IRRIGATION AND FERTILISER EFFECTS ON PRODUCTIVITY OF A PINUS RADIATA SEED ORCHARD:

RESPONSE TO TREATMENT OF AN ESTABLISHED ORCHARD

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ABSTRACT

A clonal seed orchard of **Pinus radiata** D. Don growing in Victoria, Australia, was irrigated and fertilised with urea and superphosphate over a 4-year period.

In two of the years, irrigation significantly increased female "flowering". Water input (rainfall and irrigation) in the year prior to flowering accounted for 71% of the variation in flower crops. A positive flowering response to nitrogen was observed in the 2 years of higher rainfall, and a positive interaction between irrigation and nitrogen fertiliser in the drier years. Response to nitrogen was thus dependent upon an adequate water supply.

Stem basal area increment was greatest in irrigated plots treated with urea, and our results were consistent with the hypothesis that female flowering increased as a direct consequence of increased vegetative growth.

It was estimated that mean annual seed yield over the 4-year period from the most productive treatment was 29.1 kg/ha compared with 17.4 kg/ha from untreated trees.

INTRODUCTION

Seed production in orchards of *Pinus radiata* typically commences about 5 years after establishment, and tends to increase each year thereafter, reaching 20–25 kg/ha with large annual fluctuations by age 12 years (Pederick & Brown 1976). This pattern of production is less than ideal as the high costs of establishment and early maintenance must be borne without substantial return for some years, and unpredictable fluctuations in yield make forward-planning difficult. Knowledge of the factors which influence "flowering" (production of male and female strobili) and seed production, and the development of cultural techniques to maintain production at a uniformly high level, would greatly facilitate the management of orchards.

Many environmental factors have been shown to influence flowering in conifers (for reviews *see* Jackson & Sweet 1972; Puritch & Vyse 1977; Lee 1979). These include temperature, soil moisture, light intensity, day length, and soil nutrient status. However, there appear to be no fully consistent responses to ameliorative treatments between species, sites, or even years of treatment on a single site. For example all but three of

24 studies reviewed by Puritch & Vyse (1977) showed that nitrogenous fertiliser stimulated the production of female strobili, yet Sweet & Hong (1978) were unable to obtain any such response in extensive trials with *P. radiata* in New Zealand.

Variable responses are not unexpected when the broad range of species, sites, and test environments is recognised. It is simplistic to expect consistently successful transfer of a particular cultural prescription from one species to another, or perhaps even between orchards of the same species on different sites.

An apparent association between summer rainfall and subsequent flowering in Australian *P. radiata* orchards was detected by Pederick & Brown (1976) and, as noted above, nutrient status has frequently been shown to influence flowering. An experiment was therefore established to investigate the effects of irrigation and fertiliser on the productivity of a clonal *P. radiata* seed orchard planted in Gippsland, Victoria, in 1970. This paper reports responses in flowering, seed yield, growth, and survival induced by annual treatments applied prior to the sixth, seventh, eighth, and ninth flowering seasons after establishment of the orchard.

Abbreviations

N = nitrogen treatment (urea)
P = phosphorus treatment (superphosphate)
I = irrigation treatment
Y = year
significance levels * $p < 0.10$
** $p < 0.05$
*** $p < 0.01$

METHODS

The Orchard Site

The experiment was conducted at Saxton's seed orchard south-east of Sale, Victoria (38°13'S, 147°10'E) (Saxton 1977). The site is 70 m a.s.l. on the coastal plain, 16 km from Bass Strait. Mean annual rainfall over the period 1968–79 was 650 mm and varied from a minimum of 315 mm in 1972 to a maximum of 933 mm in 1978. The area is considered marginal for growth of the species and Cromer *et al.* (1983) have shown a large growth response to irrigation in a nearby plantation.

The soil is a duplex with a distinct boundary between the sandy A horizons (depth 0.6–2.0 m) and the pedal clayey B horizons (Dy 5.4, Northcote *et al.* 1975). The soil is low in most nutrients, particularly phosphorus. An ortstein layer occurs above the clay in some areas and this, combined with the gently undulating topography, often allows the water table to approach the surface for several months of the year. Effective rooting depth is correspondingly reduced and water stress in the subsequent dry periods may be severe.

The orchard section used for the experiment was planted in 1970 with grafted ramets from the same 30 clones used by APM Forests Pty Ltd in their Golden Gully seed orchard (Griffin 1982, 1984). The section was laid out in randomised blocks containing one ramet of each clone at a spacing of 6.1 × 6.1 m (269 stems/ha).

