

Transpiration potential of contorta, radiata pine and Douglas fir for de-watering in mass wasting control

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Abstract. Trees growing on steep slopes stabilise the soils by root binding and dewatering. In areas where precipitation modestly exceeds evapotranspiration the direct water use by trees may play an important part in maintaining mass stability.

The annual and seasonal transpiration economies of contorta pine, radiata pine and Douglas-fir, exotics commonly planted in New Zealand, have been estimated from heat pulse velocity measurements made in these species at the Whakarewarewa State Forest near Rotorua, during February 1973 through April 1974. Highest rates of water uptake by individual trees occurred in 7 year old radiata pine at all seasons of the year. Annual transpirational loss from stands was also greatest in young radiata pine (700 to 1000 mm) compared to (350 to 560 mm) in contorta pine and (140 to 850 mm) in Douglas-fir. Transpiration loss during the winter (May-August) when precipitation greatly exceeds loss, was approximately 120 mm in radiata compared to less than 60 mm in either of the other species.

Winter transpiration rates varied with stocking density in contorta pine and Douglas-fir. At 100 stems/ha, a stand of 50 year old Douglas-fir was very ineffective, using only 11 mm of water in the May-August period. Fifty year old contorta at 320 stems/ha was more effective with a use of 29 mm, followed by 15 year old contorta or Douglas-fir at 1600 to 2000 stems/ha with 50 mm transpiration (May-August).

Winter transpiration by radiata pine stands from 26 to 6 years old, at 600 to 2200 stems/ha, was 106 to 140 mm.

Potentiel de transpiration de *Pinus contorta*, *P. radiata* et *Pseudotsuga menziesii* pour l'assechement des terres

Résumé. Les arbres stabilisent les pentes en fixant le sol avec leurs racines et en absorbant l'excès d'eau. Dans les régions où les précipitations dépassent légèrement l'évapotranspiration, l'utilisation directe de l'eau par les arbres peut jouer un rôle important dans le maintien de la stabilité des masses.

On a estimé les bilans de transpiration annuels et saisonniers de *Pinus contorta*, *Pinus radiata* et *Pseudotsuga menziesii*, des espèces étrangères couramment plantées en Nouvelle-Zélande, en mesurant la vitesse des variations thermiques chez ces espèces dans la forêt d'Etat de Whakarewarewa près de Rotorua, entre février 1973 et avril 1974. Les taux les plus élevés d'absorption d'eau ont été relevés chez *P. radiata* de 7 ans, pendant toutes les saisons. C'est également chez cette espèce que les pertes par transpiration des peuplements étaient les plus élevées puisque'elles atteignaient 700 à 1000 mm contre 350 à 560 mm pour *P. contorta* et 140 à 850 mm pour *P. menziesii*. Les pertes par transpiration pendant l'hiver (mai à août), alors que les précipitations dépassent considérablement les pertes, étaient d'environ 120 mm chez *P. radiata*, alors qu'elles étaient inférieures à 60 mm chez les deux autres espèces.

Les taux de transpiration hivernaux varient avec la densité des peuplements chez *P. contorta* et *P. menziesii*. Chez cette dernière espèce, à 100 tiges/ha, un peuplement de 50 ans était très inefficace puisqu'il n'utilisait que 11 mm d'eau entre mai et août. Un peuplement

de 50 ans de *P. contorta* de 320 tiges/ha était plus efficace (29 mm). Venaient ensuite des peuplements de 15 ans de ces deux espèces à 1600 à 2000 tiges/ha avec une transpiration de 50 mm pendant la même période. Enfin, la transpiration hivernale de peuplements de *P. radiata* de 26 à 6 ans, comportant 600 à 2200 tiges/ha, atteignait 106 à 140 mm.

INTRODUCTION

Steep slopes, shallow permeable soils and high rainfall are factors creating unstable conditions in mountainous terrain. High soil water pore pressure frequently occurs in such situations and is often a significant causal factor in mass wasting events. Trees growing on steep slopes play two roles in stabilising them: (1) their roots provide some mechanical strength and (2) they reduce soil water through both the interception and evaporation of precipitation on their foliage and transpiration to the atmosphere from water in the soil volume via the roots, stems and stomata (Rice and Foggin, 1971; Gonsior and Gardner, 1971; Swanston, 1971).

