SOIL WATER IN DEEP PINAKI SANDS: SOME INTERACTIONS WITH THINNED AND FERTILISED PINUS RADIATA

D. S. JACKSON, ELIZABETH A. JACKSON, and H. H. GIFFORD

Forest Research Institute, New Zealand Forest Service,
Private Bag, Rotorua, New Zealand

(Received for publication 1 March 1982; revision 12 July 1982)

ABSTRACT

In an experimental comparison of **Pinus radiata** D. Don planted with or without yellow tree lupin (**Lupinus arboreus** Sims), **versus** with or without fertiliser, the lupin and fertiliser combination had 60-70% greater volume production than the controls by tree age 13 years. Depletion of soil water by the more productive stands was also much greater, and could cause critically low levels of soil water potential (-5 bars or less) throughout the profile during late summer and autumn. Critical depletion did not occur in the less productive controls (no lupin or fertiliser).

During the first 7 years (up to the time of canopy closure) differences in stocking produced the most significant differences in soil moisture, but only in the top metre of sand. Thinning greatly reduced depletion of soil water, particularly by stands with fertiliser, but these effects rapidly diminished after 2 or 3 years, and became insignificant after 5 years. After canopy closure the effects of fertiliser began to override those due to stocking, and to produce significant soil moisture differences much deeper down the profile, at 3 to 4 m. Differences in soil water storage beneath extremes of treatment amount to **c.** 134 mm of rainfall at midwinter.

INTRODUCTION

A previous paper (Jackson *et al.* 1983) reported the mensurational results of an experiment intended to augment early development of *P. radiata* growing on deep Pinaki Sands, by thinning and fertiliser application. Because it had long been uncertain whether the poor response to thinning, of many stands in Woodhill State Forest, was due to a chronic seasonal deficiency of available soil water, or to an inadequate nutrient supply, the experiment (A 287) included seasonal monitoring of soil water beneath stands in each treatment/thinning combination. Some analyses of the resulting data are presented here.

The layout of this experiment has been detailed in the earlier paper (Jackson *et al.* 1983). It is situated on the west-facing slope of a large sand-dune that had been stabilised by planting marram and oversowing with yellow lupin. These were overplanted with *P. radiata* in 1968. The soil is classified as Pinaki sand, and any ground-water (on the evidence of adjacent lakes) must be at least 30 m below the surface of the dune. Mean

New Zealand Journal of Forestry Science 13(2): 183–96 (1983)

annual rainfall at Woodhill State Forest headquarters (15 km from the experiment site) is 1313 mm. Monthly and annual rainfalls for the period 1972–81 are summarised in Table 1, together with monthly figures recorded at the experimental site from October 1974 to July 1979.

METHODS

The design comprised two replications of a split-plot experiment, each replication containing a simple 2 × 2 factorial of the main plot treatments – plots with or without yellow lupin, *versus* plots with or without a balanced fertiliser application. The factorial combinations were designated (0), (l), (f), and (lf). On the (0) and (f) plots, lupin was eliminated by spraying followed by manual removal of regeneration as required; the marram cover was not affected. Each main plot (area 0.566 ha), planted with 2224 stems/ha in 1968, was further subdivided into four sub-plots. Three of these sub-plots were subsequently thinned to 1483, 741, and 371 stems/ha.

Within each sub-plot an assessment area of 405 m^2 was marked out for annual remeasurement, and two aluminium access-tubes for neutron probing were installed at random. The tubes had an internal diameter of 41 mm and were *c.* 460 cm long, with the bottom end sealed by a tapered hardwood plug. They were driven into position (the hole was not pre-bored) using a special hammer and a protective cap over the top of the tube. The first tube of each pair was driven only to a depth of 340 cm, but the second tube was subsequently installed to a minimum depth of 420 cm. Four tubes were also placed in an area of marram grass and lupin adjacent to the site of the experiment, as a basis for comparison with the tree plots.

Soil-water status was monitored with a Wallingford Neutron Probe, Model 225, using a rate-scaler (Model 604A). Measurements were made seasonally, in June, September, December, and February or March of each year from 1972 through to 1978, and then only during the winter of 1979 and 1980. It generally took about 3 days to measure all of the 68 tubes. Six of the sampling occasions had to be rejected for various reasons, most frequently because the series of measurements was interrupted by rain before the whole set of readings had been completed. Since we were seldom able to repeat the measurements on any one visit, such interruptions would vitiate comparisons based on our assumption that there would be no major changes of water status among the tubes during the period of measurement. Counts were taken over a standard 16-second period at 10-cm vertical intervals down each profile for the top metre of sand, and at 20-cm intervals below that. The count-rates per second provide the basic data for the plotted profiles and for the statistical comparisons that are presented below. Shield-counts were taken at the beginning and end of each profile (i.e., about 120 to 150 shield-counts per run) as a check on instrumental drift. The mean shield count per sampling ranged from 711 to 738 over the 8 years of monitoring, with a minimum standard error of 7.76 and a maximum of 28.04. There was no consistent pattern of variation or drift. The calibration chart (Fig. 1) for mean count-rate per second against soil water as a percentage by volume is adapted from Bell's (1973) calibration line for sands, gravels, and silts. Plotted against it are the results of four field-calibration checks in undisturbed Pinaki sand, using the procedures outlined by Eeles (1969). Soil-moisture characteristics of the sand were determined over a range from –0.05 to –5 bars pressure,

