounds the site, climate, history, and management of the catchment, and the development of the trees.

Puruki is a 35-ha catchment located at the southern end of the Paeroa Range in the central North Island of New Zealand, at an elevation of 600 m. The rhyolitic pumice soil, previously under rye grass/clover pasture and regularly treated with fertiliser, provides ample moisture and nutrients for **P. radiata** growth under the climatic conditions: 1500 mm of evenly distributed rainfall annually, 5 GJ/m^2 of solar irradiance annually, and average monthly temperatures of between 5° and 15°C. Puruki was uniformly planted with **P. radiata** at 2200 stems/ha in 1973 and trees in the individual subcatchments (Tahi, Rua, and Toru) were progressively pruned to 2.2 m height and thinned to 160, 550, and 290 stems/ha respectively by 1985, with further thinning intended. A part of Rua was left unthinned as a control. In closed canopy stands periodic volume increment attains 52 m^3/ha/year. The removal of between half and three-quarters of the tree basal area every 3 to 4 years reduced volume increment to between 25 and 30 m^3/ha/year, but this is likely to increase when management thinning is completed and the stand leaf area can increase uninterrupted to unthinned levels.

The interrelationships between aspects of the research work covered in the accompanying papers are illustrated using a conceptual modelling framework. The data collected at Puruki have proved valuable for testing theoretically based models and calibrating empirical models of **P. radiata** growth under conditions of ample moisture and nutrient supply.

Keywords: catchment hydrology; primary production; land use; nutrient cycling; pollution; thinning; multidisciplinary research; growth rate; model validation; **Pinus radiata**.

INTRODUCTION

General Background

Water is in abundant supply in New Zealand where it is used as a source of potable water, for domestic water supply, for generation of electricity, for irrigation of pasture and crops, and for recreation, but the resource is vulnerable to degradation. Problems have arisen owing to soil erosion and eutrophication depending on soil type, land use, and management thereby limiting its utility (Duncan 1971; Burden 1982). The need for sound hydrological data for addressing these problems has been recognised, but long-term data for hydrological forecasting have not been available. The concepts of regional and experimental hydrology were adopted by the Ministry of Works and Development (MWD) in 1959 and were given impetus by the creation of the Water and Soil Division (W&S) of the MWD in 1966. The programme was designed to provide technical information on regional hydrology on a national level (Drost 1971).

The research objectives of the W&S experimental basins programme were to:

- Carry out fundamental research to aid in understanding hydrological processes in soil/vegetation complexes;
- Characterise the quantity and quality of stream flow from different land uses;
- Find the effect of a change in land use on the hydrological regime;
- Provide data for a mathematical model of catchments for the generation of information on the effect of land use and management on the hydrology of typical soil/vegetation complexes;
- Improve techniques of observing and analysing data.

To address these objectives, representative basins were set up on a regional basis to provide hydrological data for catchments covering the range of hydrological variation in New Zealand. In experimental basins, programmed changes in land management were made (Drost 1971). The Purukohukohu experimental basin was set up in 1968 as a site for long-term research (to year 2000) into the hydrology and erosion of yellow-brown pumice soils, under the auspices of the International Hydrological Decade. The land-use catchments at Purukohukohu include:

(i) Puruorakau (37.2 ha): indigenous mesophyll forest, classified as podocarp/tawa type (M2) (McKelvey 1963);

(ii) Purutaka (22.5 ha): developed in 1957 into well-established pasture grazing sheep and cattle, after original clearing of native forest in the 1920s reverted to seral scrub;

(iii) Puruki (34.4 ha): as for Purutaka but with a land-use change from pasture to pines. *Pinus radiata* was planted in 1973, and the catchment fenced to exclude grazing animals;

(iv) Puruwai (28 ha): a further native forest catchment added in 1972;

(v) Puruhou (35 ha) a further pasture catchment added in 1979.

Various organisations were encouraged to participate at Purukohukohu – for example, universities and other Government departments including the Department of

Lands and Survey, the Department of Scientific and Industrial Research, Ministry of Agriculture and Fisheries, and the New Zealand Forest Service (NZFS) (now the Ministry of Forestry). Geological, soil, and vegetation surveys were made (MWD 1971, 1973). Collaboration was mediated through annual co-ordination meetings.

The NZFS was responsible for planting the pines in Puruki. The Forest Research Institute (FRI), then of the NZFS and from 1987 of the Ministry of Forestry, also undertook responsibility for managing the pines and investigation of *P. radiata* productivity in relation to the International Biological Programme. The research programme of the FRI was to:

- Estimate transpiration and evaporation from wet canopies of *P. radiata*;
- Measure radiation interception, photosynthesis, and carbohydrate storage;
- Measure nutrient uptake and cycling, including litter decomposition;
- Monitor insect population levels and incidence of diseases;
- Monitor climate and develop a meteorological database;
- Measure tree growth (leaves, branches, stems, roots, reproductive parts) mortality, and dry matter accumulation, including canopy structure and stem quality aspects, for a range of tree spacings;
- Provide data for mathematical models of *P. radiata* growth and water use.

Data collection was concentrated at Puruki but related studies were also undertaken at Kaingaroa Forest and at the Long Mile experimental site, FRI, Rotorua. The terrain at Kaingaroa confers advantages in studies requiring extensive level areas of *P. radiata* forest. The Long Mile experimental area, with its weighing lysimeters (Gifford *et al.* 1982; Whitehead 1983) and root trench facilities (Jackson & Chittenden 1981) set up in stands parallel to those growing at Puruki, is adjacent to FRI and therefore readily accessible for examining aspects of seasonal growth (Madgwick 1983a; Jackson *et al.* 1976). Of additional value to the programme was the provision of clonal tree material both at Puruki and the Long Mile. These clones have been investigated both in the forest (Jackson *et al.* 1976; Harris *et al.* 1978; Knight 1978; Madgwick 1983a,b) and in controlled climate growth rooms (Bennett & Rook 1978; Rook & Corson 1978).

In this paper we:

- Describe the site, climate, and forest management, and discuss the implications for tree growth;
- Illustrate aspects of the research programme covered in the accompanying papers, using a conceptual modelling framework.

DESCRIPTION OF PURUKI CATCHMENT

Location

The Purukohukohu Experimental Basin, which is at the head of the Mangakara Representative Basin, is located in the Paeroa Range in the central North Island of New Zealand, approximately 30 km south of Rotorua (Fig. 1). Puruki (38° 26′S, 176° 13′E) is situated at an elevation of 530–650 m on the southern end of the Paeroa fault block, with the basin sloping gently to the east.

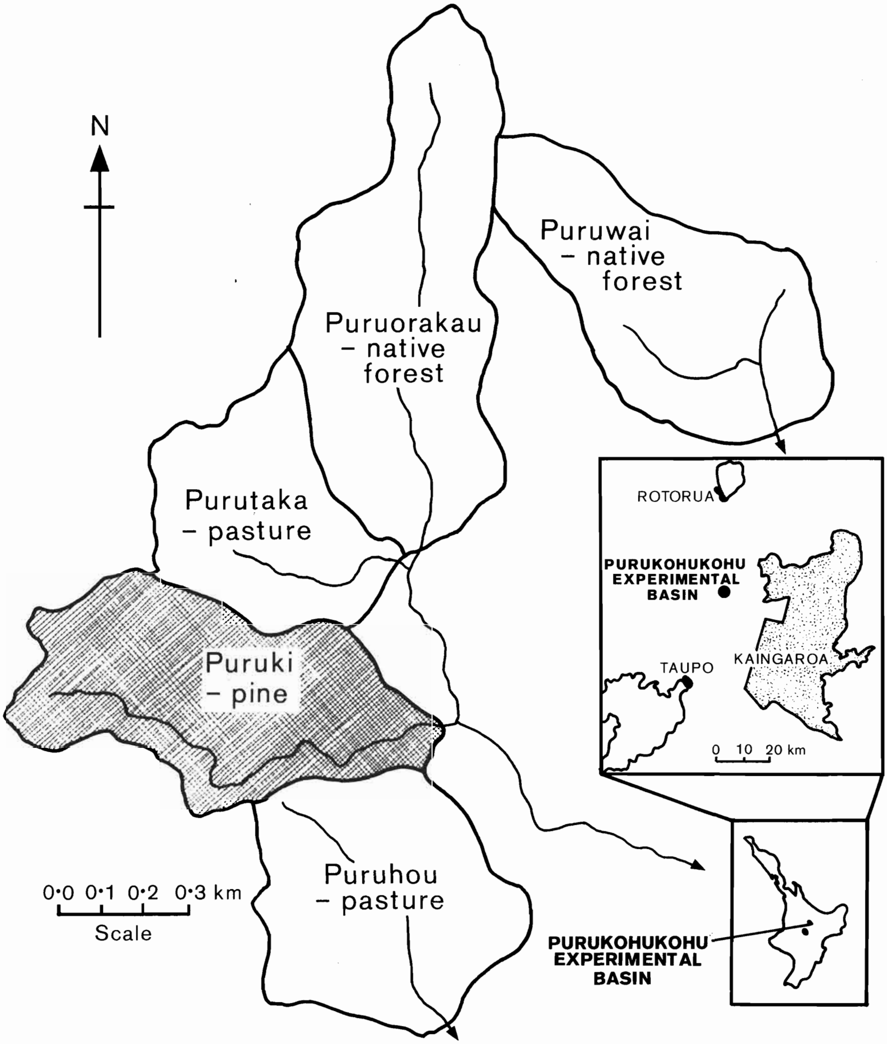

FIG. 1—Location of Purukohukohu experimental basin and land-use catchments.