The role that de-watering by trees plays in affecting soil mass stability is the subject of some debate (O'Loughlin, 1974) and cannot be the same in all instances. In areas where precipitation greatly exceeds evapotranspiration, the role of trees as de-waterers is probably minimal (Swanston, 1974). However, in more xeric conditions, the water use by trees may play an important part in maintaining soil mass stability (Swanston and Dryness, 1973).

My purpose in this paper is to examine the transpiration economy of three exotic tree species used for plantation

purposes in New Zealand, in order to better judge their capabilities in de-watering sites to aid in mass wasting control. This has been accomplished by: (1) measuring upward xylem sap flow *in situ* in individual trees of several ages and stocking densities on one fine day each month over the period February 1973 through April 1974 using the heat pulse velocity technique, (2) converting these fine-day measurements to average daily, monthly and annual water use estimates by combining the sap flux and stand density measurements with 1973-74 climatic data from the Whakarewarewa State Forest Park near Rotorua. These transpiration data are then compared with monthly and annual precipitation to elucidate the role of the species-stockings arrangement in the seasonal and annual water economy.

METHODS

The technique used to estimate transpiration involves determining the average xylem flow rate of several trees on a site, and by proper sampling intensity, extrapolation of these data to the particular stand in question. The stands sampled in this study were located on or adjacent to the Whakarewarewa State Forest Park near Rotorua, and ranged from 0.04 to 39 ha in area, Figure 1. Seven trees were sampled in each area. The physical and vegetational characteristics of these plots are given in Table 1.

Theoretical heat pulse velocity (HPV) was measured as an indication of sap speed (Marshall, 1958). Sensing apparatus

consisted of two temperature sensors, one 10 mm above and the other 5 mm below a 50 mm long electric heater (Swanson, 1974). The sensors were installed to depths measured from the cambium ranging from 5 to 35 mm into three 1.6 mm diameter holes drilled in the sapwood. Sixteen sets of sensors were installed at each plot during February and March 1973, and left in place for reading during the period April 1973 to April 1974.

Two determinations of heat pulse velocity from all 16 sets of sensors, one between 0900 and 1200, the second between 1300 and 1500 hours were taken each month. In general, the forenoon values represented low transpiration rates associated with morning dew or fog and the afternoon readings represented the day's optimum conditions for high water loss. The data from all depths were averaged to obtain a single HPV value for the sapwood. The morning and afternoon readings were averaged to obtain a mean value for the day.

Subsequent to this study, Swanson and Whitfield (1980) showed that HPV values derived directly from Marshall's (1958) equations underestimate true HPV and that the degree of underestimation is a function of the flow disruption caused by sensor implantation and physiological reaction of the tree to the sensors to isolate them from the sap stream. They called the width of disrupted sap stream "wound width" and numerically derived a family of equations to correct HPV's measured at various wound widths and derived from Marshall's (1958) theoretical equation to true HPV. The wound width of several excised sensor installations from each plot was

measured at the conclusion of this study and their equations (Swanson and Whitfield, 1980) have been used to derive the actual HPV values used in this paper.

Transpiration (sap flow) is calculated from sap flux values and sapwood area. Sap flux, the sap flow per unit area of sapwood, is a function of HPV and sapwood moisture content and is useful in comparing specific sap flow rates between trees of the same or differing species on the same or differing sites (Marshall, 1958). Heat pulse velocity is a site variant and sapwood moisture content may be too.

Waring and Running (1978) report significant diurnal and seasonal variation in Douglas fir sapwood moisture content. Waring and Roberts (1979) suggest similar variations occur in Aleppo pine. In both instances, moisture content was determined from increment borings.

Swanson (1970) reported that the results obtained in determining moisture content in Aleppo pine depended upon the technique used to obtain the cores. Those determined from increment borings decreased as xylem pressure potential increased, whereas the moisture contents determined from cores obtained simultaneously with those bored, but with the sharp blow of an increment hammer, increased or remained constant.

Swanson and Whitfield (1980) used a constant value of wood moisture content to calculate transpiration of Aleppo pine over a wide range of xylem pressure potentials within 5% of that measured by lysimetry. In view of this fact, the moisture contents used to obtain the sap flux values

reported in this paper were obtained from excised wood sections taken in February 1975, and have been applied as constants for the 1973-74 sap flux calculations. One should thus regard possible moisture content changes as a potential source of error in transpiration estimates from heat pulse velocities. I consider the uncertainty in the sap flux and subsequent transpiration estimates reported here as $\pm 10\%$ in the pines and $\pm 20\%$ in Douglas fir.