TABLE 1—Monthly rainfalls (mm) at Woodhill State Forest headquarters (1972-81) and at the experimental site from October 1974 to July 1979 (in parentheses)

Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Mean
Jan.	34	49	8	28(38)	176(169)	65(49)	47(47)	15(11)	104	75	71
Feb.	37	5	23	32(19)	25(20)	41(69)	48(48)	140(111)	109	32	91
Mar.	230	78	45	68(36)	22(29)	127(69)	41(45)	108(117)	179	47	91
Apr.	134	98	150	199(107)	106(47)	69(55)	159(159)	124(89)	94	163	112
May	174	95	117	141(129)	126(103)	182(99)	75(69)	102(49)	73	82	137
June	122	188	131	184(145)	130(105)	221(164)	161(174)	191(199)	141	175	145
July	115	129	163	79(65)	166(147)	151(115)	197(173)	137(145)	133	137	140
Aug.	139	162	119	159(64)	147(94)	95(61)	193(79)	159	174	N/A	140
Sep.	164	161	152	145(81)	203(119)	92(72)	102(70)	119	64	109	99
Oct.	108	68	83(64)	112(111)	81(67)	77(64)	46(35)	150	33	75	107
Nov.	77	98	20(26)	108(60)	112(128)	61(65)	115(85)	113	154	N/A	94
Dec.	44	72	52(85)	33(34)	89(83)	113(113)	89(82)	133	97	N/A	86
Total	1378	1203	1063	1288	1383	1295	1183	1491	1355	–	1313

and are plotted in Fig. 2 against probe count-rate (derived from Fig. 1 for the corresponding mean soil moisture content), so that field-profile levels of soil water can be interpreted directly in terms of soil water potential if required.

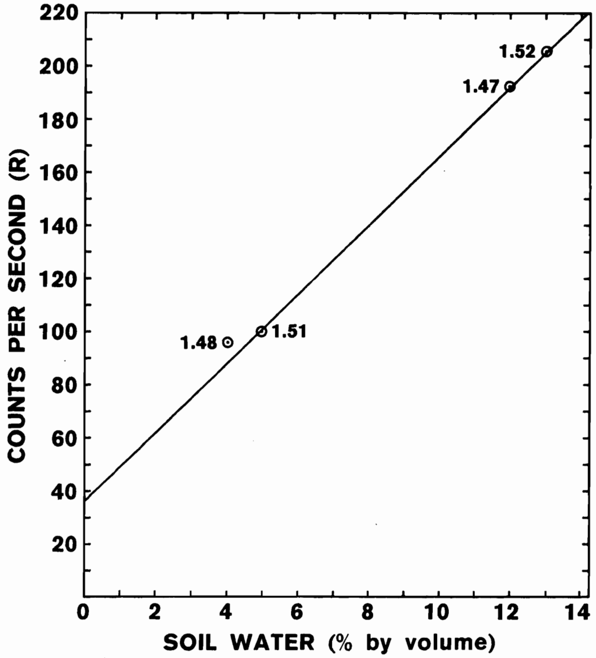

FIG. 1—Calibration of Wallingford Probe Type 225 for Pinaki sand of 1.50 mean bulk density (water standard count R_s = 1172). Points plotted are field-checks: each is the mean of five separate determinations in sand at its natural bulk density (recorded alongside).

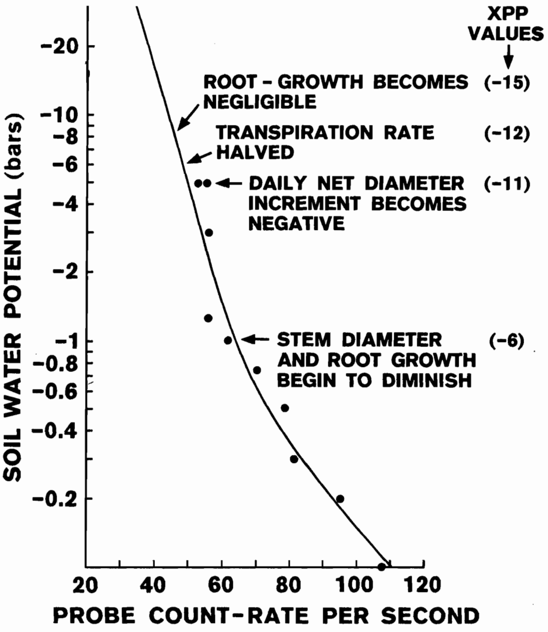

FIG. 2—Soil moisture potentials for mean 16-second count-rates in Pinaki sand. Physiological stress - points for **P. radiata** are indicated, together with corresponding xylem pressure potentials (XPP) after Rook **et al.** (1977).