Soils

The soil parent materials, geology, and topography, and their relationship to soil formation have been described for Purukohukohu by Rijkse & Bell (1974). Parent materials originated from Taupo (1850 ± 100 BP) and older ash showers from Taupo and Okataina volcanic centres. These ash beds are underlain by the Huka Formation, consisting of siliceous pumice breccias and siltstones forming an impervious base.

Topography is very variable and determines the erosion pattern of the various ash layers (Rijkse & Bell 1974). Four categories of slope (Appendix 1) include:

(i) Flat to easy rolling (<12°)

(ii) Moderately steep slopes (12°–23°)

(iii) Moderately steep to steep slopes (18°–30°)

(iv) Steep to very steep slopes (mainly 30°–38°)

The yellow-brown pumice soils belong predominantly to the Oruanui series. Oruanui series are composed of sandy loam, sand, and gravel (Taupo lapilli). Topsoils are deep and friable with weakly developed structures while subsoils have a loose coarse texture. Typical profiles for the major soil groups at Puruki are given in Appendix 1 and soil physical properties in Appendix 2. Soil chemical proerties of Oruanui soils under bracken fern have been examined in detail near Taupo (Appendix 3) and the results below 20 cm depth are considered applicable at Puruki (W. C. Rijkse pers. comm.). Data from the top 20 cm of the soil were also collected at Puruki, as this part of the soil profile is more easily modified by the recent history of pasture establishment and management. Soil bulk densities are low to medium, ranging from 0.5 t/m^3 in the top 15 cm and Taupo lapilli, to 0.7 t/m^3 in the Taupo and older ash layers (Beets 1977; Appendix 3).

Climate

Climate data have been recorded on an hourly basis (*see* Table 1) since January 1976 at the FRI meteorological tower, this fully automated data storage facility complementing and for some parameters superseding a climate station set up in 1970 by the MWD. The climate parameters measured (radiation, temperature, humidity, windspeed, and rainfall) were intended to provide a record of the physical environment, sufficient to cater for the requirements of a wide range of projects relating to canopy processes, growth, and health of the pine stands. Rainfall records date back to 1964 in relation to the Mangakara representative basin.

TABLE 1—Measurements and present height/depth relative to ground level of instruments used at the Puruki-Rua meteorological tower. Data are recorded continuously and stored as 1-hour averages (or totals for rainfall)

Parameter	Height/depth of sensor(s)
Solar irradiance (duplicated)	35 m
Reflected solar radiation	35 m
Diffuse solar irradiance	35 m
Net all-wavelength radiation (duplicated)	35 m
Photosynthetic irradiance	35 m
Diffuse photosynthetic irradiance	35 m
Soil heat flux density (duplicated)	depth 2 cm
Air temperature	2 m above canopy*
Wet bulb air temperature	2 m above canopy and 35 m
Soil temperature	0, 5, 10, and 30 cm depth
Wind speed (duplicated)	2 m above canopy
Wind speed	35 m
Rainfall	Collector funnel above canopy

* "Canopy" denotes tree top level given in Table 3.

Ten-year means of monthly climate data are given in Fig. 2. Solar irradiance averages 5 GJ/m^2/year, with annual variations of less than 6%. Average monthly temperature 2 m above the canopy ranges between 5° and 15°C with average temperature exceeding 10°C for 6 months of the year. Freezing temperatures occur on 3 days on average in July, and 1 day per month in June and August. The minimum air temperature 2 m above the canopy was –1.8°C in 1979. Thus, freezing temperatures are rare within the canopy but ground frosts occur commonly in the adjacent pasture

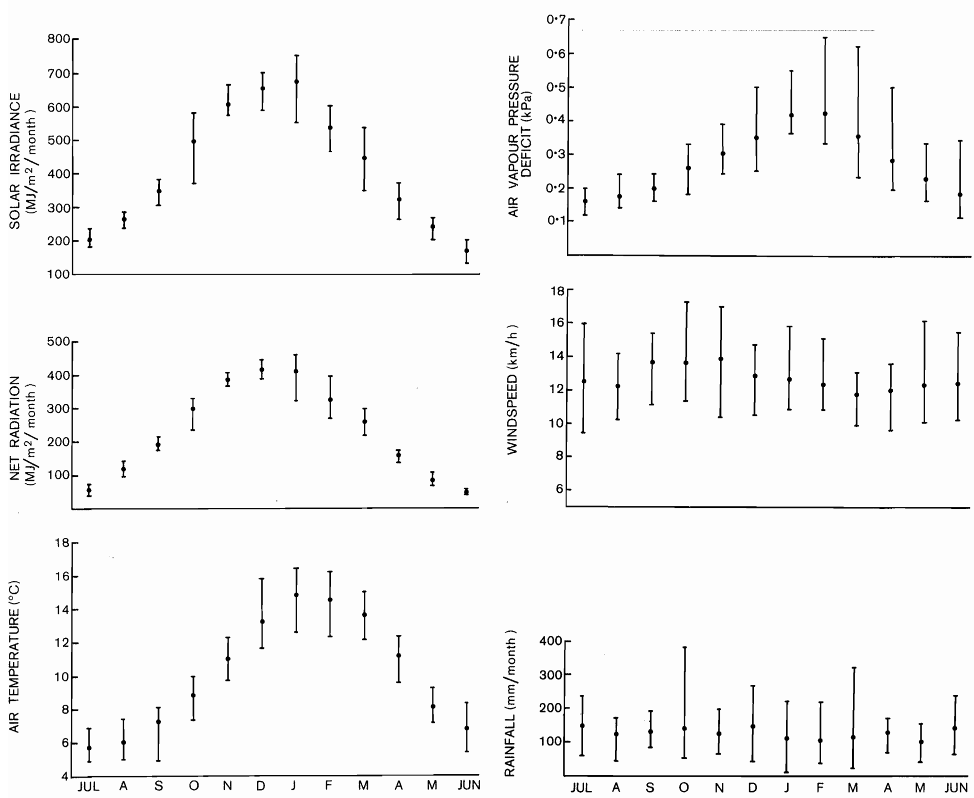

FIG. 2—Monthly means of climate parameters measured continuously from 1976 to 1985. Vertical lines represent the range.

catchments. Vapour pressure deficit 2 m above the canopy ranges between 0.15 and 0.45 kPa. Spring (September-November) tends to be the windiest season. Precipitation averages 1500 mm/year. This is evenly distributed with monthly averages ranging between 100 and 150 mm/month, falling almost exclusively as rain. Rain in excess of 1 mm fell on 144 days/year on average, ranging between 122 and 172 days/year. Fog is rare at Puruki which lies above the zone of fog characteristic of the low-lying areas in winter.

Indigenous Forest

Podocarp/tawa forest, the natural vegetation of the area, has a three-tiered structure and is rich in species. A botanical survey of the indigenous forest was made in the Puruorakau catchment (MWD 1971). Rimu (*Dacrydium cupressinum* Lamb.), 25–30 m tall, emerge over a 12- to 25-m canopy dominated by kamahi (*Weinmannia racemosa* L.f.) in association with miro (*Prumnopitys ferruginea* (D. Don) de Laub.), hinau (*Elaeocarpus dentatus* (J.R. et G. Forst) Vahl), and occasional rewarewa (*Knightia excelsa* R.Br.) and tawa (*Beilshmiedia tawa* (A. Cunn.) Kirk). The sparse understorey is comprised of hardwood trees, shrubs, and ferns. The understorey is more prevalent in valley bottoms where the rimu and kamahi overstorey trees are virtually absent and the irregular canopy, which ranges between 2 and 10 m in height, is composed of wineberry (*Aristotelia serrata* (Forst.) Oliver), tree fuchsia (*Fuchsia excorticata* (Forst. f.) L.f.), mahoe (*Melicytus ramiflorus* Forst.), five-finger (*Pseudopanax arboreus* (Murr.) Philipson), rangiora (*Brachyglottis repanda* J.R. et G. Forst.), tree nettle (*Urtica ferox* Forst. f.), other shrubs, and tree fern (*Dicksonia squarrosa* (Forst. f.) Swartz). In contrast to the interfluves the valley bottoms have an almost continuous ground cover comprised of ferns (*Asplenium bulbiferum* Forst. f., *Blechnum chambersii* Tind., *B. fluviatile* (R. Br.) Salom., *Leptopteris hymenophylloides* (A. Rich.) Presl, *Polystichum vestitum* (Forst. f.) Presl), mosses, liverworts, sedges, and herbs.