Transpiration is a relatively straight-forward calculation from sap flux values. The average sapwood area for the trees on each plot was determined from increment cores. Average sap flux times sapwood area is the transpiration rate, $\text{cm}^3 \text{hr}^{-1}$, for the average tree of the plot. The number of hours each day that this rate continued was taken as the monthly average of the number of hours of bright sunshine each day as recorded at the Forest Research Institute (FRI), Rotorua. The number of days each month that this daily rate applied was taken as the number of days with less than 1 mm of rain - also, as reported at FRI. Finally, the monthly average tree transpiration, in litres per month, was multiplied by the number of stems per hectare and divided by 10,000 to obtain unit area transpiration in mm per month.

RESULTS

The morning and afternoon sap flux ($\text{cm}^3 \text{cm}^{-2} \text{hr}^{-1}$) values for the day of measurement are given in Table 2. Highest average sap flux occurred in the 1968 radiata pine thinned to 1100

stems ha^{-1} ; the lowest occurred in 1908 contorta pine at 321 stems ha^{-1} . The highest value obtained occurred during the forenoon reading in the 1968 radiata (1100 stems) in September. Zero sap flux was recorded on only one occasion, the July forenoon reading in 1947 radiata.

Monthly, seasonal and annual transpiration, in mm, is given in Table 3. This table also contains the monthly precipitation (mm), the average number of daily hours of bright sunshine each month, the average monthly dry bulb temperature and the number of days each month with less than 1 mm of rain.

Highest annual transpiration, 996 mm, occurred in 1968 radiata pine at 2200 stems ha^{-1} . As a group, all stands and ages of radiata pines transpired more than either of the other species, although annual transpiration from the 1958 Douglas fir at 1600 stems ha^{-1} was of the same order of magnitude.

Winter (May through August) transpiration was noticeably greater in all of the radiata plantations than either of the other species. Again, this value is highest in 1968 radiata (2200 stems ha^{-1}) at 140 mm but the 1956 radiata (1500 stems ha^{-1}) at 130 mm and the 1947 radiata (600 stems ha^{-1}) at 120 mm were not far behind.

DISCUSSION

The role that these three species play in de-watering is fairly clear. Radiata pine transpired heavily throughout the year using greater than 60% of annual precipitation. More important is its high winter transpiration compared to that of the other

two species; radiata transpired approximately 25% of the precipitation that fell during the May-August period compared to 10% or less by the other species.

Douglas fir planted and maintained at high density stocking would be equally effective with radiata pine in September through April water use. However, its winter transpiration is only one-third that of radiata of comparable age and stocking. This lesser winter use may be more of a response to cold temperatures or reduced day length than to high atmospheric humidity during the wet winter period since transpiration in September and January, which were high rainfall months, was generally greater in the 1958 Douglas fir plantations than in all of the radiata pine plantations. If this reduced winter response in Douglas fir was caused primarily by low temperature and not by day length, then perhaps it could serve equally well with radiata pine as a de-waterer on warmer sites.

The transpiration values for 1907 Douglas fir at 100 stems ha⁻¹ are probably not indicative of this species' potential water use. Diameter growth in these trees was sharply reduced after 1968, probably resulting from infection by a needle cast fungi (Cameron, Alma and Hood, 1974). Even so, the sap flux values obtained in these trees were higher than those in comparably-aged contorta pine and the 1956 and 1947 radiata pine. The plantation that these data are from were an overstory for very vigorous undergrowth (mostly blackberry and bracken fern) from which the trans-

piration was not measured. If Douglas fir were maintained at a sapwood basal area comparable to that of radiata pine, it probably would show equal warm-season potential for site de-watering. However, it appears to suffer very reduced winter transpiration and sap flux does not approach the magnitude of that found in the older radiata pine until October.

Contorta pine of any age or stocking density was not as effective in de-watering during September through April as either young Douglas fir or any age radiata pine. The May through August transpiration from the 1958 contorta pine was not significantly different from that of the 1958 Douglas fir on the same sites.

Inasmuch as these data reflect actual transpiration of stands of these species at various ages, stocking density, physiological condition and physical situations, it would be presumptuous to attach too much significance to small differences in either their sap flux or areal transpiration values. Nonetheless, it appears that two further comparisons should be valid, namely: (1) The thinned-unthinned 1968 radiata pine which were on the same site, (2) the apparent tendency toward a constant value of sap flux in all pines with increasing age regardless of site or stocking density.