RESULTS

The data are generally presented as profiles of soil moisture content (expressed as a percentage by volume) at each of the levels monitored. However, as there is always a minimum of 64 such profiles available on each occasion, it is necessary to group these according to treatment or stocking means, in order to present the results succinctly.

The initial soil moisture profiles, in July 1972 prior to the first major thinning, are represented in Fig. 3A by the mean soil moisture content at each level down to 220 cm beneath the four main treatments, and in Fig. 3B by similar profiles for each of the four groups of sub-plots that were to be subsequently thinned to different stockings. There were no significant differences of soil moisture between any of the latter, but four of the comparisons in Fig. 3A were significant. At this stage of the experiment, differences in the cover of lupin and marram (Fig. 3A) provided the most conspicuous differences between treatments.

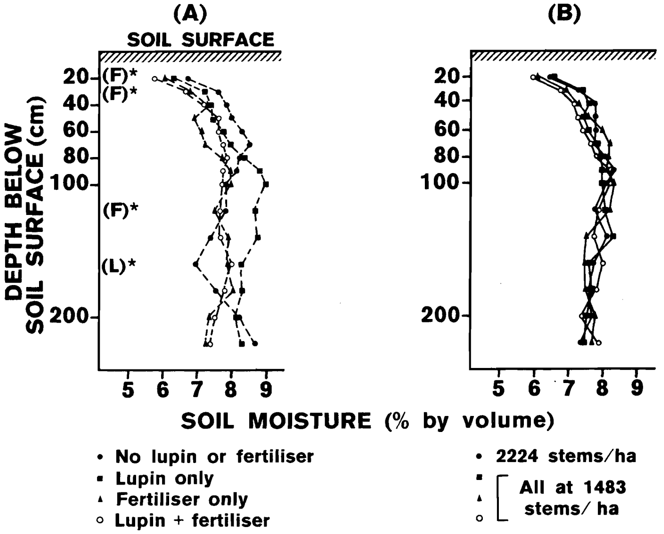

FIG. 3—Initial comparisons (* = significant differences) between mean soil moisture profiles for (A) main treatment groups and (B) main stocking groups. Two of the latter had still to be thinned to their final stocking. All plots contained marram grass. Each point is the mean of probe counts in 16 different locations.

A typical annual cycle of soil moisture recharge from its autumnal low during March 1975, through its spring maximum and summer depletion to the autumn of March 1976, is illustrated in Fig. 4 for the eight sub-plots at the maximum stocking of 2224 stems/ha and the eight in which stocking had been reduced to 741 stems/ha. Because of the wide range of soil moisture values produced by recurrent wetting fronts moving down each profile, the data have been analysed separately for each level in the profile for each occasion. Except that there is an additional estimate of variance for the differences between individual tubes within each assessment plot, the analysis follows the same format as for the mensurational data in the previous report (Jackson *et al.* 1983).

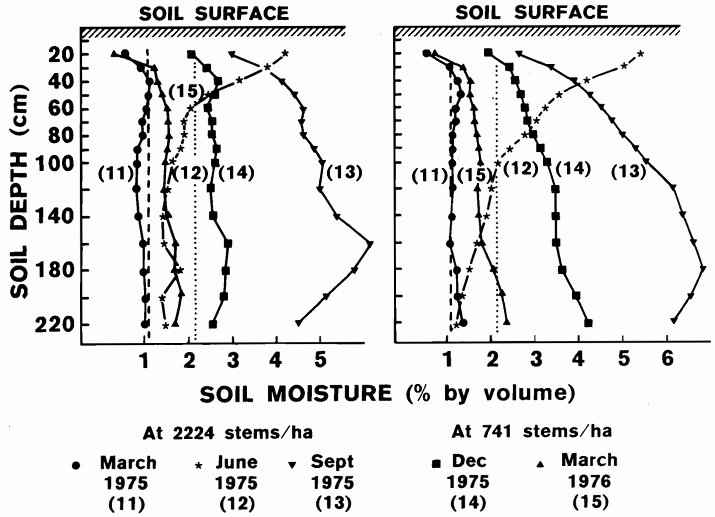

FIG. 4—Annual cycle of soil water recharge and depletion between March 1975 and March 1976, for sub-plots at maximum stocking of 2224 stems/ha and those thinned to 741 stems/ha in September 1972. Each point plotted represents the mean probe-count at 16 different locations.