Experimental Design and Layout

The whole orchard was laid out as a square of 30 rows by 30 trees. As irrigation was to be applied through a reticulated trickle system it was convenient to treat complete rows of trees. Five pairs of well-stocked rows were selected, with at least one buffer row on either side of each row. One row in each pair was selected at random to be irrigated and an irrigation line was placed along its length. The other row of each pair received only natural rainfall.

The rows were then split into five sections each containing a nominal six trees, and fertiliser treatments were assigned to these in a Latin square arrangement. The adjacent unirrigated and irrigated sections of each pair of rows, and their respective buffer rows were treated as a single unit for applying fertiliser.

The fertiliser treatments included a factorial combination of two levels of nitrogen (N_0,N_1) and two of phosphorus (P_0,P_1) as shown in Table 1. The fifth treatment was a lower level of nitrogen plus phosphorus. While this was assessed in the same way as the other treatments and results are available on request, we decided to simplify the analysis and discussion by presenting only results for the complete 2 × 2 factorial of nutrient treatments in this paper.

The experiment included a nominal 30 trees in each fertiliser × irrigation combination and a nominal 150 trees for each of the I_0 and I_1 treatments. However, the orchard layout did not permit the clonal content of each treatment to be balanced. Flower production is known to have a reasonably high heritability and variability (Griffin 1982), and a degree of clone × treatment interaction would be anticipated. Such variation forms part of the experimental error in subsequent analyses.

Irrigation

The trickle irrigation system was designed to apply 9.1 *l*/tree/h at an operating pressure of 100 kPa, equivalent to a depth of 0.245 mm/h on an area basis. Water was pumped from a shallow underground aquifer into an open earth dam and thence to the orchard as required. Irrigation commenced in January 1976 and continued until March 1979.

TABLE 1—Fertiliser application schedule

Year applied	Elemental nitrogen (N_1) and/or phosphorus (P_1) (g/tree)	(kg/ha)	(cumulative kg/ha)
1974	120	32	32
1975	170	46	77
1976	200	56	133
1977	240	65	198
1978	260	70	268

NOTES: For the treatment N_1P_1 when N and P were applied together, the ratio of N : P was 1 : 1.
The N_0 treatment had no N application but P_0 plots received 16, 23, and 28 kg/ha in 1974, 1975, 1976 respectively.

Both the frequency and duration of irrigation were based on the daily flow method described by Black (1971). It was expected that a young, widely spaced plantation would use an amount of water equivalent to about 50% of evaporation from a free water surface, so application was calculated to provide 60% of pan evaporation minus daily rainfall. Average Class A pan evaporation was determined from records at a nearby meteorological station (Dutson Downs) and rainfall was measured daily at the orchard site.

Chemical analysis of the irrigation water showed concentrations of both sodium and chloride to be high. The electrical conductivity of 1.8 mS/cm placed the water in the "intermediate hazard" range for salinity, and chloride concentration was in the "severe hazard" range for sensitive crops (Ayers & Westcot 1976). Whilst these characteristics indicated that the water could be hazardous for long-term irrigation, *P. radiata* possesses considerable tolerance to salinity (Cromer *et al.* 1982) and significant dilution could be expected from natural rainfall, particularly in winter when the orchard was not irrigated. The most serious practical problem encountered was the precipitation of calcium carbonate in the irrigation lines and drippers, which was alleviated by periodically flushing the lines with hydrochloric acid.

Fertiliser

The fertilisers were applied every October from 1974 until 1978, with nitrogen in the form of urea (46% N) and phosphorus as single superphosphate (9.6% P). Fertiliser was applied on an individual tree basis and was increased each year according to the schedule in Table 1. Each fertiliser was spread separately by hand under the crown projection of each tree. The site was presumed to be highly deficient in phosphorus so, to ensure reasonable growth, phosphorus was applied to the nominal P_0 plots during the first 3 years of the experiment, at an annual rate which was half that of the P_1 treatment.

Assessment

The current year's crop of female strobili on each ramet was counted each September–October, initially from the ground and in later years from a 6-m mobile platform (Saxton 1977). Two observers made counts and an average figure was recorded. Data on the yield of ripe cones were obtained from annual harvests. Male flowering was assessed in only one season (1976), by scoring the strobilus crop on each ramet on a scale of 0 (none) to 5 (heavy crop).

It was important to establish whether treatments induced changes in either seed weight or in the number of seed per cone. Hence in 1976 all ripe cones were harvested, the seed extracted and cleaned in a forced-air blower, and the average number of seed per cone and 100-seed-weight determined for each ramet. Observations were repeated in 1977 but, in order to reduce the workload involved, a sub-sample of only four representative branch cones was collected from each ramet.