1. Thinning has a marked effect on sap flux in 1968 radiata pine. The thinning occurred in March 1973, and by July the sap flux of the thinned group exceeded that of the unthinned. The difference between the two reached a peak during August and September when precipitation was high and

soil water apparently freely available. The difference between the thinned and unthinned sap flux diminishes during the summer (December-March) when water availability rather than tree physiological conditions appear to control the rate of uptake.

The transpiration from the thinned group did not drop to half that of the unthinned as would be expected, largely because the trees removed were less vigorous than those left behind. Their daily sap fluxes during April through June are roughly equal, but the greater diameter and consequently greater sapwood area of the trees left after thinning compensated for much of the reduction in tree numbers. Linear extrapolation through time of ratio of the monthly transpiration (thinned/unthinned) predicts that it will go from its initial value of 0.7 to 1.0 in 30 to 40 months. If one were managing this stand for its winter de-watering capabilities, he should probably carry out thinning in September rather than March and then only in numbers sufficient to ensure that the increased sapwood increment would compensate for the number of stems removed by the beginning of the next rainy season (April or May).

2. Maximum sap flux in radiata pine appears to decrease with age and to stabilise as a value of 13 to 16 $\text{cm}^3 \text{cm}^{-2} \text{hr}^{-1}$. This value was also found in all three contorta pine plantations. Once this stable sap flux value is achieved, any difference in transpiration between stands must be reflected in sapwood basal area, that is, the greater the sapwood basal area on a given hectare, the greater the transpiration.

This tentative finding of a stable maximum sap flux needs further exploration as it may extend to other species as well. (For instance, the 1907 Douglas fir plantations maximum sap fluxes were mostly in this range.) However, even if a stable maximum sap flux does exist, it is not clear from these data at what age it is reached. Although it appears to be present in the 1958 contorta pine stand, it was not observed in the 1958 Douglas fir plantation which was on the same site. It is doubtful that the attainment of this stable rate is solely related to age. More likely, it would correspond with some function of growth rate, perhaps the point of inflection in the sigmoidal growth rate curve. This would be an interesting area for future work.

CONCLUSIONS

Annual transpiration by radiata pine, contorta pine and Douglas fir, varied with species, age and stocking density. Highest annual values of transpiration (840 to 1000 mm) were obtained in densely stocked, 7 year old, radiata pine and 5 year old Douglas fir stands. The lowest value (135 mm) occurred in a sparsely stocked, 65 year old Douglas fir plantation. Transpiration from contorta pine stands (260 to 550 mm) at any age or stocking density was less than that from all ages of radiata pine or 15 year old Douglas fir.

Transpiration during the wet, cool winter season (May-August) was 100 to 140 mm in radiata pine stands compared to 11 to 55 mm in either contorta pine or Douglas

fir. Precipitation during this same time period, was 442 mm. Thus, radiata pine stands transpired roughly one-fourth of the precipitation received compared to one-eighth or less by the other two species.

Highest water loss per unit area of sapwood (sap flux) $48.9 \text{ cm}^3 \text{ cm}^{-2} \text{ hr}^{-1}$, occurred in 7 year old radiata pine that had been recently thinned from 2200 to 1100 stems per hectare. Maximum sap flux in all species declined with increasing age (or decreasing growth rate), and appeared to be stabilising at 13 to $16 \text{ cm}^3 \text{ cm}^{-2} \text{ hr}^{-1}$.

Zero sap flux (and transpiration) occurred on only one occasion during the 1973-74 study year; this in radiata and in response to highly humid, foggy conditions existing during the forenoon set of heat pulse velocity readings. This indicates that transpiration from this coniferous species can occur year around (in the favourable climate found at Rotorua, New Zealand) and that atmospheric vapour deficit rather than any lack of physiological activity is the factor most limiting to the role that radiata pine play in de-watering.

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Species	Year Planted	Area [ha]	1973-74 [Stems/ha]	Average 73-74			Slope [%]	Aspect	CPT ² No.
				DBH [cm]	Height [m]	CBA ¹ [cm ²]			
<i>P. contorta</i>	1958	0.04	2037	18.7	12	202	10	NNE	12
	1944	1.62	598	27.0	18	359	40	ENE	17
	1908	0.12	321	58.9	33	801	40	ENE	17
<i>P. radiata</i>	1968	0.40	2200	13.8	11	128	00		FRI
	1968 ³	0.40	1100	15.8	12	171	00		FRI
	1956	2.83	1500	27.4	29	417	10	NNE	8
	1947	6.88	600	44.3	40	958	00		8
<i>Ps. menziesii</i>	1958	0.24	1600	19.0	14	188	10	NNE	12
	1907 ⁴	39.27	100	78.4	45	1016	10	S	7

¹ CBA = Average sapwood area per tree during 1973-74. Actual sapwood areas that existed each month were used to calculate the transpiration values in Table 3.