In order to isolate the main differences most clearly, the orthogonal comparisons are presented as a multiple of the appropriate error variance at each level. All differences are jettisoned that do not attain the requisite F-ratio for any individual comparison – i.e., a minimum of 10.13 for main treatments (with 1 and 3 d.f.) and of 4.75 for comparisons between individual rates of stocking (with 1 and 9 d.f.), both at the 5% level of significance. In this way, large but erratic differences are eliminated and relatively smaller differences, if they are consistent across the profile, are drawn to attention. Such ratios are presented in Fig. 5 for the two comparisons that became most apparent during 1972–77, i.e., that between sub-plots at stockings of 2224 and 741 stems/ha, and that between main plots with and without fertiliser. The variance ratio (i.e., mean square attributable to the particular comparison, divided by its appropriate error variance) is plotted horizontally on a logarithmic scale, but only if it is significant at a minimum 5% level. Similar comparisons were made for all the stocking differences and treatment effects, and the more important of these are considered below, in greater detail.

The first of the soil moisture differences to become significant was that between the plots at 2224 stems/ha and those plots that had been reduced to 741 stems/ha in September 1972. A small difference appeared at a depth of 100–110 cm in the first growing-season (Fig. 5, Profile 3 for December 1972) and this increased substantially through to the autumn of March 1973 (cf. also Profile 4 in Fig. 6). Since only a third

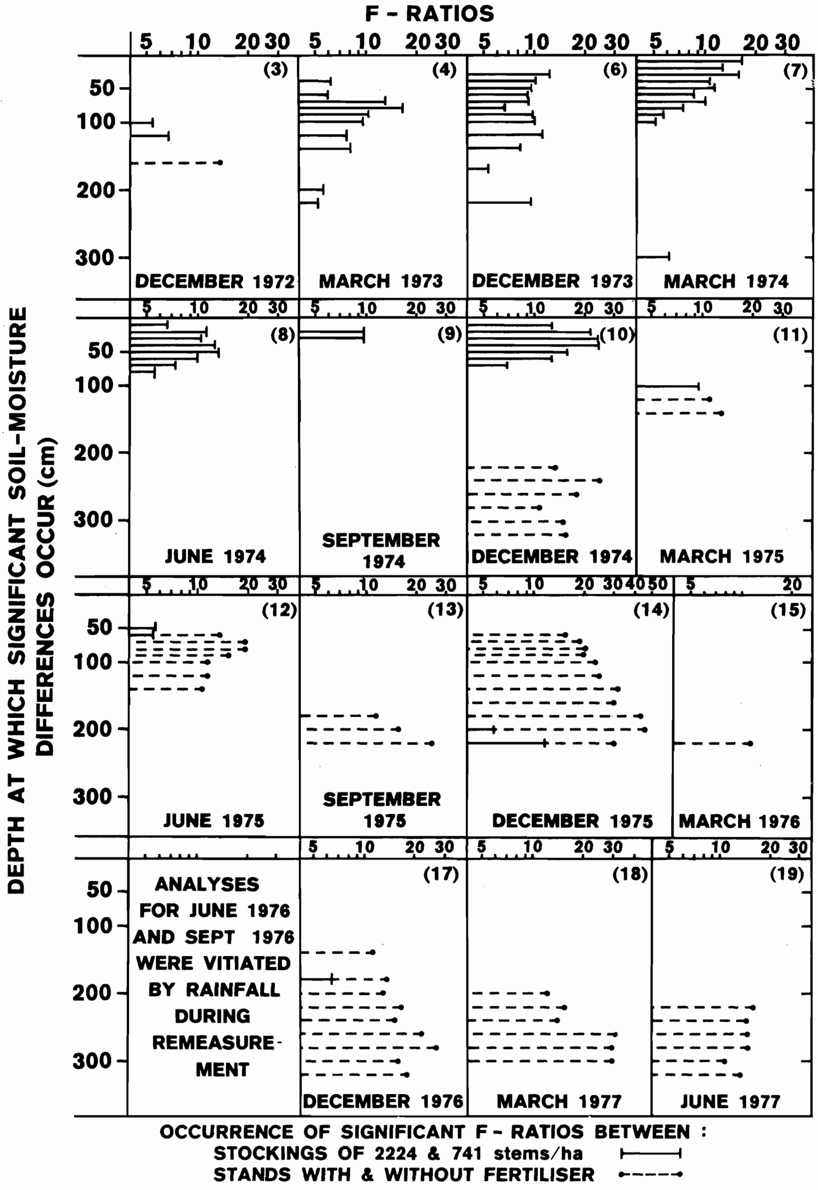

FIG. 5—Composite diagram representing the occasions and soil depths at which statistically significant differences of soil moisture occurred, between December 1972 and June 1977. Differences are expressed as a multiple of the error variance at each level (horizontal scale is logarithmic), and are significant at 4.75 for stocking and 10.13 for treatment comparisons.

of the trees remained in the thinned plots and their crown size was substantially the same as those in the unthinned plots, water demand was reduced and throughfall increased. This difference in soil-water content was maintained throughout 1974 (cf. Profiles 7, 8, 9, and 10, in Fig. 5) but it was notably confined within the top metre of the soil profile. Towards the end of the third growing season after thinning (Fig. 5, Profile 11) it became evident that the crowns and root systems of the thinned plots had expanded sufficiently to re-occupy the space vacated by the thinned trees, and thereby to eliminate significant differences between the relevant profiles (Fig. 6, Profile 11). By March 1976 (Fig. 6, Profile 15) the profile differences between the two stockings had become minimal, and have remained so up to the present (Fig. 6, Profile 23). For this series of autumnal profiles, precipitation during the month immediately preceding measurement is given to illustrate the effect of an unusually high late-summer rainfall on the profiles for March 1978.