Along forest margins influenced by logging, juvenile dense kamahi stands approximately 3 m tall are the dominant cover. The indigenous forest at Puruki was cleared in the 1920s and sown into pasture which subsequently reverted to seral scrub.

Pasture

Puruki was re-developed into well-established pasture in 1957. Pasture establishment typically involved burning the scrub, sowing perennial ryegrass (*Lolium perenne* L.)/ white clover (*Trifolium repens* L.), and applying cobaltised superphosphate. Invading weed species – for example, ragwort (*Senecio jacobaea* L.), bracken fern (*Pteridium esculentum* (Forst.f.) Kuhn.), scotch thistle (*Cirsium vulgare* (Savi) Ten.), catsear (*Hypochaeris radicata* L.) – periodically co-dominate with Yorkshire fog (*Holcus lanatus* L.) and cocksfoot (*Dactylis glomerata* L.). Regular applications of cobaltised or potassic superphosphate combined with judicious control of grazing maintain clover in the pasture, resulting in high levels of nitrogen fixation for pasture growth. "Bush sickness" due to cobalt deficiency previously limited pastoral farming on the central North Island volcanic plateau which was therefore extensively planted with *P. radiata* commencing in the 1920s (Will & Knight 1968). Prior to tree planting at Puruki, isolated self-seeded *P. radiata* trees, which established after burning during pasture development, were poisoned in 1969 and again in 1970. Fertiliser application also ceased in 1969.

Streamflow Structures

Puruki catchment is subdivided into three subcatchments each with streamflow structures installed, designated Tahi (5.9 ha), Rua (8.7 ha), and Toru (13.8 ha). Streams flowing from these three subcatchments and the additional areas (6.0 ha) to the east are measured collectively by the Puruki weir (Fig. 3). The Puruki weir was installed

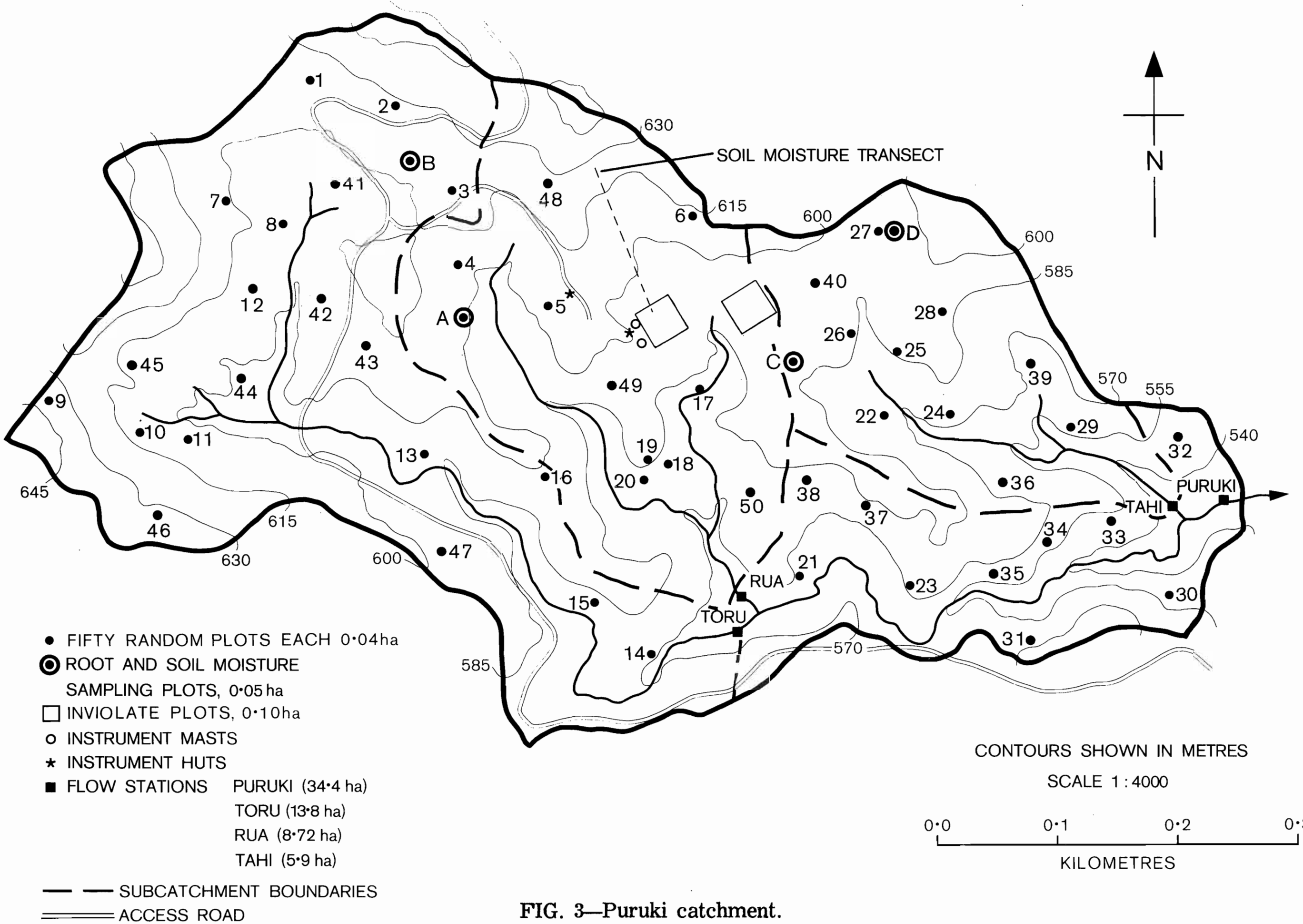

FIG. 3—Puruki catchment.

in 1968, and the weirs in Tahi, Rua, and Toru were installed later in 1971 and 1972 to cater for differential management of the *P. radiata* stands in the subcatchments.

Forest Establishment and Management

Pinus radiata seedlings (1/0) were uniformly planted at 2.4 × 1.8 m (6 × 8 feet) spacing in winter, 1973 after the entire catchment was sprayed to kill the pasture. Seedling survival was excellent (>90%) in Rua and Tahi but as low as 10–30% in Toru, particularly at higher elevations which were planted with bare-rooted stock in frosty, sunny weather. Survival in Toru exceeded 90% after replanting in 1974 and Toru is regarded as 1 year younger. Scotch thistle, nodding thistle (*Carduus nutans* L.), ragwort, and flatweeds made rampant growth but had largely disappeared by 1975 after the return of Yorkshire fog, cocksfoot, and a range of minor species and by which time the pines were well established (Fig. 4). Estimates of ground vegetation dry

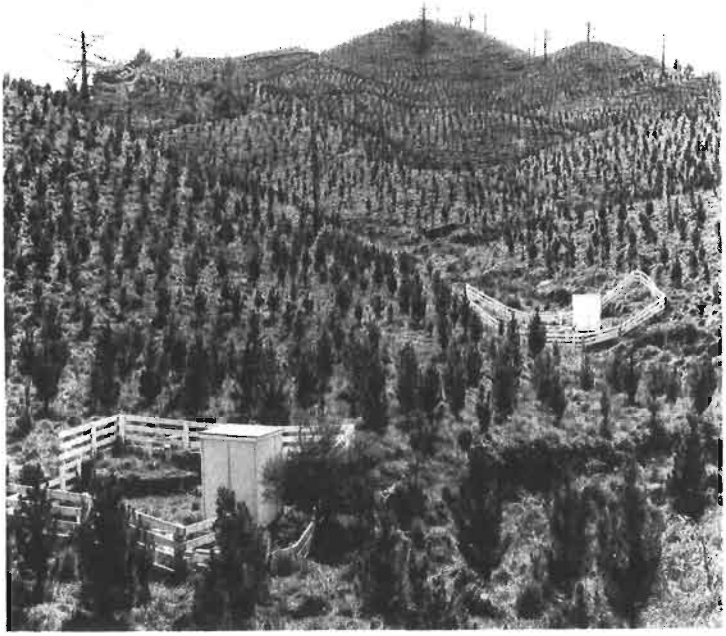

FIG. 4—Puruki-toru and Puruki-rua subcatchment flow stations, with **Pinus radiata** trees photographed in October 1975, 2 years after planting at 2.4 × 1.8 m spacing. Total area of Puruki catchment is 35 ha.

matter and nutrient content are given in Table 2. Ground vegetation has been largely absent since canopy closure by the pines in 1979 but vigorous bracken regrowth occurs after thinning. Visual inspection of the Tahi stand in 1985 gave the impression of even greater amounts of ground vegetation than measured previously (Table 2).