² CPT = Compartment on Whakarewarewa State Forest, or at Forest Research Institute, FRI.

³ Part of the 2200 stem per hectare stand was thinned to 1100 stems in March 1973.

⁴ These trees represent only the overstory on this area. There was considerable undergrowth here that was mainly absent on the other plots.

TABLE 2. Clear Day Sap Flux, Whakarewarewa State Forest, Average For Each Tree on Plot cm²cm²hr⁻¹.

1973												1974				
YEAR	TIME	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	MEAN		
[st/ha]																
PINUS CONTORTA																
1958 (2037)	AM	7.3	2.6	1.8	2.6	1.7	9.0	10.0	7.2	11.4	13.9	12.0	11.7	7.6		
	PM	11.0	5.9	3.6	4.0	7.1	11.7	12.6	13.3	16.1	16.4	15.9	12.5	10.8		
1944 (598)	AM	8.1	1.1	1.3	1.5	3.7	9.2	9.0	9.3	11.7	13.6	13.3	11.2	7.8		
	PM	9.5	3.9	3.9	3.6	5.6	8.1	8.4	11.7	12.3	13.3	13.3	12.8	8.9		
1908 (321)	AM	9.3	1.8	2.4	2.2	4.8	7.2	8.3	8.3	10.0	12.3	12.9	10.4	7.5		
	PM	10.5	6.5	2.6	5.0	5.6	7.7	6.1	9.5	11.0	11.1	12.1	10.4	8.2		
PINUS RADIATA																
1968 (2200)	AM	30.4	22.6	7.6	7.1	26.6	41.0	27.0	32.2	36.5	34.7	29.8	27.4	26.8		
	PM	19.1	11.1	17.7	27.8	24.8	33.8	32.6	31.0	29.4	27.8	24.1	18.4	24.8		
1968 (1100)	AM	31.7	15.3	5.2	10.6	36.9	48.9	31.8	37.4	36.5	38.7	32.2	29.8	29.6		
	PM	21.4	15.5	18.9	32.6	34.3	36.9	36.9	34.3	31.4	30.6	27.0	21.0	28.4		
1956 (1500)	AM	14.4	9.3	2.2	2.0	9.5	12.8	10.5	12.7	14.7	14.5	12.4	10.5	10.5		
	PM	9.5	8.1	8.2	9.0	10.3	10.9	11.8	11.4	13.0	11.8	10.7	8.0	10.2		
1947 (600)	AM	14.1	9.7	1.9	0	13.6	16.2	9.8	11.2	12.7	10.8	9.3	8.5	9.8		
	PM	10.7	8.0	7.9	8.7	13.0	12.7	12.5	11.0	10.6	8.4	9.3	6.8	10.0		
PSEUDOTSUGA MENZEISII																
1958 (1600)	AM	10.1	4.9	2.5	2.6	4.6	31.9	27.6	22.4	24.4	27.6	23.2	14.0	16.3		
	PM	18.5	7.9	5.9	7.3	18.5	30.4	35.4	29.0	32.4	35.9	30.9	18.5	22.6		
1907 (100)	AM	7.0	4.8	0.9	3.2	4.3	5.7	7.6	10.5	14.2	15.5	17.6	9.5	8.4		
	PM	7.4	4.1	2.5	2.9	7.2	4.2	10.5	12.6	14.7	17.6	19.0	10.5	9.4		

TABLE 3 Monthly and seasonal transpiration, mm, 1973-1974 at
Whakarewarewa State Forest Park, Rotorua, New Zealand