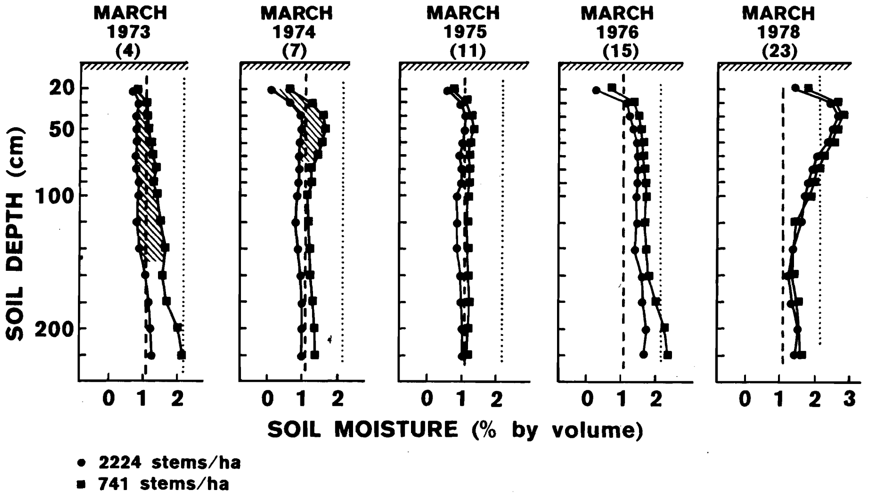

FIG. 6—Soil-moisture profiles beneath sub-plots at stockings of 2224 and 741 stems/ha respectively, during autumn 1973 to 1978. Depths at which differences are significant in Profiles 4 and 7 are shaded; there are no significant differences in Profiles 11, 15, and 23. Rainfall during the preceding month was 5 mm for Profile 4, 23 mm for Profile 7, 19 mm for Profile 11, 20 mm for Profile 15, and 48 mm for Profile 23. Each point plotted represents the mean probe-count at 16 different locations.

The same stocking comparison is represented by the midsummer profiles of Fig. 7, showing the strong differential depletion of soil-water in the uppermost metre of sand during the first 2 years after thinning, but shifting down to 1 or 2 m depth in the third year. The absence of any significant difference between the last pair of profiles (21), taken in December 1977 in the middle of the fifth growing-season after thinning, may be explained by the occurrence of heavy rain (40–50 mm) on the day before probing began. We were further interrupted by rain when halfway through, but were able to repeat all the invalidated readings down to 220 cm. The passage of a double wetting-front down the profile is clearly apparent.

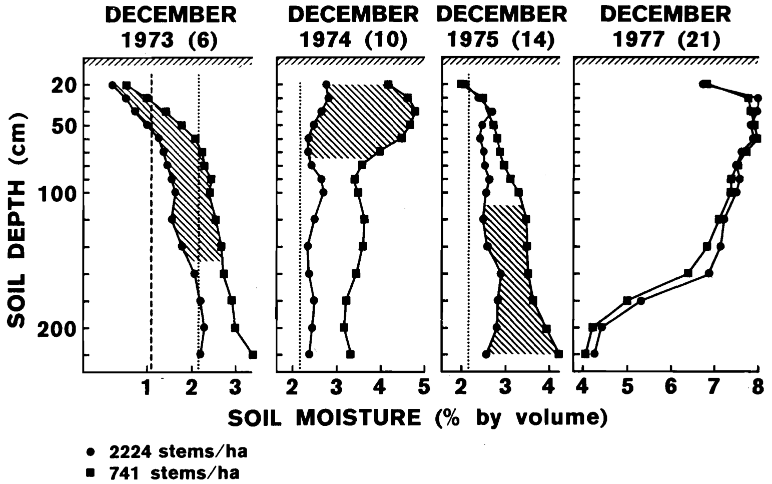

FIG. 7—Soil-moisture profiles beneath sub-plots at stockings of 2224 and 741 stems/ha respectively, at midsummer of the years 1973–77. Depths at which differences are significant are shaded. Each point represents 16 different locations.