Clonal trees interspersed with seedling spacers were planted in three blocks with a total area of 1 ha. Every third seedling in every third row was replaced by a rooted

TABLE 2—Ground vegetation (grasses, weeds, fern) sampled using a 30-cm-square frame placed over the vegetation and clipped flush with the ground surface. A total of n randomly located samples from throughout Puruki prior to canopy closure were ovendried (65°C) and analysed for nutrient content

Year	n	Dry weight* (t/ha)	Nutrient content								
			N	P	K	Ca	Mg	B	Cu	Zn	Mn
			(% dry weight)					(ppm)			
1976	45	7.9	1.72	0.19	0.88	0.67	0.16	12	4	40	339
1977	45	10.5	1.41	0.13	0.66	0.44	0.13	10	40	38	341
1978	90	9.5	1.72	0.18	0.56	0.65	0.15	11	>60	51	460

* Includes live and dead vegetation.

cutting belonging to one of six standard clones (FRI No. 850. 448, 450, 451, 454, 455, 456), with 250 rooted cuttings planted in total. The history and selection of these clones have been documented by Knight (1978). Selection for thinning has favoured the retention of these clones, regardless of other thinning criteria (see later), so that comparisons can be made of the response to thinning of clonal *versus* seedling material.

Stand Assessment and Thinning

Stand data are given by year in Table 3, including the timing and intensity of thinning to waste. Stand development was monitored using permanently established circular assessment plots which were located randomly throughout Puruki (Fig. 3). Assessment plots were 0.01 ha but increased to 0.04 ha immediately after the first thinning of each subcatchment to 550 stems/ha. The number of assessment plots was increased from 30 to 50 to maintain adequate numbers of trees measured for height and diameter (see Table 3 footnote). All trees were pruned to 2.2 m immediately prior to thinning to facilitate access for subsequent research and management purposes. Sample trees for biomass determination were harvested annually (Fig. 5). Tahi and the additional catchment areas were managed as a single unit of 11.9 ha. The later thinning of Toru compensated in part for the delayed establishment of the trees there, with less green crown removed through pruning. Pruning removed, on average, 25% of the green crown length (Beets & Pollock 1987) from the Tahi plots – little effect on stand growth is expected (West *et al.* 1982; Koehler 1984). A flat to easy rolling part of Rua was left unpruned and unthinned; it comprised two 0.10-ha inviolate plots with surrounds 17 m wide on average.

Subsequent thinning was carried out to give a wide range of final-crop stockings. Tahi was thinned to 160 stems/ha in 1983 (Fig. 6) and Toru to 290 stems/ha in 1984. It is intended that Rua remain at 550 stems/ha, and that Tahi and Toru be thinned to 50 and 150 stems/ha in 1987 and 1988, respectively. Final-crop stocking levels in New Zealand typically range between 200 and 400 stems/ha in stands destined for sawlog production (Elliott 1982), though much lower stocking levels have been promoted for agroforestry (Chavasse 1985). Lower tree stockings are necessary where it is intended to maintain good pasture growth in silvo-pastoral systems.

TABLE 3—Stand characteristics of *P. radiata* undergoing different intensities of thinning

Sub catchment	Year	Age (years)	Stocking (trees/ha)	Basal area (m^2/ha)	Mean height (m)	Volume under bark (m^3)	Basic wood density (kg/m^3)
Tahi	1975	2	1970	0.28	1.6		
	1976	3	1960	2.22	2.6		
	1977	4	1960	6.77	3.8		
	1978	5	1950	15.8	5.7	47.7	317
	1979	6	1950	24.2	8.4	84.3	289
	1979*	6	495	8.56	8.4	29.8	289
	1980	7	495	13.2	9.6	55.1	296
	1981	8	495	19.2	11.3	93.9	307
	1982	9	495	24.7	13.2	132.6	344
	1983	10	495	30.2	15.4	160.1§	342
	1983†	10	159	10.0	15.4	53.2§	342
	1984	11	156	13.0	17.4	86.7§	349
	1985	12	156	16.4	19.3	111.6§	361
Rua	1975	2	1843	0.18	1.5		
	1976	3	1843	1.30	2.3		
	1977	4	1843	5.18	3.3		
	1978	5	1843	12.9	5.1	43.3	279
	1979	6	1843	21.1	6.9	78.2	267
	1980	7	1843	28.4	8.2	129.9	292
	1980*	7	550	11.9	8.2	54.4	292
	1981	8	550	16.8	11.1	82.2	327
	1982	9	550	21.8	12.6	106.8	334
	1983	10	550	26.9	14.4	152.0§	365
	1984	11	550	31.9	15.9	200.0§	345
	1984‡	11	577	33.0	15.9	206.5§	345
	1985	12	575	37.3	17.8	262.0§	366
Toru	1975	2	2123	0.11	1.2		
	1976	3	2092	0.97	1.9		
	1977	4	1969	3.48	2.6		
	1978	5	1969	9.21	4.5	30.0	340
	1979	6	1962	17.5	5.7	57.9	301
	1980	7	1962	26.8	7.4	106.6	279
	1981	8	1962	34.7	9.1	154.7	310
	1981*	8	561	14.2	9.1	63.0	310
	1982	9	549	17.1	11.4	84.4	312
	1983	10	540	21.9	12.9	114.1§	355
	1984	11	538	27.5	15.0	159.1§	338
	1984†	11	292	17.8	15.0	102.9§	338
	1985	12	292	22.0	17.1	139.6§	343
Inviolate	1975	2	1975	0.57	1.8		
	1976	3	1935	3.46	2.9		
	1977	4	1930	9.82	4.3		
	1978	5	1930	20.2	6.3	69.5	
	1979	6	1910	29.3	8.3	119.6	
	1980	7	1905	37.9	9.6	172.5	
	1981	8	1875	42.8	10.9	217.3	
	1982	9	1750	46.3	12.4	259.9	
	1983	10	1645	51.6	13.9	318.8	
	1984	11	1610	55.7	15.3	365.2	
	1985	12	1550	59.0	17.8	427.4	

*Stands thinned from 2220 to 550 stems/ha nominal stocking and trees pruned to 2.2 m height. Assessment plot area increased from 0.01 to 0.04 ha.

† Stands thinned from 550 to either 140 (Tahi) or 275 (Toru) nominal stocking. Assessment plot number increased from 10 to 20 in Tahi, and from 13 to 20 in Toru.

‡ Assessment plot number increased from seven to 10 in Rua. Two inviolate plots each 0.10 ha in area were established in Rua in 1974 and left unthinned.

§ Volume under bark (v_i) of five to seven sample trees was measured each year in Tahi, Rua, and Toru. Other volumes were estimated from tree height (ht) and diameter at 1.4 m (dbh) using a common tree volume equation based on Puruki data collected from 1978 to 1980: $\ln (v_i) = -9.945 + 1.739 \times \ln (dbh) + 1.110 \times (ht^2/(ht-1.4))$.

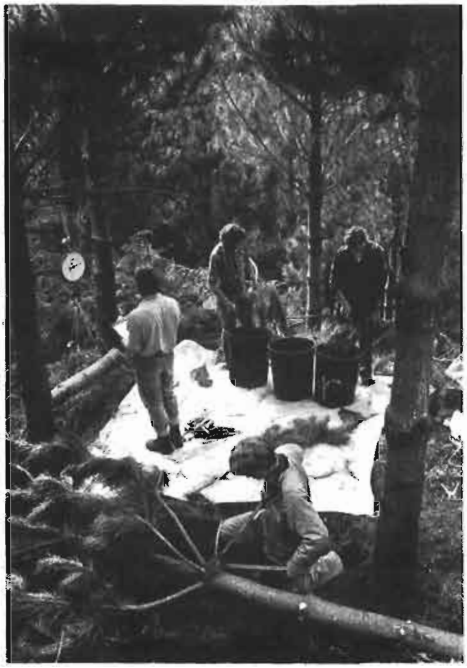

FIG. 5—Biomass field procedures. Between 15 and 21 trees were divided into components and weighed during May through August each year from 1975 to 1985; Puruki-rua stand photographed at 8 years of age and thinned to 550 stems/ha.