The diameter at breast height and height of each tree in the experiment were measured annually, to the nearest millimetre and decimetre respectively.

Statistical Analysis

Thirty-seven percent of the trees died or became moribund because of stock-scion incompatibility during the course of the experiment. The effects of such incompatibility on flowering are not clear but it is likely that the trees which died had been under stress for some years. To eliminate the possibility that this had confounded the direct effects of the treatments, only those trees which remained healthy to the end of the period of experimentation were included in statistical analyses. This resulted in an imbalance in numbers of trees per plot, but no plots were completely lost. The effects of treatment on mortality due to incompatibility were analysed separately.

In 1975, prior to commencement of irrigation, the mean number of female strobili per ramet in each plot varied from three to 62. This wide range may be ascribed at least in part to genetic variation in fecundity of the sample of clones included in each plot, which would create a source of error variation throughout the experiment. All analyses of mean female strobilus production per ramet per plot were therefore adjusted using 1975 flowering as a covariate. A square root transformation was applied prior to analysis. Many ramets were only just coming into flower in 1974 and had not yet had time to express their genetic potential, so data obtained prior to commencement of the experiment were less useful for covariance analysis. Fertiliser effects were not significant in 1975, so the implicit assumption that flowering in that year was unaffected by treatment remained valid.

The growth of the trees was analysed each year on the basis of plot mean-tree basal area (calculated from diameter) and height, using the tree basal area or height in the previous year as a covariate. Both traits were also analysed at the end of the experiment in 1979, using the initial size of the tree in 1974 as a covariate.

RESULTS

Flower, Cone, and Seed Production

The analyses of covariance for production of female strobili per ramet in each individual year are given in Table 2. A highly significant response to irrigation occurred in 1977 and 1978 but not in 1976 or 1979. Conversely, the effect of nitrogen was significant only in 1976 and 1979. Effects due to phosphorus and N × P interactions were not significant and have therefore been omitted from the table. The use of the 1975 data as a covariate was considered justified as the effect was significant ($p < 0.10$) in 3 of the 4 years for both irrigation and fertiliser treatments. The presence of significant year-to-year variation, together with Y × I and Y × N interactions, was confirmed by analyses of variance.

The data on female strobili for respective pairs of years with similar response patterns were combined and subjected to an analysis of covariance. As in the analyses for individual years, the effect of irrigation was highly significant for (1977 + '78) when average flowering was light (39 strobili per ramet), and a nitrogen response was evident in the heavier flowering years (1976 + '79) when an average of 70 strobili per ramet were produced.

The net result of treatment over this sample of four flowering seasons was that I_1 trees produced a total (on average) of 261 female strobili each, compared with 175 for I_0 trees – an increase due to irrigation of 49%. The most productive treatment (I_1N_1) produced a cumulative yield over the 4-year period of 294 strobili per tree – an increase of 90% over I_0N_0 (Table 2).

TABLE 2—Mean number of female strobili per ramet, back transformed and adjusted for 1975 production by covariance analysis

Year		I_0	I_1	$\bar{I}$	Statistical significance			
					$\bar{N}$	$\bar{I}$	Cov. 1	Cov. 2
1976	N_0	54	60	57				
	N_1	71	87	79				
	$\bar{N}$	63	74	68	**	NS	**	*
1977	N_0	21	49	35				
	N_1	21	67	44				
	$\bar{N}$	21	58	40	NS	***	*	*
1978	N_0	22	51	36				
	N_1	17	61	39				
	$\bar{N}$	20	56	38	NS	***	*	NS
1979	N_0	58	67	62				
	N_1	86	79	82				
	$\bar{N}$	72	73	72	*	NS	**	*
Σ 1976 to 1979	N_0	155	227	191				
	N_1	195	294	244				
	$\bar{N}$	175	261	218				

NS Not significant
* $p < 0.10$
** $p < 0.05$
*** $p < 0.01$
Cov. 1 Covariance for fertiliser treatments (covariate was 1975 flowering)
Cov. 2 Covariance for irrigation treatment (covariate was 1975 flowering)

As already noted, the production of female strobili was the most comprehensively measured factor in this experiment. However, it is the yield of ripe cones and seeds which is important to the seed orchardist. The relationship between the strobilus counts and the number of cones actually harvested 2 years later was therefore investigated. Over the 4-year period, the cone harvest was 93% of that which was predicted by assuming the strobilus counts to be accurate and that each survived to produce a ripe cone (Table 3). Neither irrigation nor fertiliser treatment significantly affected this conclusion. The treatments had no significant effect on male strobilus production in 1976, the only year in which this trait was evaluated.