Figure 8 illustrates a series of responses for the two groups of plots that were maintained at a stocking of 1483 stems/ha until February 1976, when one group was reduced to 25% of the stocking of the other. Up to that date the soil moisture profiles

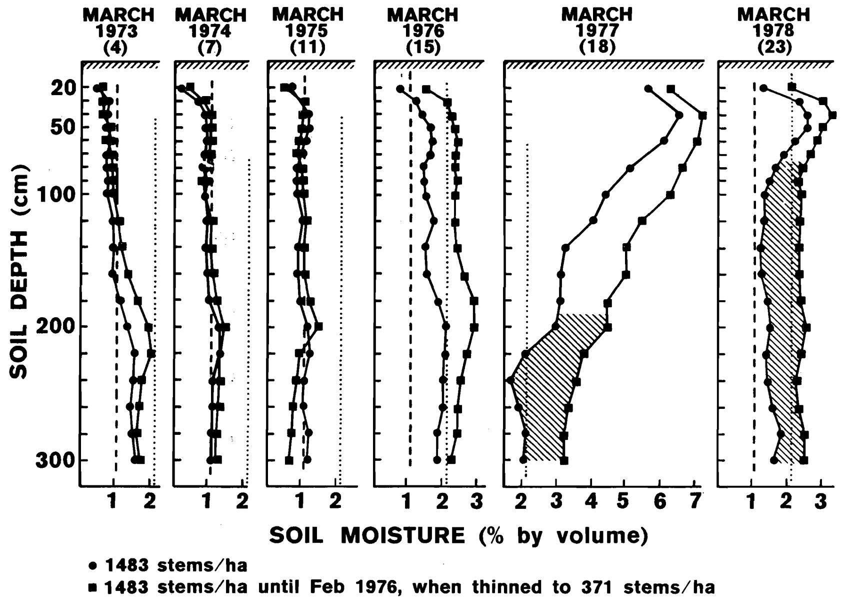

FIG. 8—Soil-moisture profiles during autumn 1973–78 beneath sub-plots at stockings of 1483 stems/ha, and 1483 stems/ha thinned to 371 stems/ha in February 1976. Depths at which differences are significant are shaded. Each point represents 16 different locations.

beneath the two groups had been virtually identical (cf. Profiles 4, 7, and 11). However, within a month of thinning the increased throughfall and reduced rate of soil mositure depletion were reflected as profile differences (Profile 15, for March 1976). The probing a year later (Profile 18) followed a day of heavy rain, as reflected by the wetting front in the upper part of both profiles. Although these differ substantially throughout the depth monitored, it is only below 2 m that the differences are statistically significant, probably because the rewetting process has increased the variance of measurements in the upper part of the profile. This did not occur in March 1978 (Profile 23) so that differences are significant at all depths below 70 cm. Also compare Profiles (15) and (23) in Fig. 8 with the contemporaneous ones for a much earlier thinning in Fig. 6.

Concurrently with the relatively transient responses due to thinning, there had been developing since the beginning of the seventh growing-season (i.e., 1974–75) a deeper and more extensive difference in soil water status beneath the blocks with and without fertiliser (*vide* the F-ratios for Profiles 10 onwards in Fig. 5). Figure 9 illustrates this trend of increasing differences over the identical sampling occasions depicted in Fig. 6, and shows how the major treatment effects had then come to override those due to thinning. It is noteworthy that this differentiating effect of treatment on soil moisture status did not appear until soon afer the deterioration in condition that occurred in the control (0) plots in the autumn-winter of 1974, as described by Jackson *et al.* (1983). That these differences are mainly apparent in the deeper soil-layers, below about 180 to 200 cm, is almost certainly attributable to complete root-occupancy of the top metre of soil and to the resulting general depletion of soil water in this zone by

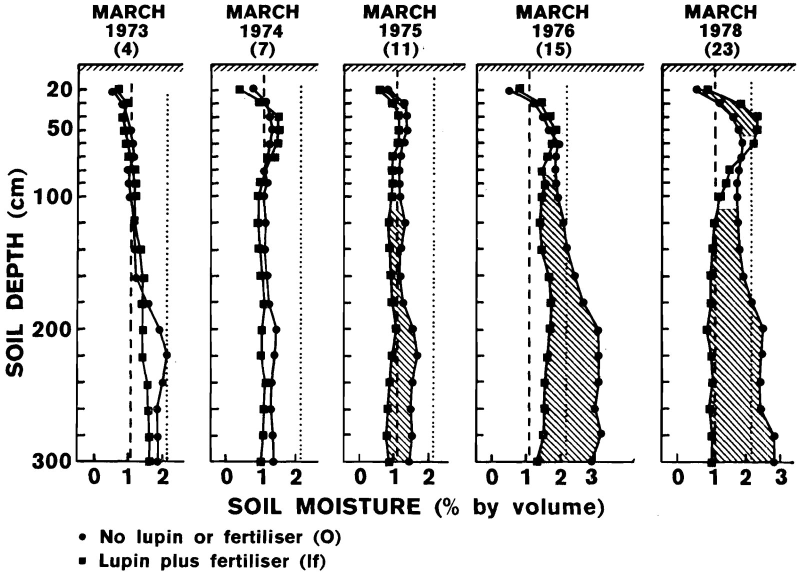

FIG. 9—Soil moisture profiles beneath plots with lupin + fertiliser and the control plots without either, during autumn 1973 to 1978. Profiles are concurrent with those in Figs 6 and 8. Depths at which differences are significant are shaded. Each point represents 16 different locations.

all treatments and stockings. The topsoil is also more frequently and rapidly affected by precipitation and the passage of wetting-fronts, so that random variation is greater in this zone.