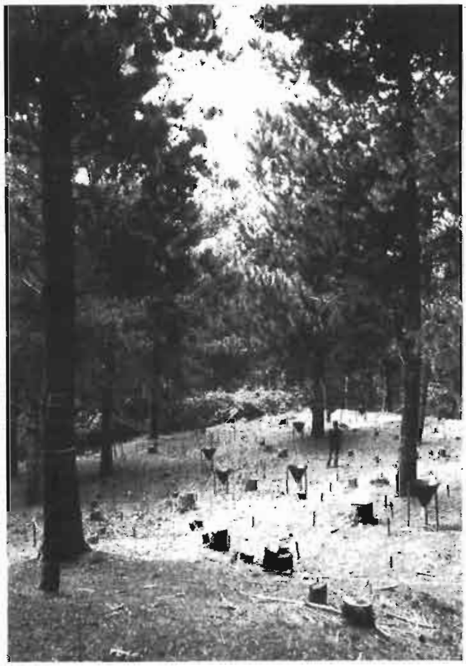

FIG. 6—Root growth plot located in Puruki - tahi subcatchment, photographed in April 1986 at a stocking of 160 stems/ha. Thinnings have been removed to the plot margin and the undergrowth sprayed to facilitate fine root growth studies. Bracken fern in background is the dominant understorey vegetation in stands with open canopies.

Tree selection for thinning was based on quality and spacing criteria. Straight trees free of forks and with small branches and healthy crowns were favoured, with tree size and spacing of secondary importance (Sutton 1973). Because of the high fertility of the site, trees generally had large branches and were top-heavy. Instability in the first few years of growth also resulted in many trees developing sweep in the lower portion of the stem. Thinning to 50 stems/ha, giving a selection ratio of 1 in 40, removed almost all malformed trees. In contrast, the clonal trees clearly showed the straightness of stem and fine branching which were the bases for their original selection, giving cuttings silvicultural advantages over seedlings (Klomp & Hong 1985).

Disease Control Measures

Two species of needle-cast fungi with the potential to influence *P. radiata* growth markedly are *Dothistroma pini* Hulbary and *Cyclaneusma minus* (Butin) DiCosmo *et al.* The assessment and control of *D. pini* are undertaken at a national level as described by Kershaw *et al.* (1982). *Dothistroma pini* infects trees between 2 and 15 years old and so Puruki has been sprayed regularly with copper oxychloride at recommended rates (Kershaw *et al.* 1982) during November/December, and effective control achieved. *Cyclaneusma minus* is prevalent in stands aged 6 to 25 years (van der Pas, Bulman, Slater-Hayes 1984), and marked reductions in growth of individual trees have been recorded (van der Pas, Slater-Hayes, Gadgil, Bulman 1984). No chemical control measures have been devised that are effective at an operational level (Hood & Vanner 1984). The incidence of *C. minus* at Puruki varies depending on climatic conditions and thinning; thinning favours the removal of the more susceptible genotypes and improves stand aeration, particularly in Tahi and Toru with their more severe thinning regimes. In Rua the disease-prone trees are gradually being suppressed, this natural process of elimination resembling a management thinning.

GROWTH LIMITATIONS

Environmental, biological, and management factors influencing the growth of *P. radiata* were reviewed by Raupach (1967). A recent review of physiological constraints on productivity in relation to climate has been given by Rook (1985) which, in conjunction with the following site-specific information, will assist in the interpretation of the growth data.

Water Supply

The *P. radiata* trees at Puruki have an abundant supply of water. Although extended droughts are unusual on the volcanic plateau, it is the great depth of soil and its peculiar physical and hydrological characteristics which determine the supply of readily available water to *P. radiata,* which has root-systems extending down 4 m or more (Will 1966). Will & Stone (1967) calculated that, over large areas of Kaingaroa Forest, sufficient moisture was available to meet evapotranspiration demands through the severest drought on record. Subsequent research has endorsed this conclusion. For example, in Puruki-Rua between November 1975 and March 1977 the soil moisture volume fraction ranged between 0.41 and 0.48 in the profile down to 1.9 m (Beets 1977), representing a 140-mm change in soil moisture content relative to the 800–900 mm, on average, in storage. The corresponding matric potentials are around –25 to –10 kPa (based on the data in Appendix 3), indicating ample moisture supply to the trees throughout the year.

Nutrient Supply

Foliar analysis results at Puruki (Table 4) indicate high levels of all nutrients except magnesium and boron which are marginal according to Will (1985). However, fertiliser trials have not shown a growth response to magnesium in stands with foliar levels at 0.08% Mg (dry weight) (Hunter *et al.* 1985). Furthermore, no clear-cut foliar boron level signifying deficiency has proved generally applicable (Will 1985)

TABLE 4—*Pinus radiata* foliar analysis averaged over period 1984–87. Mature length needles from current season's growth were collected from late February to March. Twenty trees were sampled from each Puruki subcatchment/year

Subcatchment	N	P	K	Ca	Mg	S	B	Cu*	Zn	Mn
	(% dry weight)						(ppm)			
Tahi	1.45	0.19	1.10	0.15	0.10	0.12	11	12	46	83
Rua	1.58	0.17	1.05	0.13	0.08	0.12	12	14	45	88
Toru	1.58	0.19	1.08	0.13	0.08	0.13	12	11	44	84
Inviolate (1986–87)	1.63	0.15	1.05	0.13	0.08	0.12	11	4	43	90
Satisfactory (Will 1985) if	>1.5	>0.14	>0.50	>0.10	>0.10	?	>12	>4	>20	>20?

* Copper fungicide aerially applied.
? Insufficient information and experience. S values are normal for *P. radiata* (P.J. Knight, pers. comm.).

and, since no recognised boron-deficiency symptoms are evident at Puruki, it seems unlikely that boron supply restricts growth there either. Compared to Kaingaroa Forest which was developed into pine directly from scrub, Puruki has a faster growth rate but, of a range of nutrient elements reported by Madgwick (1985) for Kaingaroa Forest (nitrogen, phosphorus, potassium, calcium, magnesium, boron, manganese, zinc) only foliar nitrogen is higher at Puruki. The recent history of pastoral farming has altered the surface soil at Puruki (Table 5) compared to Oruanui soil under bracken (Appendix 3), with high rates of nitrogen mineralisation measured at Puruki (Dyck *et al.* 1987). In northern and central Kaingaroa, nitrogen supply after thinning can be marginal for maximum growth (Hunter *et al.* 1985).

TABLE 5—Soil chemical analysis based on soil cores taken at 1-m intervals along two 20-m transects in each of Tahi, Rua, and the inviolate plot surrounds in January 1985. Only pH differed (5% prob.) between subcatchments so results were averaged by depth

Depth (cm)	pH (water)	Loss on ignition (%)	C (%)	N (%)	C/N	Bray* P (ppm)	Bray cations (me%)		
							Ca	Mg	K
0–10	5.2	18.9	8.3	0.51	16	91.9	11.0	1.5	0.31
10–20	5.3	12.6	4.6	0.28	16	60.3	4.0	0.70	0.20

Above table based on unpubl. data of W.J.Dyck.
In Appendix 3, mg % = ppm/10.
* A close correspondence occurs between exchangeable (NH_4OAc) (cations as in Appendix 3) and Bray cations, but neither correlates well with foliar nutrient levels (Ballard 1978).

Pathogens/Insects

The influence of leaf-cast fungi on growth, while marked on an individual tree basis, is much less important on a stand basis owing to genetic differences in susceptibility (Wilcox 1982; van der Pas, Slater-Hayes, Gadgil, Bulman 1984). At Puruki current dry matter production increased only slightly when projected leaf area index increased above 4 (Beets & Pollock 1987). Furthermore, as 90% of the incident radiation is intercepted at a projected leaf area index of 5 in closed canopy stands of *P. radiata* (Jarvis & Leverenz 1983), the retention of 50% of the current leaf growth for a second year at Puruki is sufficient to sustain close to maximum dry matter production; leaf retention, on a stand basis, usually exceeded 50%, based on the data given by Beets & Pollock (1987), suggesting that the removal of leaf area by pathogens and insects is not likely to be important for stand growth. Defoliation of *P. radiata* by insects was examined at Puruki by Hosking & Hutcheson (1987).

Thinning

The unthinned and lightly thinned stands in Rua have closed canopies and are expected to be limited only by radiation. Periodic stem volume increment under bark currently averages 52 m^3/ha/year in these stands, which is likely to be close to the maximum for *P. radiata* at Puruki.

In the heavily thinned Tahi and Toru stands, where between half and three-quarters of the tree basal area has been removed every 3 to 4 years, the genetic potential of the trees to expand their canopies and re-occupy the site is likely to be the main limiting factor. The growth rate of 25 to 30 m^3/ha/year over the past 5 years may increase when management thinning is completed and the stand leaf area can increase uninterrupted.