TABLE 3—Relationship between counts of strobili per ramet and number of cones harvested from the same trees 2 years later over all irrigation and fertiliser treatments

Year	No. ramets sampled	Mean number per ramet		B/A(%)
		Strobili counted (A)	Cones harvested (B)	
1975–77	206	36.4	31.3	86
1976–78	196	72.8	75.8	104
1977–79	184	40.9	42.5	104
1978–80	70	58.1	49.3	84
1979–81	80	72.6	64.4	89
Mean				93

The parameters on the yield of seed which were determined for 1976 and 1977, were also unaffected by treatment. The 1976 cones were derived from flowering in 1974, prior to the first fertiliser application in October 1974. Fertilisation of the ovules, and the major period of growth of the cone and seed occurred after this treatment had started, but before irrigation commenced. An average of 78 sound seeds per cone was produced and on average, 100 seeds weighed 3.23 g. No significant treatment effects were evident. In the 1977 assessment, a mean 100-seed-weight of 3.32 g was similar to that measured in 1976; however, the number of seeds per cone rose to 116. It is possible that this increase reflected seasonal differences in pollination, but it is more likely to have arisen from the sampling procedure which was used. In a complete harvest, such as occurred in 1976, the estimate is likely to be depressed by the inclusion of some damaged or empty cones.

Survival

During the course of the experiment, 24% of the trees became debilitated and died. This was ascribed to "graft incompatibility" in the absence of any other obvious cause. It was not possible to evaluate the effect of first- and second-order interactions of treatments on survival. However, it was clear that without irrigation, nitrogen and phosphorus in combination reduced survival to 53%, but in combination with irrigation almost all trees in the N + P plots (98%) remained healthy (Table 4).

TABLE 4—Survival (%) by irrigation and fertiliser treatments for the period 1975–79

	I_0			I_1		
	N_0	N_1	$\bar{N}$	N_0	N_1	$\bar{N}$
P_0	83	88	85	80	81	81
P_1	80	53	67	70	98	88
$\bar{P}$	81	73	77	75	92	85

Growth

Phosphorus had no effect on growth, but nitrogen increased tree basal area and decreased height over the four seasons 1975–79. By 1979 the mean-tree basal area of the N_0 plots was 398 cm^2 and that of the N_1 plots was 433 cm^2, an increase of 9%. Over the same period the height of the N_0 trees was 12.2 m compared with that of the N_1 trees of 11.6 m, a decrease of 7% (Table 5).

Irrigation also increased basal area and decreased height when analysed over the full period 1975–79 (Table 5) and, in contrast to the effect of nitrogen, the effect of irrigation was discernible between growing seasons. Irrigation resulted in a highly significant ($p < 0.01$) increase in basal area in both the 1976–77 and 1977–78 seasons, but not in the 1975–76 or 1978–79 seasons. The additive effects of these treatments is also evident from Table 5, where I_0N_0 produced the tallest trees (12.5 m) with least basal area (368 cm^2). and I_1 N_1 the shortest (11.2 m) with greatest basal area (441 cm^2). It was estimated that the stem volume increment over the 4-year-period was 10.5% greater for the I_1N_1 trees.

TABLE 5—Mean height (H) and stem basal area (BA) of irrigation (I) and nitrogen (N) treatments in 1979, adjusted for 1974 values by covariance analysis

	H(m)			BA (cm^2/tree)		
	I_0	I_1	$\bar{I}$	I_0	I_1	$\bar{I}$
N_0	12.5	11.9	12.2	368	428	398
N_1	11.9	11.2	11.6	425	441	433
$\bar{N}$	12.2	11.5	11.9	397	435	416

LSD p = 0.05
H : I = 2.0
N = 0.8
BA : I = 42
N = 20

DISCUSSION

The experiment has demonstrated that, under the soil and climatic conditions pertaining at the site, it was possible to manipulate the yield of seed in the orchard through irrigation and fertiliser treatments. However, response to a particular treatment varied according to seasonal weather conditions.

To interpret the patterns of response it is helpful to consider the ontogeny of female flowering in *P. radiata.* The growth pattern of the species is polycyclic, with female strobili developing from long-shoot primordia in one or more cycles. At Rotorua, New Zealand, initiation in the first, second, and third cycles occurred respectively in mid-December, end of January, and during March (Bollmann & Sweet 1976). Strobili are normally receptive during August with fertilisation occurring 15 months later (Lill 1976). Cones then develop rapidly to full size and are ripe for harvesting the following spring (September/October). The full cycle thus averages about 33 months. Strobili are initiated during the summer when moisture stress is normally at a peak and must survive two further summer seasons prior to harvest.