DISCUSSION

In order to relate our findings more explicitly to current knowledge about the physiological behaviour of *P. radiata,* and to provide suitable points of reference across all the profiles, we have introduced a number of approximations derived from Rook *et al.* (1977). Annotated against the soil moisture calibration curve in Fig. 2 are several physiological stress-points defined by those authors. Their values of the corresponding base xylem pressure potentials (XPP) are shown in parentheses at the right-hand side. We have increased these by an assumed pre-dawn pressure difference between soil and needle xylem ranging from 5 bars at –6 bars XPP to 7 bars at about –12 bars XPP (Jackson *et al.* 1973). For the purpose of illustrating our subsequent discussion, we suggest that for *P. radiata* growing on Pinaki sand the critical points for sustained basal area growth are at –1 bar soil water potential (SWP), when diameter growth begins to diminish, and at –5 bars SWP, when net daily increment becomes zero or less (as tissue dehydration supervenes). The corresponding neutron-probe counts in Figs 4–9 are 64 counts/s and 50 counts/s respectively. These are represented on each of the figures by two vertical lines, the one dotted and the other pecked.

As was seen in Fig. 4, soil moisture is reduced below the first critical level of –1 bar throughout the profile of the denser stand only during the autumn, so that normal patterns of diameter growth (Jackson *et al.* 1976) should be affected only at this season. At all other times of the year there is an adequate supply of soil water at some level in the profile, during both the recharging and the depletion phases of the cycle. From Figs 6 and 9 it is also evident that those stands which make the heaviest demands on the reserves of soil water during the growing season (i.e., the sub-plots at the highest stocking 2224 stems/ha in Fig. 6, and the (lf) plots in Fig. 9) may reduce soil moisture potential below –5 bars by late summer. In this event, diameter growth may be expected to cease completely. However, heavy rain during February will quickly recharge the upper part of the profile (cf. Profile 23 for March 1978, in Fig. 6) and relieve water stress within the tree. As Rook *et al.* (1977) and Cremer (1972) have shown, *P. radiata* is then capable of rapidly resuming diameter growth. Even though there is a three-fold difference of stocking between the plots compared in Fig. 6, canopy development of the thinned plots by the sixth year after thinning has been such that they are both responding virtually identically to the hydrological cycle, and the early post-thinning differences in the upper profile have disappeared.

In Fig. 9, the above responses are chronologically reversed. In the earlier years (1972–75), before the main treatments had accumulated sufficient impact on stand and canopy development, all factorial combinations show an autumnal depletion of soil water through the –1 bar level to as low as –5 bars, at which point basal area growth ceases. However, in the autumn and winter of 1974 there was a sudden deterioration of all stands in the control (0) treatment (cf. Jackson *et al.* 1983), characterised by a great reduction in canopy mass and leaf surface area (*vide* Fig. 10 for a visual comparison of crown density in the (0) and (lf) blocks). From this stage onwards it has been only the more productive (f) and (lf) plots that have shown an autumnal depletion of soil water into the critical zone of –1 to –5 bars. The less productive control plots have at all times a non-limiting supply of soil moisture available to them (cf. Fig. 9, Profile 15 for March 1976 and Profile 23 for March 1978) – so that this cannot be the factor reducing their productivity. The fact that significant differences between the treatments occur only below a depth of 100 cm is probably attributable to corresponding differences in root distribution and exploitation below this level. In the top metre of soil, root occupancy is so dense and the removal of soil water after rainfall rewetting must be so effective that it is rare for significant differences to appear at all – a point that has considerable bearing on the usefulness of soil moisture studies in closed stands, if the sensors are confined to this zone. (Parenthetically, it may be stated that our early probe-samplings were accompanied by gravimetric sampling of the top 10 cm of soil on all sites; but the soil moisture measurements were so erratic that we considered them meaningless, and terminated this type of sampling.)

In an earlier paper (Jackson *et al.* 1976) it was shown that basal area increment of *P. radiata* is most vulnerable to current soil moisture deficits during the months of December to April. Although we might accordingly expect the (f) and (lf) blocks to show some differential reduction in growth *vis-à-vis* the untreated controls, particularly in response to profile differences such as those of March 1978 (Fig. 9), their actual

FIG. 10—Canopy density and foliage mass in control (0) treatment at left, and lupin + fertiliser (lf) treatment at right. Both plots were at a stocking of 741 stems/ha and were photographed on 25 March 1977.

productivity is in fact 60–70% greater than that of treatment (0), at all rates of stocking. We may conclude not only that nutritional factors are overriding the effects of occasional seasonal moisture deficits in the upper 3 m of soil, but also that the more productive stands are probably now withdrawing water from below the maximum depths monitored.