The diameter increment of the tree of mean basal area during 1984–85 was 0.8, 1.7, 3.1, and 4.1 cm in the inviolate, Rua, Toru and Tahi stands, respectively, calculated from the data in Table 3. The basal area, height, and dry matter development of the Puruki stands have been examined by Beets & Pollock (1987). The wood density values (Table 3) are moderate for the volcanic plateau, considering tree age (Cown & McConchie 1982).

CONCEPTUAL MODEL OF PURUKI RESEARCH

A considerable body of data has accumulated on different aspects of Puruki and this is the first major step in publishing this information. Integration of the various studies is currently being achieved through a modelling programme. With annual biomass measurements and continuous meteorological records, the value of the dataset for model calibration and validation purposes is already evident (Beets 1982; McMurtrie 1985; McMurtrie & Rook in press; Rook *et al.* 1985; Whitehead 1986).

The interrelationships between the papers that follow in this issue are depicted in Fig. 7. The simplicity achieved by restricting the figure to aspects covered in these papers was felt desirable. Root biomass relationships (Jackson & Chittenden 1981) and fine-root production and turnover studies undertaken at Puruki have been published separately (Santantonio & Santantonio 1987; Santantonio & Grace 1987). Storages are represented by boxes and fluxes by arrows which are regulated by the process identified next to the valve symbols. Explicit control points are depicted by circles. In this long-term programme of study, time steps range from hours to years depending on the process under investigation. Papers on tree growth focus on carbon (dry matter) and nitrogen whilst water quality aspects focus on nitrogen and phosphorus.

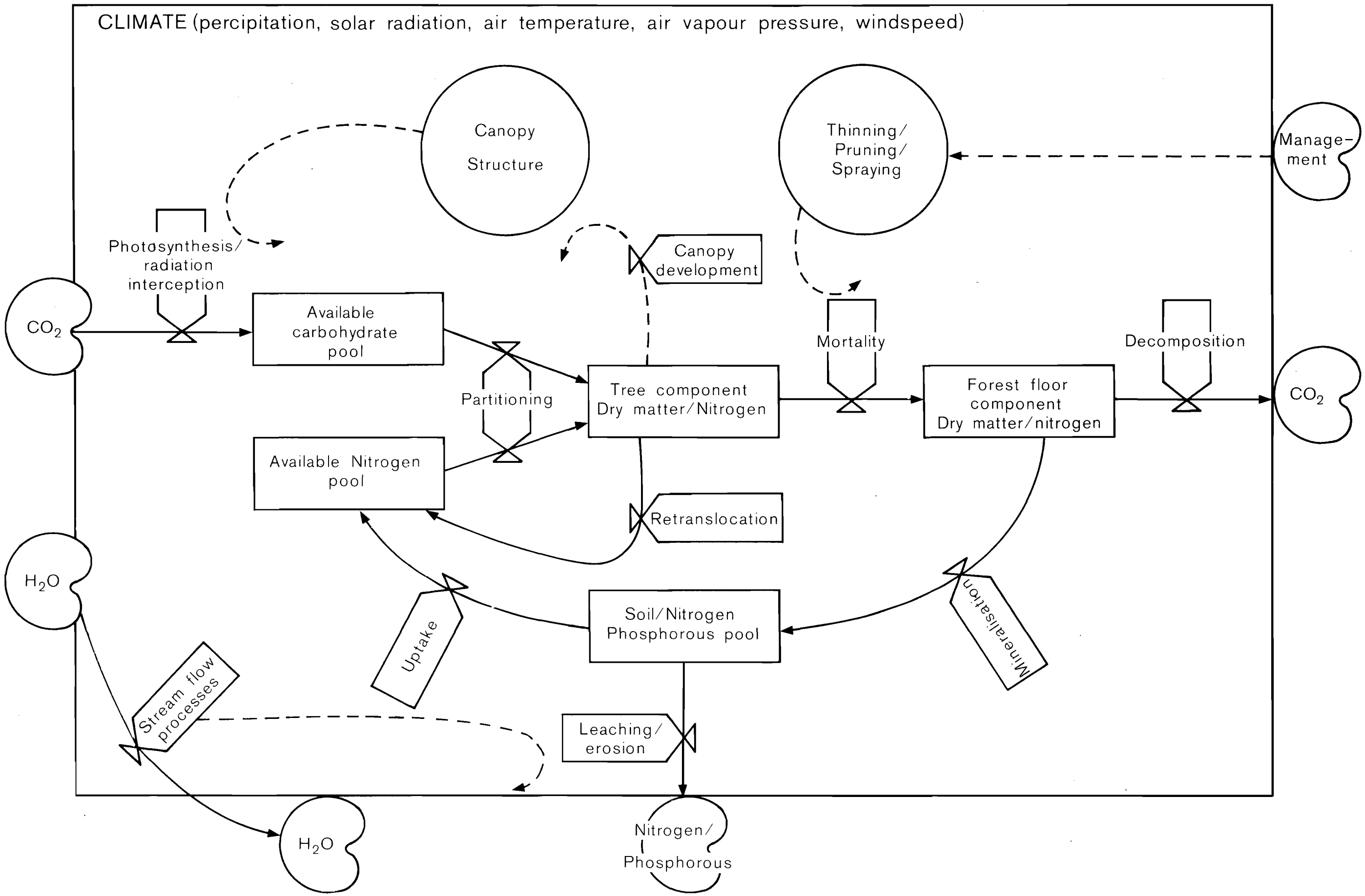

FIG. 7—Conceptual model depicting interrelationships of research results presented in accompanying papers (see text for definition of symbols).

CONCLUSIONS

The research programme at Puruki is unique for a variety of reasons.

(1) It is multidisciplinary in that it allows forest growth and development to be studied simultaneously with comparative hydrological research on variations in water yield and quality, relative to management;

(2) It is long term. Because of the rapid growth rate of *P. radiata*, rotation lengths are usually only 25 to 30 years. Investigations spanning an entire rotation are therefore concentrated within a relatively short time frame; we have proceeded almost half way;

(3) A programmed change in land-use was made. The conversion of the area from pastoral farming to production forest provides valuable information for land-use planning, especially when taken in conjunction with other land-use catchments in the Purukohukohu basin;

(4) The potential growth rate of *P. radiata* can be assessed. Because of climate, soil, and management factors, all of which are monitored, growth rates are likely to be at a maximum for this species given the radiation climate at this site. Furthermore, the wide range in nominal final-crop stocking (50 to 2200 stems/ha) will enhance the value of the base line biomass data for model validation purposes; Future research should focus on aspects relating to the end-use of the trees.

ACKNOWLEDGMENTS

This paper is based partly on Purukohukohu Experimental Basin annual and quarterly reports by H. Drost, R. J. Pittams, and H. J. Freestone, of the Ministry of Works and Development, and a Puruki catchment database set up by D. S. Jackson of the Forest Research Institute, (then) New Zealand Forest Service. Much of FRI's commitment to the Puruki project stems from the untiring efforts and enthusiasm of Dr Jackson. We extend our appreciation to all participants involved at Purukohukohu over the years for contributing to the project.

REFERENCES

BALLARD, R. 1978: Use of the Bray soil test in forestry. 2. Determination of cation status. **New Zealand Journal of Forestry Science 8:** 332–43.

BEETS, J. M. 1977: Measuring soil moisture under pine forest with a Wallingford probe. M.Sc. Thesis, University of Waikato.

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.

BEETS, P. N.; POLLOCK, D. S. 1987: Accumulation and partitioning of dry matter in **Pinus radiata** as related to stand age and thinning. **New Zealand Journal of Forestry Science 17:** 246–71.

BENNETT, K. J.; ROOK, D. A. 1978: Stomatal and mesophyll resistances in two clones of **Pinus radiata** D. Don known to differ in transpiration and survival rate. **Australian Journal of Plant Physiology 5:** 231–8.

BURDEN, R. J. 1982: Nitrate contamination of New Zealand aquifers: A review. **New Zealand Journal of Science 25:** 205–20.

CHAVASSE, C. G. R. 1985: Agroforestry promotion group – final report. **New Zealand Journal of Forestry 30:** 177–85.

COWN, D. J.; McCONCHIE, D. L. 1982: Rotation age and silvicultural effects on wood properties of four stands of **Pinus radiata. New Zealand Journal of Forestry Science 12:** 71–85..

DALY, B. K.; RIJKSE, W. C. 1974: A typical sequence of soils derived from air-fall tephra. **In** Read, N. E. (Ed.) "Soils Groups of New Zealand. Part 1: Yellow-brown Pumice Soils". New Zealand Society of Soil Science, Wellington.

DROST, H. 1971: Experimental tributary catchments. Pp. 149–66 **in** Duncan, C. (Ed.) "The Waters of the Waikato". Proceedings of the seminar held at the University of Waikato in September 1971, Hamilton, New Zealand.