		1973										1974						
	st/ha	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	MAY- AUG	SEP- APR	ANNUAL		
PINUS CONTORTA																		
1958	2037	38	12	7	16	9	20	69	36	84	128	63	76	44	514	558		
1944	598	19	4	4	7	5	9	28	19	39	60	31	39	20	244	264		
1908	321	26	7	4	11	7	9	27	19	40	61	34	39	29	229	258		
PINUS RADIATA																		
1968	2200	63	29	21	55	35	48	124	78	148	194	92	109	140	856	996		
1968	1100	44	17	13	45	31	36	96	60	104	148	68	82	106	638	744		
1956	1500	75	36	21	42	31	34	104	64	130	169	78	87	130	741	871		
1947	600	72	34	18	30	38	38	95	55	101	114	58	65	120	598	718		
PSEUDOTSUGA MENZEISII																		
1958	1600	42	12	8	18	17	42	140	66	130	202	91	75	55	788	843		
1907	100	7	3	1	4	3	2	14	10	22	34	20	15	11	124	135		
CLIMATIC DATA																		
Precipitation	mm	138	81	149	51	161	228	31	122	110	11	190	68	442	893	1340		
Days ≤ 1 mm	N	22	17	19	26	16	14	26	17	23	28	21	25					
Mean Sunshine	Hours	4.6	3.9	3.4	4.7	3.1	3.3	5.7	5.0	6.5	7.3	5.1	5.9					
Mean Air Temperature	°C	13.2	10.5	7.4	5.4	8.0	10.5	13.2	15.4	17.5	17.3	19.8	14.6					

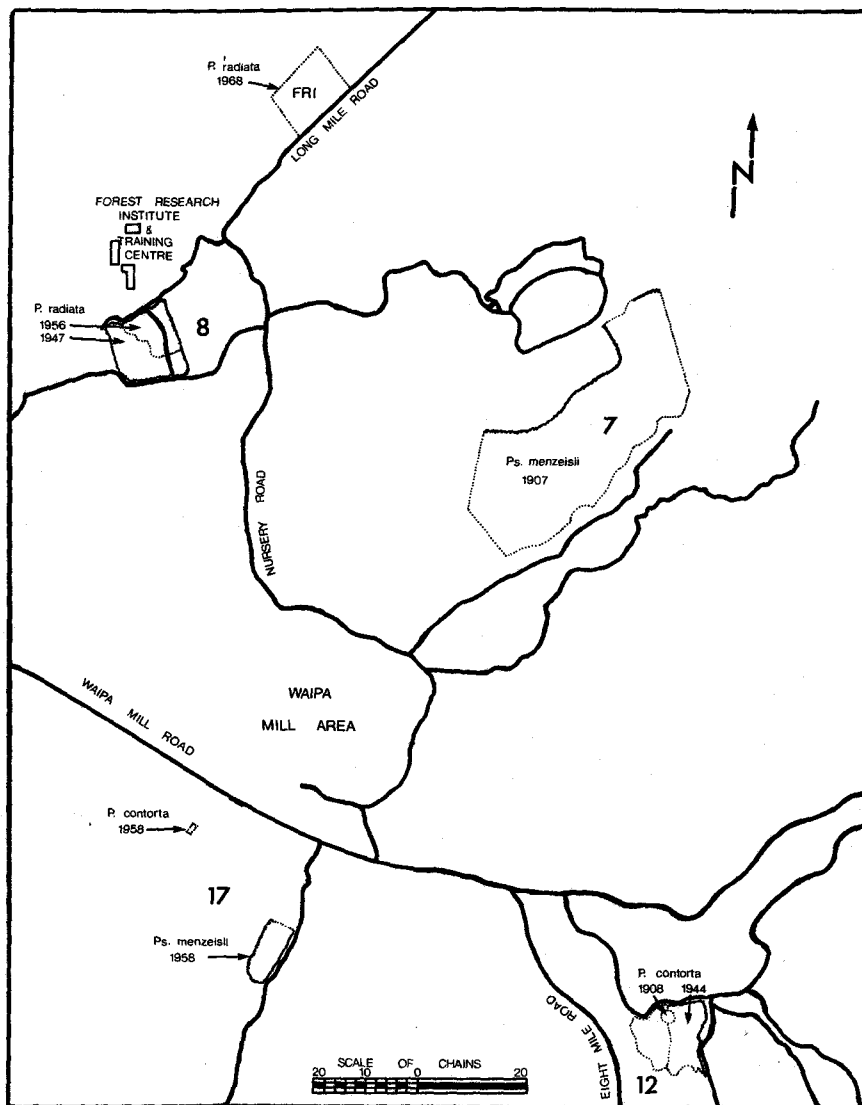


FIGURE 1. Locator map for transpiration measurement plots at Whakarewarewa State Forest Park, Rotorua, New Zealand, Lat. $38^{\circ}10'S$, Long. $176^{\circ}16'$, Altitude 300-400 MSL.