From Profile 23 in Fig. 9, it is evident that by March 1978 the heavier stockings in the (lf) treatment were depleting soil water to below the –5 bars stress-point, at least as deep as 3 m. However, we cannot assert that the same state existed throughout the root zone. Johnston (1964) emphasised the significance, in containing water stresses within individual *P. radiata* trees during periods of drought, of occasional deep roots that are able to exploit reserves of water even within deep fissures of underlying rock. That this capability may be both more extensive and more general than appreciated hitherto, is indicated by Arkley's (1981) analysis of water-balance anomalies for some Californian catchments under mixed conifer forest.

In Fig. 11 we have plotted a comparison between the mean of the two plots at 2224 stems/ha (lf) and 371 stems/ha (0) for the two latest probe-samplings, in mid-winter 1979 and 1980. These are the most extreme regimes in the experiment, but the fact that the 2224 stems/ha (lf) profiles lie within or below the stress zones at 3 and 4 m depth in midwinter may indicate that the plots with greatest canopy-mass have been encountering an absolute limit of available soil water since about age 10 years.

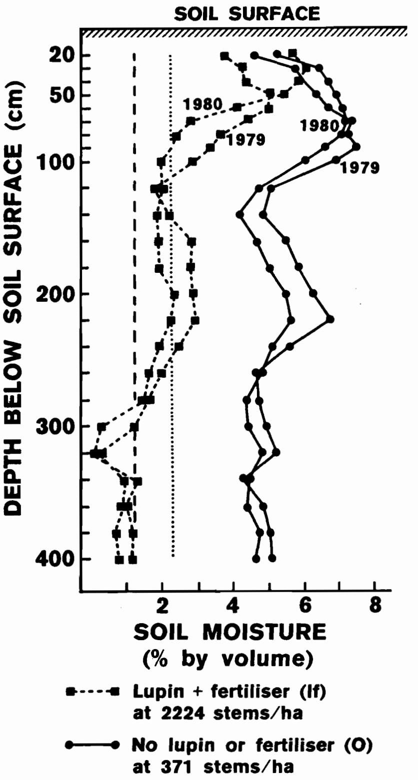

FIG. 11—Soil moisture profiles during mid-winter of 1979 and 1980 for the two extreme treatment/stocking combinations, (lf) at 2224 stems/ha and controls (0) at 371 stems/ha. Soil water potential stress-points of –1 and –5 bars are indicated by vertical lines. Each point represents the mean of four different locations at each level.

It would require more frequent monitoring to determine whether this state is now permanent throughout the year, or whether the wetting-front from heavier falls of rain can provide a flux to ground-water. We calculate that there is a storage difference of $133.8 l/m^2$ between the two profiles compared in Fig. 11, down to 4 m depth. To make up this deficiency would require well over 1 month's mean rainfall at Woodhill, even disregarding any further differences of transpiration that would occur in the meanwhile. Compared with the contemporaneous soil moisture profile beneath a marram grass cover without pine, the total soil moisture depletion down to 4 m is the equivalent of 204 mm of rainfall. The importance of this for local ground-water supplies is obvious.

ACKNOWLEDGMENTS

We express our appreciation to our colleagues R. K. Brownlie and J. Chittenden for their timely help and co-operation on many occasions. We are also indebted to R. S. Thomas for technical advice and maintenance of the instruments.

REFERENCES

ARKLEY, R. J. 1981: Soil moisture use by mixed conifer forest in a summer-dry climate. **Soil Science Society of America, Proceedings 45:** 423–7.

BELL, J. B. 1973: Neutron probe practice. **Institute of Hydrology, Wallingford, Report No. 19.** 63 p.

CREMER, K. W. 1972: Immediate resumption of growth by radiata pine after five months of minimal transpiration during drought. **Australian Forest Research 6:** 11–6.

EELES, C. W. O. 1969: Installation of access tubes and calibration of neutron moisture probes. **Institute of Hydrology, Wallingford, Report No. 7.** 21 p.

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, D. S.; GIFFORD, H. H.; GRAHAM, J. D. 1983: Lupin, fertiliser, and thinning effects on early productivity of **Pinus radiata** growing on deep Pinaki sands. **New Zealand Journal of Forestry Science 13:** 159–82.

JACKSON, D. S.; GIFFORD, H. H.; HOBBS, J. W. 1973: Daily transpiration rates of radiata pine. **New Zealand Journal of Forestry Science 3:** 70–81.

JOHNSTON, R. D. 1964: Water relations of **Pinus radiata** under plantation conditions. **Australian Journal of Botany 12:** 111–24.

ROOK, D. A.; SWANSON, R. H.; CRANSWICK, A. M. 1977: Reaction of radiata pine to drought. Proceedings of Soil and Plant Water Symposium, Palmerston North, 1976. **DSIR Information Series No. 126:** 55–68.