DUNCAN, C. 1971: The water resource. Pp. 1–9 **in** Duncan, C. (Ed.) "The Waters of the Waikato". Proceedings of the seminar held at the University of Waikato in September 1971, Hamilton, New Zealand.

DYCK, W. J.; MEES, C. A.; HODGKISS, P. D. 1987: Nitrogen availability and comparison to uptake in two New Zealand radiata pine forests. **New Zealand Journal of Forestry Science 17:** 338–52.

ELLIOTT, D .A. 1982: Review of thinning practice in New Zealand 1974 to 1981. **New Zealand Journal of Forestry Science 12:** 127–39.

GIFFORD, H. H.; WHITEHEAD, D.; THOMAS, R. S.; JACKSON, D. S. 1982: Design of a new weighing lysimeter for measuring water use by individual trees. **New Zealand Journal of Forestry Science 12:** 448–56.

HARRIS, J. M.; McCONCHIE, D. L.; POVEY, W. A. 1978: Wood properties of clonal radiata pine grown in soils with different levels of available nitrogen, phosphorus and water. **New Zealand Journal of Forestry Science 8:** 417–30.

HOOD, I. A.; VANNER, A. I. 1984: Cyclaneusma (Naemacyclus) needle-cast of **Pinus radiata** in New Zealand. 4: Chemical control research. **New Zealand Journal of Forestry Science 14:** 215–22.

HOSKING, G. P.; HUTCHESON, J. A. 1987: Population dynamics and biomass consumption of lepidopterous defoliators in a developing **Pinus radiata** stand. **New Zealand Journal of Forestry Science 17:** 331–7.

HUNTER, I. R.; GRAHAM, J. D.; CALVERT, K. T. 1985: Effects of nitrogen fertiliser on radiata pine growing on pumice soils. **New Zealand Journal of Forestry 30:** 102–14.

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.

JACKSON, D. S.; GIFFORD, H. H.; CHITTENDEN, J. 1976: Environmental variables influencing the increment of **Pinus radiata:** (2) Effects of seasonal drought on height and diameter increment. **New Zealand Journal of Forestry Science 5:** 265–86.

JACKSON, R. J. 1984: Investigation of the properties and genesis of West Coast wet land soils, South Island, New Zealand. 5: Physical characteristics of soil profiles and soil water regimes. **New Zealand Journal of Science 27:** 155–74.

JARVIS, P.; LEVERENZ, J. W. 1983: Productivity of temperate deciduous and evergreen forests. Pp. 234–80 **in** Lange, O. L.; Nobel, P. S.; Osmond, C. B.; Ziegler, H. (Ed.) "Encyclopedia of Plant Physiology" New Series, Vol. 12D. Springer-Verlag, Berlin.

KERSHAW,, D. J.; GADGIL, P. D.; LEGGAT, G. J.; RAY, J. W.; van der PAS, J. B. 1982: Assessment and control of **Dothistroma** needle blight. Revised edition. **New Zealand Forest Service, FRI Bulletin No. 18.**

KLOMP, B. K.; HONG, S. O. 1985: Performance of **Pinus radiata** seedlings and cuttings to age 15 years. **New Zealand Journal of Forestry Science 15:** 281–97.

KNIGHT, P. J. 1978: Foliar concentrations of ten mineral nutrients in nine **Pinus radiata** clones during a 15-month period. **New Zealand Journal of Forestry Science 8:** 351–68.

KOEHLER, A. R. 1984: Variable lift pruning of radiata pine. **New Zealand Forest Service, FRI Bulletin No. 78.**

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

——— 1983b: Differences in growth and weight of genotypes of pine with special reference to clones of **Pinus radiata. New Zealand Journal of Forestry Science 13:** 115–24.

——— 1985: Dry matter and nutrient relationships in stands of **Pinus radiata. New Zealand Journal of Forestry Science 15:** 324–36.

McKELVEY, P. J. 1963: The synecology of the West Taupo indigenous forest. **New Zealand Forest Service Bulletin No. 14.**

McMURTRIE, R. E. 1985: Forest productivity in relation to carbon partitioning and nutrient cycling: a mathematical model. Pp. 194–207 **in** Cannell, M. G.; Jackson, J. E. (Ed.) "Attributes of Trees as Crop Plants". Institute of Terrestrial Ecology, Huntingdon.

McMURTRIE, R. E.; ROOK, D. A. Modelling the yield of **Pinus radiata** crops limited by water and nitrogen. **Forest Ecology and Management** (in press).

MWD 1971: Purukohukohu, IHD Experimental Basins Nos 4 and 5 to 1969. **Ministry of Works and Development, Hydrological Research Annual Report 19.**

——— 1973: Purukohukohu, IHD Experimental Basins Nos 4 and 5, 1970–1. **Ministry of Works and Development, Hydrological Research Annual Report 29.**

RAUPACH, M. 1967: Soil and fertiliser requirements for forests of **Pinus radiata. Pp.** 307–53 **in** Norman, A. G. (Ed.) "Advances in Agronomy" Vol. 19. Academic Press, New York.

RIJKSE, W. C.; BELL, J. L. 1974: Soils of Purukohukohu IHD Experimental Basin, Rotorua County, North Island, New Zealand. **Department of Scientific and Industrial Research, New Zealand Soil Survey Report 18.**

ROOK, D. A. 1985: Physiological constraints on yield. Pp. 1–9 **in** Tigerstedt, P.M.A.; Puttonen, P.; Koshi, V. (Ed.) "Crop Physiology of Forest Trees". Helsinki University Press, Helsinki.

ROOK, D. A.; CORSON, M. J. 1978: Temperature and irradiance and the total daily photosynthetic production of the crown of a **Pinus radiata** tree. **Oecologia (Berl.) 36:** 371–82.

ROOK, D. A.; GRACE, J. C.; BEETS, P. N.; WHITEHEAD, D.; SANTANTONIO, D.; MADGWICK, H. A. I. 1985: Forest canopy design: Biological models and management implications. Pp. 507–24 **in** Cannell, M. G.; Jackson, J. E. (Ed.) "Attributes of Trees as Crop Plants". Institute of Terrestrial Ecology, Huntingdon.

SANTANTONIO, D.; GRACE, J. C. 1987: Estimating fine-root production and turnover from biomass and decomposition data: A compartment-flow model. **Canadian Journal of Forestry Research 17:** 900–8.

SANTANTONIO, D.; SANTANTONIO, E. 1987: Effect of thinning on production and mortality of fine roots in a **Pinus radiata** plantation on a fertile site in New Zealand. **Canadian Journal of Forestry Research 17:** 919–28.

SUTTON, W. R. J. 1973: Changes in tree dominance and form in a young radiata pine stand. **New Zealand Journal of Forestry Science 3:** 323–30.

van der PAS, J. B.; BULMAN, L.; SLATER-HAYES, J. D. 1984: Cyclaneusma (Naemacyclus) needle-cast of **Pinus radiata** in New Zealand. 3: Incidence and severity of the needle-cast. **New Zealand Journal of Forestry Science 14:** 210–4.

van der PAS, J. B.; SLATER-HAYES, J. D.; GADGIL, P. D.; BULMAN, L. 1984: Cyclaneusma (Naemacyclus) needle-cast of **Pinus radiata** in New Zealand. 2: Reduction in growth of the host, and its economic implications. **New Zealand Journal of Forestry Science 14:** 197–209.

WEST, G. G.; KNOWLES, R. L.; KOEHLER, A. R. 1982: Model to predict the effects of pruning and early thinning on the growth of radiata pine. **New Zealand Forest Service, FRI Bulletin No. 5.**

WHITEHEAD, D. 1983: Letter to the editor. Design of a new weighing lysimeter for measuring water use by individual trees by H. H. Gifford, D. Whitehead, R. S. Thomas and D. S. Jackson. **New Zealand Journal of Forestry Science 13:** 242–3.

——— 1986: Dry matter production and transpiration by **Pinus radiata** stands in relation to canopy architecture. Pp. 243–62 **in** Fujimori, T.; Whitehead, D. (Ed.) "Crown and Canopy Structure in Relation to Productivity". IUFRO, Proceedings of an International Workshop held in Japan 14–20 October 1985.

WILCOX, M. D. 1982: Genetic variation and inheritance of resistance to **Dothistroma** needle blight in **Pinus radiata. New Zealand Journal of Forestry Science 12:** 14–35.

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

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

WILL, G. M.; KNIGHT, P. J. 1968: Pumice soils as a medium for tree growth. 2: Pot trial evaluation of nutrient supply. **New Zealand Journal of Forestry 13:** 50–65.

WILL, G. M.; STONE, E. L. 1967: Pumice soils as a medium for tree growth. 1: Moisture storage capacity. **New Zealand Journal of Forestry 12:** 189–99.