The differential response to irrigation (1976 and '79 c.f. 1977 and '78) strongly suggested that the availability of soil moisture at or before the initiation of female strobili was a critical factor. To test this hypothesis we examined the pattern of rainfall and irrigation over the period from January 1975 to June 1979. Records of monthly rainfall over this period are shown in Fig. 1 together with the total of rainfall-plus-irrigation for each month. Also plotted in Fig. 1 is the line showing 60% of pan evaporation. The irrigation applied to the trees, combined with natural rainfall, supplied water equivalent to about 60% of pan evaporation each year, as intended. Although flowering in the I_1 plots ($\overline{N}$) exceeded 56 strobili per ramet every year, yield in the I_0 plots dropped to 21 and 20 strobili in 1977 and 1978 respectively (Table 2). During the summers preceding these years of light flowering there were large water deficits in the unirrigated plots (Fig. 1).

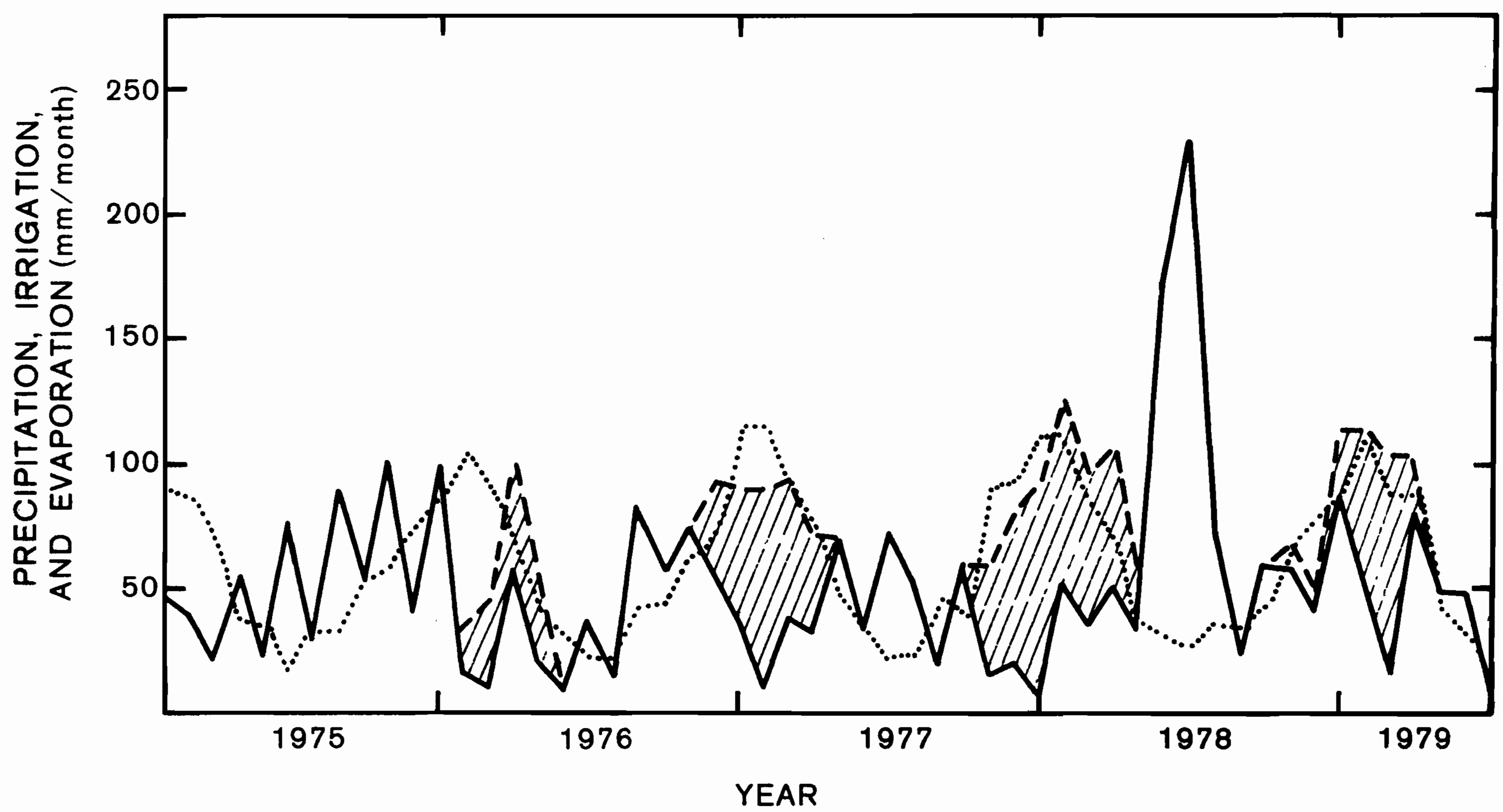

FIG. 1—Monthly rainfall (———), irrigation plus rainfall (- - - -) at the orchard site, and class A pan evaporation X 0.6 (·····) at a meteorological station 13 km east of the orchard. The hatched area represents the difference between irrigation and rainfall.

The availability of soil moisture at a particular time may be influenced markedly by antecedent pattern of rainfall or drought. It is therefore not possible to define a particular pattern of rainfall which is most beneficial for flowering. However, it was possible to demonstrate a general relationship between high annual rainfall and heavy flowering in the following year. A linear regression of strobilus production on the logarithm of water supply (natural rainfall or rainfall plus irrigation) in the previous calendar year accounted for 71% of the variation in flowering. Yield was severely reduced if the total input of water fell below about 600 mm in the previous year (Fig. 2). This result is in accordance with Pederick & Brown (1976), who compiled data from six Australian *P. radiata* orchards over a 6-year period and attributed the particularly poor harvest of seed in 1970 to the severe drought experienced in 1967–68.

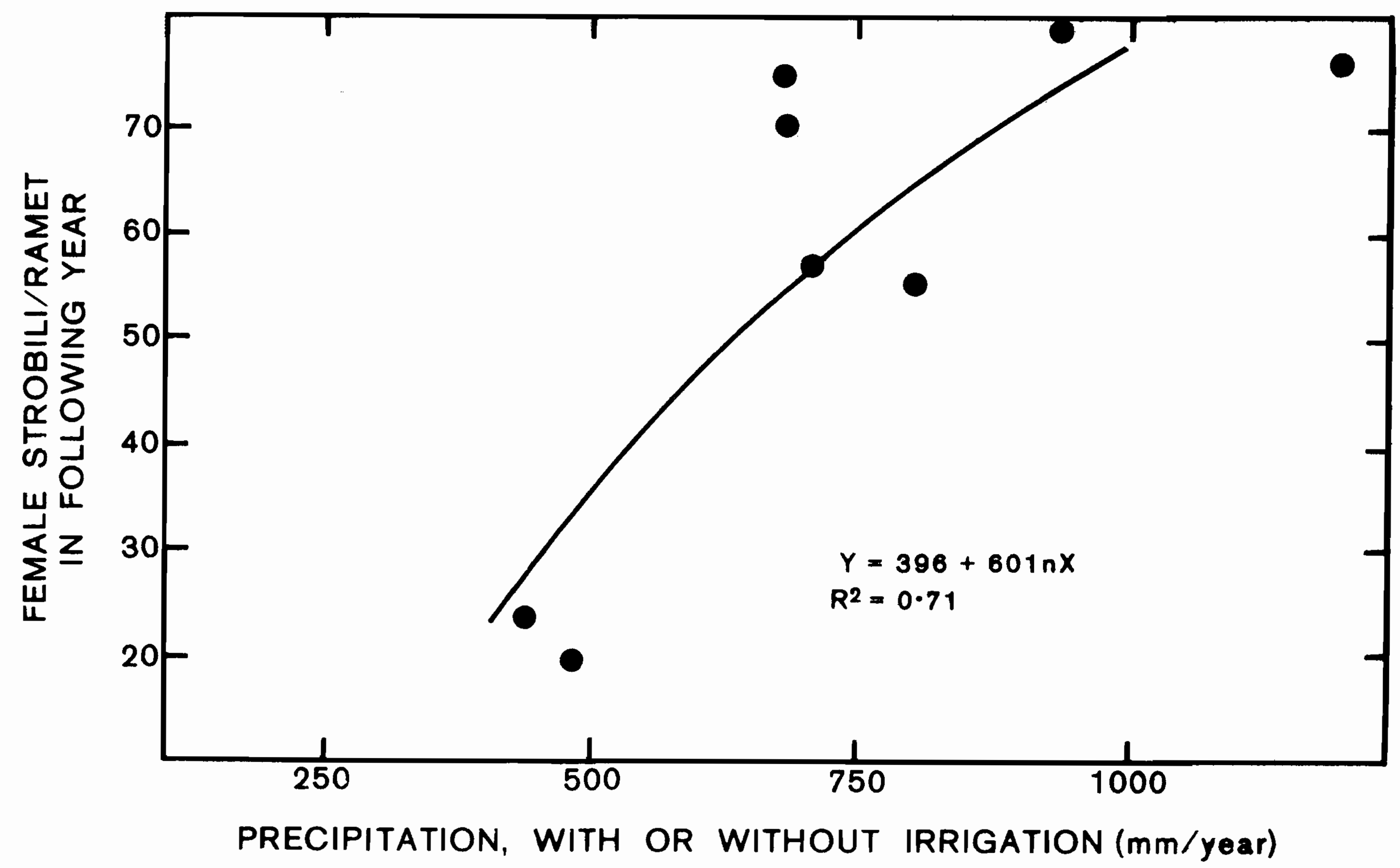

FIG. 2—Relationship between annual rainfall (or rainfall plus irrigation) and the number of female strobili per ramet produced in the following year.

Lee (1979) reviewed the literature relating climate to flowering of *Pinus* species and concluded that abundant rainfall in the spring prior to initiation, combined with low summer rainfall, were generally associated with heavy crops. The latter condition was assumed to induce moderate water stress and reduce vegetative growth in the latter part of the season. The conclusion that adequate moisture early in the growing season was of benefit would seem to have general validity, but our data do not support the view that a period of moisture stress in the summer is important. Each year in which a positive response was obtained, the trees were irrigated until autumn. It is important to note that the observations in the literature all relate to temperate Northern Hemisphere species which initiate one cycle of flower primordia before entering a period of winter dormancy. In *P. radiata,* strobili are associated with each of a series of branch clusters initiated sequentially throughout the growing season. Thus any check of growth during summer might be expected to reduce the total number of strobili produced. The work of Bollmann & Sweet (1976) illustrated this point. They found that a particular clone of *P. radiata* at Rotorua, New Zealand, produced five clusters of branches during a years growth, the first three of which bore female strobili. However, at a colder site, only three or four clusters were produced, with a maximum of two containing female strobili.

The literature contains few direct reports of responses to irrigation in seed orchards. Barnes & Bengston (1968) failed to obtain a response in a slash pine (*P. elliottii* Engelm. var. *elliottii*) orchard in Florida, but their site had an average rainfall approaching 1300 mm per year, double that received at Saxton's. A member company of the N.C. Co-operative Tree Improvement program reported favourably on the economics of irrigation in a loblolly pine (*P. taeda* L.) orchard in South Carolina (CTIP 1975) and Dewers & Moehring (1970) found that irrigation in spring followed by summer drought was the most beneficial treatment in their experiment with loblolly pine in Texas.