APPENDIX 1

EXTENDED LEGEND TO SOIL MAP OF PURUKOHUKOHU EXPERIMENTAL BASIN, ROTORUA COUNTY (from Rijkse & Bell 1974)

Soil reference symbol	Soil name	Topography	Parent material	Native vegetation	Natural drainage	Brief description of soil profile	Remarks
YELLOW-BROWN PUMICE SOILS - from subaerial ash							
O	Oruanui loamy sand	Easy rolling and rolling slopes	40–70 cm Taupo Pumice, on Waimihia, Rotoma, Waiohau and Rotorua ash beds, on Huka Formation.	Bracken fern and scrub	Well drained	0–13 cm black (7.5YR 2/0) sandy loam; friable; weakly developed fine nut and crumb structure, 13–20 cm dark brown (7.5YR 3/2) sandy loam; firm; weakly developed fine nut and crumb structure; few fine Taupo Lapilli, 20–28 cm light yellowish brown (10YR 6/4), often with tongues of dark brown (7.5YR 3/2) loamy sand; firm; weakly developed fine nut and crumb structure. 28–36 cm light yellowish brown (10YR 6/4) coarse sand; loose single grain; horizon contains much dark grey (2.5YR4/0) rhyolite, 36–50 cm light yellowish brown (10YR 6/4) pumice gravel (Taupo Pumice) (diameter 1/4 to 11/2 cm); loose, single grain, 50–69 cm yellowish brown (10YR 5/6) greasy sandy loam; friable; weakly developed fine nut structure; many fine lapilli (Rotoma Ash and Waiohau Ash), 69–120 cm yellowish brown (10YR 5/6) greasy sandy loam; firm; massive, 120–220 cm yellowish brown (10YR 5/6) greasy silt loam; firm; massive, on white (5Y 8/2) siliceous pumice and siltstone (Huka Formation).	Negligible erosion; some accumulation of washed organic matter in hollows. High permeability in horizons that contain Taupo Pumice; moderate to low permeability in older yellowish brown ash layers. Huka Formation is impermeable to water. Moderately leached soil.
Oh	Oruanui loamy sand, moderately steep phase	Moderately steep slopes	20–60 cm Taupo Pumice, on Waimihia, Rotoma, Waiohau and Rotorua ash beds, on Huka Formation.	Bracken fern and scrub	Well drained	Similar to above profile but often with Taupo Pumice gravel in topsoil. Depth to Huka Formation varies from 160 to 220 cm.	Minor slump erosion with few terracettes.

Appendix 1 cont.

Soil reference symbol	Soil name	Topography	Parent material	Native vegetation	Natural drainage	Brief description of soil profile	Remarks
OH	Oruanui hill soils, loamy sand	Moderately steep to steep slopes	10–40 cm Taupo Pumice, on Waimihia, Rotoma, Waiohau, and Rotorua ash beds, on Huka Formation.	Bracken fern and scrub	Well drained	0–16 cm black (10YR 2/1) loamy sand; friable; weakly developed fine nut and crumb structure; few fine Taupo Lapilli, 16–28 cm yellowish brown (10YR 5/6) loamy sand; firm; weakly developed coarse and fine nut structure; few fine Taupo Lapilli, 28–39 cm yellow (10YR 7/6) pumice gravel (Taupo Pumice); loose; single grain, 39–44 cm yellowish brown (10YR 5/4) coarse loamy sand; friable; single grain (Waimihia Lapilli and Rotoma Ash), 44–67 cm strong brown (7.5YR 5/6) greasy sandy loam; very friable; weakly developed crumb structure; few fine lapilli (Waiohau Ash), 67–182 cm yellowish brown (10YR 5/6) greasy silt loam; firm; massive, on hard siliceous pumice (Huka Formation).	Marked terracettes which channel surface runoff, some shallow slumps, some pugging by cattle.
STEEPLAND SOILS RELATED TO YELLOW-BROWN PUMICE SOILS - from subaerial ash							
TaS	Tauhara steepland soils	Steep to very steep slopes	Mixed Taupo Pumice with older brown ash bed, on Huka Formation.	Bracken fern, scrub and forest	Well drained	0–18 cm black (7.5YR 2/0) gritty loam sand; friable; weakly developed granular structure; many fine and medium Taupo Lapilli, 18–30 cm dark brown (7.5YR 3/2) coarse sand and fine gravel; loose; single grain; many fine and medium Taupo Lapilli, 30–66 cm olive brown (2.5Y 4/4) and yellowish brown (10YR 5/4) coarse sand and fine gravel; loose; single grain; abundant medium Taupo Lapilli, 66–180 cm yellowish brown (10YR 5/8) greasy sandy loam; friable; weakly developed fine nut structure; few Taupo Lapilli in upper 10 cm of horizon, on white (5Y 8/2) siliceous siltstone; hard Huka Formation).	Soil profiles variable, having 10–20 cm volcanic ash on hard siliceous pumice and siltstone;outcrops of siliceous siltstone occur. Taupo Pumice varies from 0 to 80 cm in depth. Marked terracettes, many small slumps, few larger slumps where siltstone is exposed.

APPENDIX 2

PHYSICAL PROPERTIES OF ORUANUI SOIL PROFILES AT PURUKI

Soil name	Horizon	Depth (cm)	Bulk density (t/m^3)	Water content (% volume) at tension (kPa) indicated									Saturated hydraulic conductivity (m/s)
				Natural*	0†	2.5	5	10	20	40	100	1500	
Oruanui	A	2–7	0.68	44	63	58	53	49	43	38	31	14	5.1×10^{-5}
loamy sand	AB	9–14	0.61	29	49	41	37	33	27	21	14	7	4.9×10^{-5}
	B	18–23	0.50	33	68	47	39	35	29	24	18	8	1.9×10^{-4}
	C	35–40	0.79	39	60	54	47	39	29	25	19	7	2.3×10^{-5}
		53–58	0.82	40	59	51	44	37	29	23	17	5	5.3×10^{-5}
		89–94	0.90	26	65	34	29	25	21	18	15	3	1.8×10^{-4}
Oruanui	A1	1–6	0.58	36	63	54	48	42	34	27	19	11	–
hill soil,	B	8–13	0.66	37	60	51	46	41	35	29	22	14	–
loamy sand	B	20–25	0.54	35	66	47	41	36	29	22	16	9	–
	C11	35–40	0.73	43	63	55	47	41	30	21	15	6	–
	Upper Taupo	46–51	0.73	38	69	50	42	33	22	16	13	4	–
	Upper Taupo	60–65	0.76	41	60	51	48	45	41	38	40	16	–
	Brown ash	75–80	0.72	47	62	56	53	50	47	44	41	21	8.2×10^{-5}

Appendix 2 based on unpubl. data of R.J. Jackson, using methods described by Jackson (1984).

* Natural water content likely to be close to field capacity, given antecedent weather conditions.

† Submerged but not saturated as vesicular pumice leaves some pores air-filled.

APPENDIX 3

CHEMICAL ANALYSIS OF ORUANUI SOIL PROFILE UNDER BRACKEN FERN; PALMER MILL ROAD, TAUPO (grid ref N94:589490). These data are considered appropriate for the soil profile below 20 cm depth (Table based on Daly & Rijkse 1974)

Horizon	Depth (cm)	pH (water)	C (%)	N (%)	C/N	P (mg%)			P retention (%)	Exchangeable cations (me%)				Tamm's extract (%)	
						Inorganic	Organic	Total		Ca	Mg	K	Na	Al	Fe
A1	0–8	5.6	11.7	0.70	17	30	63	93	27	12.6	2.95	1.92	0.42	0.43	0.22
A1	8–19	5.4	7.8	0.33	24	22	44	66	50	9.2	0.91	0.50	0.14	0.49	0.28
(B1)	20–25	5.8	3.2	0.19	17	26	37	63	58	2.6	0.26	0.28	0.33	0.73	0.33
(B)	28–36	5.8	2.6	0.15	17	25	34	59	62	2.3	0.25	0.21	0.49	0.88	0.30
(B)	40–60	6.0	1.0	0.07	14	28	13	41	44	1.1	0.09	0.46	0.92	0.62	0.17
C1	65–71	5.8	0.6	0.03	20	28	5	33	28	0.4	0.05	0.52	0.94	0.37	0.12
C2	75–100	6.5	0.3	0.02	15	35	0	35	14	0.4	0.09	0.29	0.44	0.20	0.10
Dr	113–119*	6.7	0.2	0.02	10	15	3	18	12	0.9	0.05	0.83	1.11	0.15	0.26
–	119–129	6.4	0.7	0.06	12	15	20	35	35	1.4	0.10	0.73	1.15	0.59	0.32

*113–119 cm is Rotangaio Ash.