Pawsey (1960) found that, for plantation-grown *P. radiata,* drought during the summer prior to maturation resulted in a high incidence of dry cones which contained no seed. Under some conditions irrigation may therefore serve the double function of enhancing initiation and permitting successful development of the crop initiated 2 years beforehand. Our counts of cones (Table 3) did not distinguish between normal and dry cones. Although the latter have certainly been observed at Saxton's, the orchardist did not identify this as a serious problem during the course of the experiment.

The flowering response observed to nitrogen fertiliser was less than that due to irrigation, but is in accordance with the majority of reports in the literature. Of the 37 papers reviewed by Lee (1979), 32 reported a positive female flowering response to nitrogen fertiliser. However, the mechanisms involved are not well understood. The form of nitrogen and time of application have been regarded as critical by some workers (e.g., Ebell 1972), but in a comprehensive series of experiments on *P. radiata,* Sweet & Hong (1978) were unable to demonstrate any specific role of nitrogen in cone production. They concluded that the responses reported in the literature could probably be explained in terms of increased growth and hence in the number of potential sites of strobilus initiation on the tree crown.

In the orchard used in Sweet & Hong's study, the content of nitrogen in the foliage was some 30% above the 1.6% (o.d. wt.) regarded as limiting for vigorous vegetative growth in New Zealand (Will 1978) and application of nitrogenous fertiliser in their experiments did not result in increased stem growth. Pederick & Brown (1976) reported experience from two *P. radiata* orchards in Victoria, one of which had high foliar nitrogen levels (1.9%) and showed no response to fertiliser. The other orchard, where initial foliar nitrogen was 1.6%, responded to fertiliser with increased colour and density of the foliage, and produced more female strobili than the unfertilised ramets.

In this experiment, where the content of nitrogen in the foliage of the unfertilised plots was about 1.5%, a positive growth response was obtained (Table 5). Since we did not measure the growth of branches, which carried the majority of cones produced, we cannot demonstrate a direct relationship between flowering and growth responses. Nevertheless, our data are consistent with such a hypothesis. Cultural treatment may certainly alter the form of *P. radiata* trees, and Will (1971) has shown that application of nitrogen can result in increased branch development and hence reduced apical dominance as well as greater growth in stem diameter. The change in height/basal area ratio induced by the I_1N_1 treatment (Table 5) suggests that irrigation could have had an effect on branch growth similar to that obtained by Will (1971). The flowering response to nitrogen occurred only when soil moisture was available (all plots in 1976 and 1979, and irrigated plots in 1977 and '78), i.e., when vegetative growth was not limited by moisture stress. The 2 years in which we demonstrated a highly significant effect of irrigation on basal area increment (1976–77 and 1977–78) were those which directly preceded seasons in which a strong flowering response was also obtained (1977 and 1978).

The effect of an interaction between fertiliser and irrigation on survival is of practical importance for those seed orchardists who still use grafting as a means of propagation, in that it emphasises the danger of attempting to enhance growth by fertiliser application without also supplying adequate water to the trees. The problem may be circumvented by using rooted cuttings (Griffin *et al.* 1976). In a parallel experiment to be reported separately, we applied similar treatments to an adjacent orchard section planted with cuttings. Over the same sequence of years mortality was only 4%.

Since there was no significant effect of treatments on seed yield per cone, seed weight, or cone loss during development, it was possible to estimate seed yield per hectare directly from the flowering data (Table 6). For the purposes of estimation we used the mean values obtained from the 1976 and 1977 assessments, i.e., assuming that 78 full seeds were produced by each cone, 100 seeds weighed 3.23 g, and that 93% of the strobili counted would produce a ripe cone. Although the effect of treatments on graft incompatibility would have some influence on the yield of seed per hectare, it is not realistic to estimate these directly from mortality in small plots. This is because losses on one individual will to some extent be compensated for by additional yield from adjacent trees. We therefore assumed that mortality was distributed uniformly across the experiment. Of the 245 trees present at the start of the experiment, 154 were healthy at the conclusion (or 169 stems/ha) so this factor was used in computation. The estimates are conservative in respect of total production per hectare as no account was taken of cones harvested from trees which produced for part of the 4-year period before they became unhealthy or died.

It is apparent (Table 6) that the I_1N_1 treatment resulted in an additional 13.8 kg seed/ha per annum compared with I_0N_0. The highest yield in the control plots of 23.0 kg/ha was less than the poorest I_1N_1 crop (24.2 kg/ha). Most importantly from the planning viewpoint, the year-to-year variation in cone crop, which was noted by Pederick & Brown (1976) as a feature of *P. radiata* seed orchards in Australia, was greatly reduced by the treatments employed.

TABLE 6—Estimated seed yield per hectare per year

Treatment	Mean annual yield 1976–79 (kg/ha)	Range in yield 1976–79 (kg/ha)
Unirrigated ($I_0\bar{N}$)	17.4	6.7–34.1
Irrigated ($I_1\bar{N}$)	25.8	19.4–34.5
* Least productive treatment (I_0N_0)	15.3	8.3–23.0
* Most productive treatment (I_1N_1)	29.1	24.2–34.5

* On an individual ramet basis

The improved yields which we have demonstrated can be achieved only at an increased cost to management. It remains for the individual orchardist to determine whether such an investment is worthwhile. The superficially obvious course of siting seed orchards on more fertile, higher rainfall sites, is of doubtful benefit in Australia. Such sites tend to be at higher elevations, with cooler cloudier weather conditions that may be unfavourable for initiation of flowers and pollination (Griffin 1984). They are also likely to present problems of soil trafficability. Since it is possible to manipulate water and nutrients, but not temperature or hours of sunshine, we suggest that the latter factors should be accorded higher priority when selecting the site for a seed orchard.

This experiment tested the potential of irrigation and fertiliser treatments for improving the yield of seed orchards of *P. radiata* in Australia, and showed conclusively that both irrigation and nitrogen may be beneficial. However, the experiment was not designed to define an optimum rate or form of fertiliser application, nor to explore the possibility of irrigating for only part of the growing period. Irrigation was not required on this site in years of high rainfall and further work to predict periods when trees are responsive to irrigation from measurement of rainfall and the availability of soil moisture in springtime, together with chemical analyses of the foliage to determine the necessity for fertiliser application, would pay dividends for those orchardists interested in maximising their returns on investment in cultural treatments.

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